Environmental Monitoring of PGPR-Based Seed Bio-Priming in Petroleum-Contaminated Soils

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Abstract

Petroleum contamination is a significant environmental problem that disrupts soil quality, seed germination, and early plant establishment. Oil-polluted soils often reduce germination percentage, delay seedling emergence, and restrict plant growth due to hydrocarbon toxicity, oxidative stress, and disturbances in hormonal balance. These negative effects not only reduce agricultural productivity but also hinder ecological restoration and long-term land recovery. Plant growth-promoting rhizobacteria (PGPR)-based seed bio-priming has emerged as a promising and environmentally sound strategy to enhance plant performance under petroleum stress. Recent studies published between 2018 and 2025 demonstrate that seeds treated with selected PGPR strains exhibit higher germination rates, faster and more uniform emergence, and improved seedling vigor in contaminated soils. These benefits are mainly associated with enhanced antioxidant activity, better regulation of phytohormones, reduced accumulation of reactive oxygen species (ROS), and improved cellular integrity during early growth stages. Beyond improving plant establishment, certain PGPR strains are capable of degrading petroleum hydrocarbons in soil, thereby lowering phytotoxicity and stimulating beneficial microbial activity. Environmental monitoring indicators, including total petroleum hydrocarbon (TPH) reduction, soil enzyme activity, microbial biomass, and plant growth parameters, provide measurable evidence of soil recovery. Overall, PGPR-based seed bio-priming represents a practical, nature-based approach for restoring petroleum-affected soils and supporting sustainable land management strategies.

Keyword: PGPR, Seed bio-priming, Petroleum-contaminated soils, Seed germination.

الرصد البيئي لعملية التنشيط الحيوي للبذور باستخدام بكتيريا PGPR في التربة الملوثة بالنفط

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المستخلص

يُعدّ التلوث النفطي مشكلة بيئية خطيرة تُؤثر سلبًا على جودة التربة، وإنبات البذور، ونمو النباتات في مراحلها الأولى. وغالبًا ما تؤدي التربة الملوثة بالنفط إلى انخفاض نسبة الإنبات، وتأخر ظهور الشتلات، وتقييد نمو النباتات بسبب سُمّية الهيدروكربونات، والإجهاد التأكسدي، واضطرابات في التوازن الهرموني. ولا تقتصر هذه الآثار السلبية على تقليل الإنتاجية الزراعية فحسب، بل تمتد لتشتت جهود الاستعادة البيئية واستعادة الأراضي على المدى الطويل.برزت تقنية التنشيط البيولوجي للبذور باستخدام بكتيريا الجذور المُحفِّزة للنمو (PGPR) كاستراتيجية واعدة وصديقة للبيئة لتحسين أداء النباتات في ظل الإجهاد الناتج عن النفط. وتُظهر الدراسات الحديثة، التي نُشرت بين عامَي 2018 و2025، أن البذور التي تُعالج بسلالات مختارة من هذه البكتيريا تُظهر معدلات إنبات أعلى، وظهورًا أسرع وأكثر تجانسًا، إضافة إلى تحسن في حيوية الشتلات في التربة الملوثة.تُعزى هذه الفوائد بشكل رئيسي إلى تحسن النشاط المضاد للأكسدة، وتنظيم أفضل للهرمونات النباتية، وتقليل تراكم أنواع الأكسجين التفاعلية (ROS)، وتعزيز سلامة الخلايا خلال المراحل المبكرة من النمو. وبجانب تحسين إقامة النباتات، تمتلك بعض سلالات البكتيريا الميكروبية المُعزِّزة للنظام العصبي (PGPR) القدرة على تحليل الهيدروكربونات البترولية في التربة، مما يقلل من السمية النباتية ويعزز النشاط الميكروبي المفيد.تُعد مؤشرات المراقبة البيئية، مثل انخفاض إجمالي الهيدروكربونات البترولية (TPH)، ونشاط إنزيمات التربة، والكتلة الحيوية الميكروبية، ومعايير نمو النباتات، أدلة قابلة للقياس على تعافي التربة. وبشكل عام، يُمثِّل التنشيط البيولوجي للبذور القائم على PGPR نهجًا عمليًا ومستمدًا من الطبيعة لاستعادة التربة المتأثرة بالبترول، ودعم استراتيجيات إدارة الأراضي المستدامة.

الكلمات المفتاحية: PGPR، التنشيط البيولوجي للبذور، التربة الملوثة بالنفط، إنبات البذور.

Introduction

As seed priming is a sustainable pre-sowing treatment to improve germination/seedling growth and crop productivity/quality under abiotic stress conditions (Guha et al., 2021; Fiodor et al., 2023), it can possibly alleviate the adverse effects of global warming on crops. The method makes use of controlled moistening which induces metabolic activity in the seed without causing radicle emergence, leading to earlier and more synchronized germination following sowing (Ajinde et al., 2023). Out of all the aspects, formation of seed activation through bio-priming is a particular method involving additional inoculation of beneficial microorganisms such as plant-growth-promoting bacteria attached on the surface of seed in order to promote the germination, establishment of a robust plant and tolerance (Torres-Abe et al., 2024). This depends on the interplay between plant and microorganisms (macromolecules) in rhizosphere, the two main key players that can significantly regulate their status and ultimate yield (Geetha et al., 2022). Essential elements of plant resilience, these microbial communities (e.g., plant-growth-promoting bacteria and arbuscular mycorrhizal fungi) induce enhanced physiological, chemical, and biological responses to various abiotic constraints (Fiodor et al., 2023, Anon., 2025). This article will comprehensively cover the physiological applicability of the bacterial seed activation in sustainable agriculture by offering seed germination performance enhancement, bioremediation of oil pollution soils and food security contribution. In addition to shortening the lag phase for metabolic processes in seeds with higher germination rates, better nutrient uptake and stronger pathogen resistance these offer key components for sustainable agricultural production (Bano et al., 2024). Apart from

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the direct advantages, the activation of bacterial seeds offers a green and sustainable substitute for the regular chemical agricultural inputs, which, in many cases, is associated with considerable ecological risk (Shaffique et al., 2023). Since the method is based on an early interaction of beneficial members of a microbiome with an emerging root, bacterial seed priming can provide the first line of microbe-mediated plant stability to external influences, leading to crop cultivation (Kumar et al., 2024). This review discusses the mechanistic underpinning of bacterial seed activation and how these microbial inoculants help in alleviating the challenges of stress and stimulating the physiological functions of plants. Specifically, it addresses the involvement of endophyte-associated bacteria and rhizobacteria in plant hormone regulation, enhancing water and nutrient uptake, and inducing systemic resistance to biotic and abiotic stresses (Li et al., 2021; Torres-Abe et al., 2024). Moreover, this research also provides the solution on the role of seed activation with bacteria to reduce the oil pollution stress of soil in particular through enhancing the bioremediation process and assisting the plant stand growth in a destroyed bottom. Such information is perceived to be an invaluable approach to sustainable agriculture, reducing reliance on synthetic inputs and promoting long term environmental stewardship of a land use (Roy et al., 2022). Indeed, evidence suggests that repetitive applications of biological strategies, both bio stimulants and microbial inoculants, increase the microbial diversity in the rhizosphere, boosting crop productivity on multiple soil types and agricultural systems, and thus fostering resilience in ago-ecosystems (Anon., 2025). This method follows to the overall aims of sustainable agriculture which aims to lower environmental footprint of production while increasing outputs (Mitra et al., 2021). Advances in biotechnology, such as high-throughput selection of desirable strains and CRISPR-based microbial engineering (Anon., 2025). improving their quality, efficiency, and broadening their applicability in modern agricultural systems, are achieved rapidly in this field (Dudeja et al., 2025).

This review article aims to examine the role of seed bio-priming technology using plant growth–promoting rhizobacteria (PGPR) in enhancing seed germination and seedling establishment in petroleum-contaminated soils, and to elucidate its physiological and biochemical mechanisms in reducing hydrocarbon-induced toxicity. It also highlights the contribution of this approach to restoring degraded soil fertility and mitigating land degradation processes associated with desertification by improving soil recovery indicators and supporting sustainable agroecosystem management, based on recent studies published between 2018 and 2025.

Research Gap and Scope of the Review

Although many studies have investigated the role of plant growth-promoting rhizobacteria (PGPR) in enhancing seed germination under general abiotic stresses such as salinity, drought, and heavy metals, limited attention has been given to their specific application in petroleum-contaminated soils (Rai et al., 2022). Most previous research has either focused on bioremediation processes alone (hydrocarbon degradation in soil) or on seed priming under conventional stress conditions, without clearly linking seed physiological responses to in situ remediation outcomes (Geetha et al., 2022). In addition, existing studies are often fragmented, crop-specific, or limited to short-term germination assessments, lacking an integrated perspective that connects hormonal regulation, oxidative stress mitigation, microbial degradation pathways, and early plant establishment in polluted environments (Rehman et al., 2025). Therefore, this review aims to bridge this gap by synthesizing recent evidence (2018–2025) on PGPR-based seed bio-priming as a dual-function strategy that simultaneously enhances seed performance and contributes to hydrocarbon detoxification in soil(Anon., 2025). The scope of this review includes (Table 1): (i) the physiological mechanisms underlying improved germination in oil-contaminated conditions, (ii) the microbial traits responsible for hydrocarbon degradation and stress alleviation, (iii) comparative analysis of recent experimental findings, and (iv) future research directions for field-scale implementation(Ehis-Eriakha et al., 2024; Qiao et al., 2025). By integrating seed biology with soil bioremediation concepts, this review provides a clearer framework for developing sustainable crop establishment strategies in petroleum-affected ecosystems(Geetha et al., 2022; Ehis-Eriakha et al., 2024). This comprehensive approach underscores the potential of plant growth-promoting rhizobacteria as a multifaceted tool for both sustainable agriculture and environmental remediation, advancing the concept of next-generation biofertilizers and bioremediation agents (Oubohssaine et al., 2025). Further exploration into the multi-omics approaches, such as genomics, transcriptomics, and metabolomics, can elucidate the molecular and biochemical pathways governing heavy metal detoxification and the intricate interactions between PGPRs and plants (Kaushal and Pati, 2025).

Table 1. Research Gap and Scope Framework of PGPR-Based Seed Bio-Priming in Petroleum-Contaminated Soils

Aspect	Status in Previous Studies	Identified Gap	Contribution of This Review
PGPR under abiotic stress	Extensively studied under salinity, drought, and heavy metals	Limited focus on petroleum-contaminated soils	Focused synthesis on oil-contaminated environments
Bioremediation research	Emphasis on hydrocarbon degradation in soil	Weak linkage with seed physiology and early germination	Integration of seed physiological responses with in situ remediation
Seed priming studies	Mostly under conventional stress conditions	Lack of studies connecting priming with soil detoxification	Dual-function framework: germination enhancement + hydrocarbon reduction
Experimental scope	Often crop-specific and short-term	Fragmented evidence, limited cross-study comparison	Comparative analysis of studies (2018–2025)
Mechanistic understanding	Partial discussion of ROS or hormones	No integrated mechanistic model linking ROS, hormones, and degradation enzymes	Proposed integrated physiological–microbial framework
Field application	Mostly laboratory-based findings	Limited field-scale validation	Practical implementation perspective included
Future direction	Rare use of multi-omics approaches	Limited molecular-level insight	Highlighting genomics, transcriptomics, metabolomics for future research

Petroleum-Contaminated Soils and Constraints on Germination:

Oil contains harmful substances that strongly interfere with important cell functions and nutrition uptake and hence have drastically negative effects on seed germination and plant development(Correa et al., 2022). Working oil derivatives (polycyclic aromatic hydrocarbons) are suspected of damaging genetic material (DNA) and causing oxidative stress, which kills plants at the time of their germination and early developing stages of their seed hydras (Haider et al., 2021; Correa et al., 2022; Felisardo and Gonçalves, 2023). Not only these complex compounds disrupt the signaling pathway and cellular functions in the seed (Shelar et al., 2024) , but also these complex compounds are known to have adverse effects on enzyme activities and on the integrity of the cell membrane (Shelar et al., 2024). Moreover, the effect of oil pollution will cause changes of soil microbial communities, which subsequently influence important microbial–plant interactions and nutrient cycles (Zhuang et al., 2023), and are major drivers of germination and plant stability success. In this sense, this contaminant may lead to reduced water and soil acidification, which could create adverse germination conditions for seeds (Sahito et al., 2025). In fact, such inhibiting effects should be overcome by establishing the use of innovative treatments, e.g., the activation of seed by co-cultivation with bacteria, to enable the establishment of plants in soil contaminated with heavy metals (Imran et al., 2024). Herein, one of the most deleterious forces destroying seeds and impeding seed germination are noxious xenobiotic materials such as petroleum hydrocarbons, heavy metals, and salinity, which disrupts metabolic processes and ultimately causes lethal cytotoxicity (Mohamed et al., 2025). Strikingly, hazardous environmental materials such as petroleum hydrocarbons, heavy metals, and salinity represent some of the most important aspects responsible for seed vivacity and germination through hindering of metabolic activities and inducing severe cell damage (Luo et al., 2024). Various mitigation strategies have been arranged to counter these adverse effects, one of them is seed priming by beneficial microorganisms, to enhance tolerance to seeds and establish plant growth more properly in niche conditions (Chakraborti et al., 2021; Mohamed et al., 2025). For example, petroleum compounds form a hydrophobic layer on the seed surface that prevents water and oxygen access to the growing embryo, and causes plants oxidative stress and chlorophyll degradation (Table 2).

Table 2. Effects of petroleum-contaminated soils on seed germination and early seedling development

Stress factor	Key biological mechanisms affected	Impact on germination and early growth
Petroleum hydrocarbons (PAHs)	DNA damage, oxidative stress, disruption of cellular signaling pathways	Severe inhibition of germination and high mortality at early seedling stages
Complex oil-derived compounds	Enzyme inhibition and loss of cell membrane integrity	Reduced water and nutrient uptake; decline in seed vigor
Petroleum-contaminated soils	Interference with core metabolic pathways; cytotoxic effects	Delayed germination and impaired seedling establishment
Xenobiotic pollutants (petroleum hydrocarbons, heavy metals)	Metabolic dysfunction and oxidative cellular injury	Loss of seed viability and abnormal early development
Combined stresses (oil pollution, heavy metals, salinity)	Cumulative physiological and cellular damage	Severe suppression of germination and early growth

Concept of Bacterial Bio-Priming

Bacterial activation of seeds is the treatment of seeds with beneficial microorganisms (mainly beneficial PGPR) which provides, promotes germination, enhance seedlings vigor and plant defense against occurrences of various abiotic and biotic stresses (Shelar et al., 2024). This process triggers metabolic activities after imbibition but does not allow the emergence of the radicle, resulting in a longer lag phase and postponing the germination exponential growth phase (Bano et al., 2024). This prior treatment for agriculture induces the antioxidant defense system of the seeds, activates enzymatic activity, adjusts hormone balance which provides a positive response in germination percentages and vigor of seeds (Singh et al., 2021). This is a successful strategy that facilitates overcoming the negative effects of toxic environmental contaminants such as petroleum hydrocarbons by up-regulating seed self-defense (Jatana et al., 2024), in addition to inducing more sophisticated physiological responses In the early developmental stages of plants, the support of beneficial bacterial communities in the vicinity of the root part contributes to the establishment of stable microbiomes assisting detoxification processes and nutrient uptake (Khanna et al., 2022). Moreover, the reliance of this strategy on the interaction of plant and microorganisms leads to increased stress tolerance and improved plant performance under harsh environmental conditions. Actually (Anon., 2025), the bacteria secrete plant hormones and Siderophores that enhance the growth of plants, their nutritional potential, and density even from unfriendly environments (Ali et al., 2023). Together, such a symbiosis allows enhanced nutrient mobilization and uptake that supports plant establishment and the resilience of the enteral system in degraded soils (Figure 1).

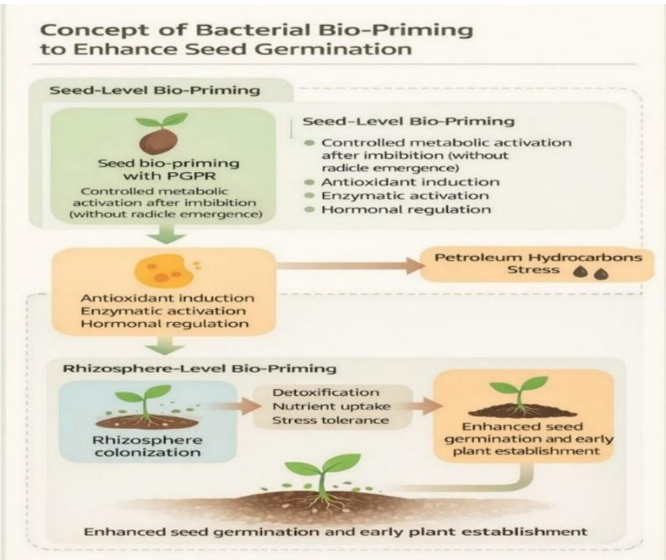

Figure 1. Seed- and rhizosphere-level mechanisms of bacterial bio-priming conferring tolerance to petroleum hydrocarbon stress.

Key Bacterial Groups Used in Bio-Priming

Bacillus and Pseudomonas species are some of the most widely used bacterial taxa for the activation of seeds, as they are well-defined in their PGP traits and their potential to withstand different stress factors (Geetha et al., 2022). These strains are characterized by multiple modes of action which include indole-3-acetic acid, siderophores and lytic enzymes that together act synergistically to stimulate nutritional and mineral absorption, pathogen antagonism, and induce plant defense (Shaffique et al., 2023). Such potential for specific-microbe-based improvement of stress tolerance for these key plants has been shown by S-level or cross-inoculation by strains in stress-adapted genera of S-level such as Acinetobacter, Cronobacter and Priestia (Singh et al., 2023) .Similarly, specific strains of Pseudomonas, (e.g. *P. aeruginosa* {P8 and P9}) not only enhance root elongation as well as seedling biomass, but also exhibit antioxidant activity, showing that these strains behave as growth promoters and stress alleviators (Zboralski and Filion, 2023). Those bacteria also play a role in inducing systemic resistance, whereby, they prime plants to more faster and efficiently respond to following biotic and abiotic stresses (Dhiman et al., 2026). Also, through LEfSe analysis, other genera such as Rhizobacter, Enterobacter, and Chitinophagales were identified as a unique species in plant-treated bacteria, suggesting their regulatory role of the soil bacterial community and their potential to impart stress tolerance (Monohon et al., 2021). Interaction dynamics of activating factors and beneficial communities can be demonstrated, for example, when the abundance of some genera (for instance, Sphingomonas, Arthrobacter, and Novosphingobium) increased in the root region after seed treatment with Na_2SeO_3 (Liu, et al., 2025). Among these genera, Bacillus megaterium is regarded as one of the most unique species for its ability to regulate both physiological and biochemical pathways to ensure higher plant growth and endurance, especially in stress-prone growth environments (Zhang et al., 2023). Besides, broad range of metabolic potential of some Bacillus species such as biosurfactant production and heavy metal chelation ability is advantageous for further improvement of plant protection potential and phytoremediation efficiency in polluted soils (Figure 2).

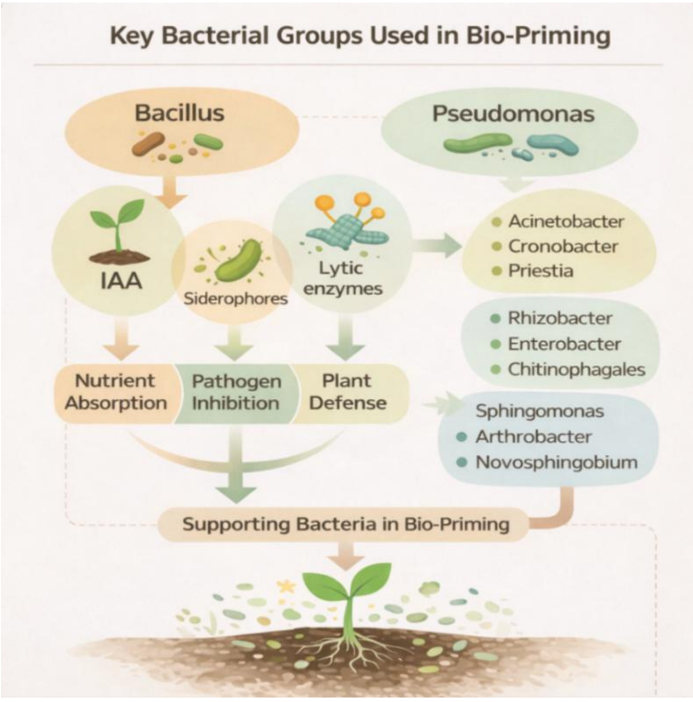

Figure 2. Key bacterial groups supporting seed- and rhizosphere-level bio-priming responses.

Mechanisms of Action

An integrated array of physiological, biochemical, and rhizosphere mechanisms are responsible for the beneficial effects of PGPR on seed germination and seedling establishment via early growth (Backer et al., 2018). They are plant growth promoting bacteria that produce plant hormones, dissolve mineral elements and fix atmospheric nitrogen which increase nutrient availability and stimulate metabolic processes during early plant growth steps (Azam et al., 2025). PGPR additionally favor root architecture by increasing root length and surface area supporting roots to intercept water and nutrients under stress conditions in the soil (Azam et al., 2025). Stress alleviation via ACC deaminase, an enzyme that reduces ethylene levels induced by stress, which is associated with enhanced plant tolerance to salinity, drought, and heavy metal toxicity (Shahid et al., 2023). At the same time, PGPR sequester minerals through the production of siderophores to maximize the uptake of micronutrients but also reduce the toxicity of heavy metals such as lead, cadmium, arsenic, zinc and copper in plants (Kaushal and Pati, 2025). Second among these mechanisms is the antioxidant defense mechanism because PGPR can attenuate the accumulation of reactive oxygen species (ROS) and thus maintain cell integrity during germination via the upregulation in activity of enzymes such as catalase and superoxide dismutase, which has been reported in many research studies such as (Anon., 2025). PGPR broadly enhances root system architecture by enhancing root length and surface area to improve uptake of water and nutrients under stress soil conditions (Alturki et al., 2023). Among them, the main mechanism of stress alleviation is the activity of 1-aminocyclopropane-1-carboxylic acid deaminase (ACC deaminase) reduce stress-induced ethylene levels to improve plant tolerance under salinity, drought and heavy metal toxicity (Shahid et al., 2023). Additionally, PGPR produces siderophores that not only chelate minerals and but also enhance micronutrient uptake and decrease metal toxicity in the plants (Giannelli et al., 2023). Antioxidant defiance system is another one of the major mechanisms in which PGPR reduce the accumulation of reactive oxygen species (ROS) both by elevating the catalase and superoxide dismutase (SOD) enzymes activity that maintain the integrity of cells during germination (Sheng et al., 2025). In addition to stimulating plant growth directly, PGPR can activate systemic acquired resistance through salicylic acid and jasmonic acid-dependent signaling pathways, priming the plant to respond more vigorously to subsequent biotic and abiotic stresses (Bano et al., 2022; Sali et al., 2025). Specific bacterial strains, because of their production of extracellular sugars which bind to excess cations and decrease soil electrical conductivity at the root zone level, alter the physical and chemical properties of soil to alleviate osmotic stress (Anon 2025). As demonstrated in previous studies with Bacillus megaterium, it can alleviate drought-induced oxidative stress by upregulating the gene expression of multiple antioxidant enzymes as well as the mobilization of macronutrients and micronutrients through phosphate solubilization and iron chelation (Anon 2025). Additionally, some PGPR can also synthesize exopolysaccharides that facilitate soil aggregation and improve its water-holding capacity, thus directly alleviate drought stress (Figure 3).

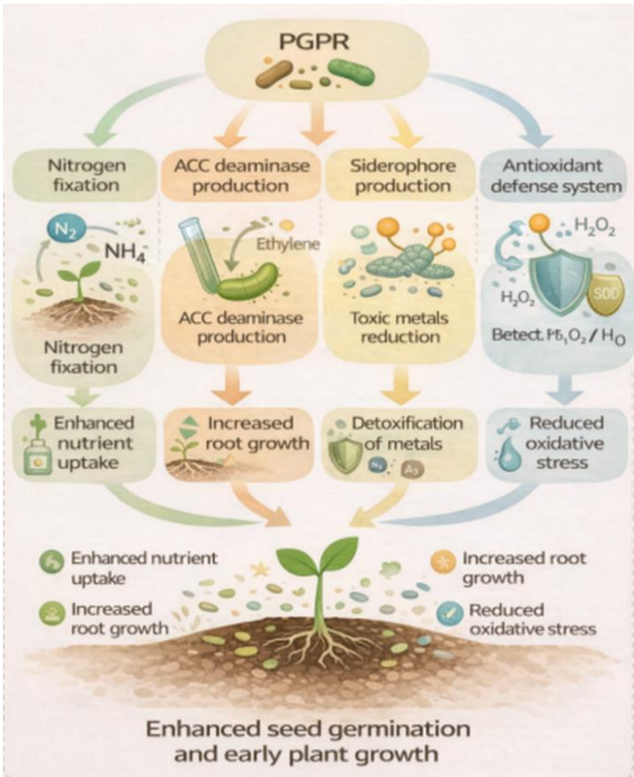

Figure 3. Integrated mechanisms of action of plant growth-promoting rhizobacteria (PGPR) enhancing seed germination and early plant growth under stress conditions.

1- Effect of PGPR concentration on early seed germination dynamics

The effectiveness of plant growth-promoting bacteria on increasing seed germination and seedling vigor during the early development stages depends on the initial concentration applied because the most favorable level of inoculation gives rise to maximum enhancement rates in germination and growth vigor, but very low or very high concentrations of bacteria tend to become ineffective (Satognon et al., 2025). Suitable bacterial densities increase the effectiveness of photosynthesis, enhance antioxidant capacity, and ameliorate the plant water status, thereby decreasing oxidative stress production and improving the physiological stability of plants subjected to stress (Chen et al., 2025). The contribution of PGPR seed inoculation to support osmotic adjustment, evidenced by increases in leaf proline accumulation and stable chlorophyll content, was especially detectable under drought (Alturki et al., 2023).Furthermore, PGPR strains may also modulate the release and bioaccumulation processes of heavy metals, as well as metabolism of PAs, which may improve the storage capacity of the plant and decrease the amounts of metals that migrate to the aerial sections (Manzoor et al., 2025). These targeted response confirmations highlight the need for enhanced formulations to properly activate the bacteria once in the seed, permanently and consistently, and in high-performance under field conditions (Faizan et al., 2024).

2- Germination performance of seed from soil remediation with bacteria

PGPR-mediated bioremediation enhances seed germination at soil level by reducing pollutant bioavailability and their phytotoxicity (Torres-Abe et al., 2024). Microbial breakdown or immobilization or bioremediation of contaminants offers a pollution-free habitat for seedling germination and initial root formation (Chen et al., 2025). The soil characteristics that contribute to these improvements are increased germination rates, increased seedling vigor, and or better stability of plants in contaminated soils (Pan et al., 2025). Apart from their direct reduction of pollutants, PGPR also enhance soil quality at large, through the restoration of microbial activity and nutrient cycling, as well as improvements of soil structure (Sidhu et al., 2025). Resulting benefits include germination rates, increased seedling vigour and stability of plants in contaminated soils, leading to improved soil characteristics (Oubohssaine et al., 2025).

Current Status Review (2018–2025): Impact of PGPR-derived Bio-Priming on Seed Germination in Hydrocarbon-Contaminated Sediments

Studies have repeatedly evidenced that plant growth-promoting bacteria (PGPR) can significantly reduce the negative effects of oil pollution on the seed germination and seedling establishment performance at early stages (Qiao et al., 2025). There is ample evidence between 2018 and 2025 for considerable enhancement in germination rate (%), acceleration of germination dynamics and seedling vigor due to PGPR mediated bacterial seed priming in oil-seeded soils through activation of detoxification pathways and enhancement of nutrient availability (Torres-Abe et al., 2024). In some cases, seed inoculation enhanced seed germination and early plant growth in crude oil-contaminated soils, through a pronounced enhancement of antioxidant enzyme activities and reduction of hydrocarbon toxicity when seeds were impregnated with the bacterium Pseudomonas putida (Ehis-Eriakha et al., 2024). In a similar vein, PGPR treatments alleviate oil pollution-induced oxidative stress, by enhancing important antioxidant enzymes, such as catalase and superoxide dismutase, to safeguard germinated seeds against the harmful effects of reactive oxygen species (Ali et al., 2024). Whereas a few strains of root zone bacteria secrete extracellular enzymes like laccases, peroxidases, P450 monooxygenases and glutathione-S-transferases associated with improved biodegradation of polycyclic aromatic hydrocarbons and other petroleum products (Ehis-Eriakha et al., 2024). The biosurfactants produced by the PGPR also enhance the solubility and bioavailability of hydrophobic hydrocarbons subsequently enhancing microbial degradation and diminishing the hydrophobicity of these and other phytotoxic non-water-soluble compounds in the soil (Karamchandani et al., 2022). Overall, these results are consistent with PGPR-mediated bacterial activation to create a soil environment that is more biologically safe and better able to provide conditions that allow seeds to cope with oil pollution stress and to establish as healthy seedlings (Varjani et al., 2020; Ehis-Eriakha et al., 2024). Such flexibility is an important component of agricultural sustainability in land areas potentially impacted by oil and industrial land pollution due to the reduction of water, oxygen and nutrient availability by oil compounds, and adverse effect on seed germination and plant growth (Correa et al., 2022). Moreover, root exudates such as root exudates: fats, carbohydrates, and proteins are released by germinated seeds and seedlings which secrete passerine bacteria, forming needed relationships between plants and beneficial bacteria, resulting in a favorable increase in plant growth and robustness towards a polluted environment (Anon., 2025). This mutualistic connection of PGPR with plants is strengthened by some species of bacteria like Pseudomonas sp. SB, to synthesize indole acetic acid, siderophores, and 1-aminocyclopropane-1-carboxylate deaminase to induce plant growth promotion as well as providing aid in phytoremediation processes (Table 3).

Table 3. Recent advances (2018–2025) in PGPR-mediated bio-priming for improving seed germination in hydrocarbon-contaminated soils

PGPR-related mechanism	Mode of action in contaminated soils	Observed effects on seed germination and seedlings	Representative PGPR / examples
PGPR-mediated seed bio-priming	Activation of detoxification pathways and enhancement of nutrient availability	Increased germination rate (%), accelerated germination dynamics, improved seedling vigor	Mixed PGPR consortia
Antioxidant enzyme induction	Upregulation of catalase (CAT) and superoxide dismutase (SOD); reduction of ROS	Protection of germinating seeds from oxidative stress; enhanced early establishment	*Pseudomonas putida*
Enzymatic biodegradation of hydrocarbons	Secretion of laccases, peroxidases, cytochrome P450 monooxygenases, GSTs	Degradation of PAHs and petroleum fractions; reduced phytotoxicity	Root-zone associated PGPR strains
Biosurfactant production	Increased solubility and bioavailability of hydrophobic hydrocarbons	Enhanced microbial degradation; reduced soil hydrophobicity	*Pseudomonas* spp., *Bacillus* spp.
Rhizosphere engineering	Creation of biologically safer soil microenvironment	Improved seedling establishment and plant stability	PGPR-enriched rhizosphere
PGPR–root exudate interactions	Utilization of root exudates (lipids, carbohydrates, proteins) to stimulate beneficial microbes	Strengthened plant–microbe symbiosis; enhanced tolerance to oil stress	Rhizosphere PGPR communities
Sustainability-related outcomes	Restoration of soil biological activity and nutrient cycling	Improved agricultural resilience in oil-impacted lands	PGPR-assisted remediation systems

Differences Between the Mechanisms of PGPR in Seed Germination and Petroleum-Contamination Soils

Although in both systems the general aim of PGPR application is improved plant growth, the underlying mechanisms used by these bacteria are often different, as the challenges posed for seed germination in unpolluted environments differ fundamentally from those contributing to remediation in petroleum-contaminated soils. During germination in uncontaminated soils where PGPR promote plant growth and health and indirectly assist phytoremediation process, PGPR break down hydrocarbons and reduce their toxic nature more directly in case of petroleum contaminated soils (Kumar et al., 2021). Plant growth-promoting rhizobacteria (PGPR) use various mechanisms to promote seed germination and growth in oil-contaminated soils, which can be contingent on the bacterial strain and soil conditions.

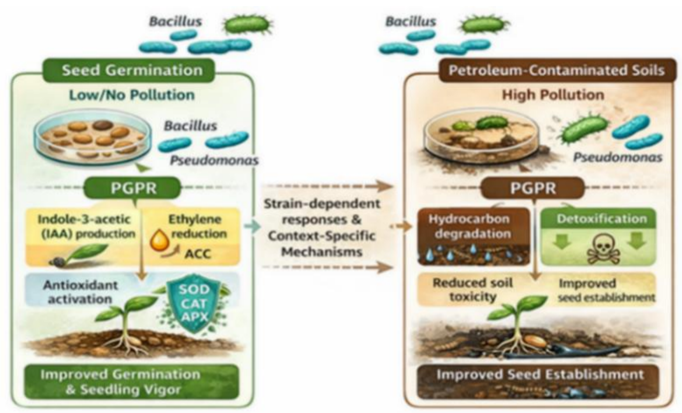

Figure 4. Comparative mechanisms of plant growth-promoting rhizobacteria (PGPR) in seed germination and petroleum-contaminated soils.

Certain bacteria, including Pseudomonas and Bacillus that mostly functions in plant hormone production such as indole-3-acetic acid (IAA) or through lowering ethylene (Baz et al., 2025). These triggers aid in seed germination and early establishment under stressful conditions (Torres-Abe et al., 2024). Additional strains of PGPR facilitate seed germination by stimulating the antioxidant system of plants, great assistance is also received from this system during seedling growth, protecting young seedlings against the oxidative damage imparted by petroleum pollutants (Ali et al., 2024). Some of these bacteria, at soil level, can degrade petroleum hydrocarbon, thus decrease the soil toxic load and enriching the environment around the seed (Ehis-Eriakha et al., 2024). Not all PGPR strains can act as both plant growth promotor and biocontrol agents. Some are only for seed performance improvement, without major soil remediation effects (Begum et al., 2024). This provides a reason why bio-priming is effective and has variable success between studies/environments (Figure 4).

Why Some Bio-Priming Treatments Fail

Even when PGPR bio-priming positively affects seed germination, in some conditions, seeds are unresponsive to treatment or lose performance ability (Shelar et al., 2024). One common reason is that a too high or too low a concentration of bacteria was used (Fiodor et al., 2023). Extreme levels of bacteria can reduce oxygen around the seed or generate compounds that inhibit germination (Begum et al., 2024). A further reason is an unsuitably match of the seed species and the bacterial strain employed (Torres-Abe et al., 2024). It has an oily, non-wettable surface and its high permeability can cause high permeability, low penetrative percolation (Simarmata et al., 2021). Petroleum toxicity in soils extremely contaminated with oil may be so mighty that some bacteria cannot stand it and, thus, will be less efficient (Ali et al., 2022). Furthermore, many laboratory studies that look very good in vitro utterly fail in the field because natural soils are much more complex and variable (Anon 2025). Thus, failure of a treatment is usually a consequence of poor optimization rather than an inherent limitation of the bio-priming strategy (Ptaszek et al., 2023). Still, to achieve the expected outcomes of inoculation and, as a result, predictable success in agriculture and phytoremediation, further studies are needed for better understanding the intrinsic hormonal status and sensitivity of the plant itself, and the intricate network of multiple phytohormones produced by both PGPR and endogenous plant pathways (Figure 5).

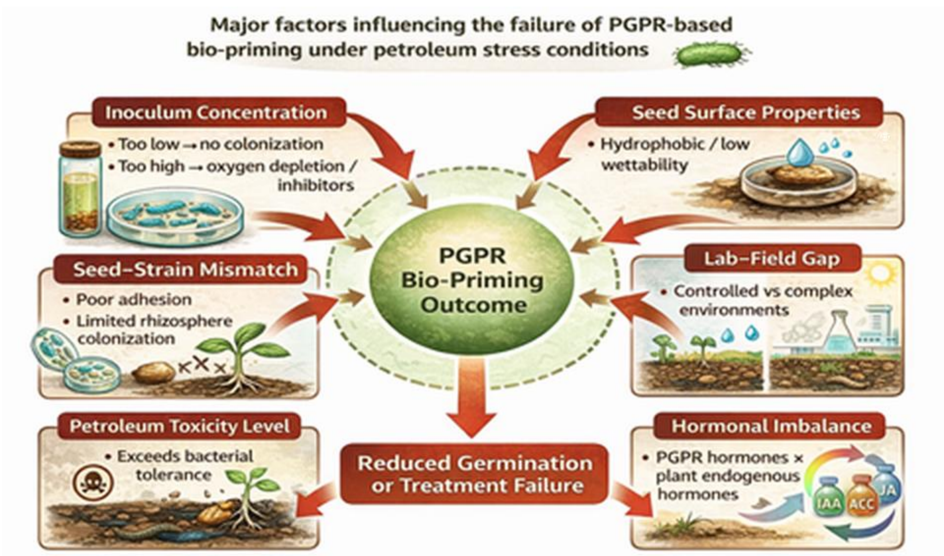

Figure 5. Major factors contributing to the failure of PGPR-based seed bio-priming under petroleum stress conditions.

Constraints for Field Application of PGPR Bio-Priming

Although bio-priming using PGPR can be highly advantageous, it is associated with multiple challenges when applied in the field (Jalmi and Sinha, 2022). The heterogeneity of oil pollution in terms of contamination extent, soil texture, and soil microbial community makes it difficult for addition or application of bacteria since survival and activity of them vary significantly in these types of soils (Kakde and Sharma, 2024). Moreover, it is challenged to keep the bacterial viability on the primed seeds during storage and transportation, which may compromise efficacy at planting. However, there is also an inherent limitation of lack common of guidelines for application in field (Yadav et al., 2024). It is crucial to note that many of these studies are small-scale and thus inadequate when trying to implement the same techniques on large areas for land restoration (Stanturf et al., 2024). Yet long-term data on economic benefits and performance are scarce, hindering adoption by farmers and decision-makers (Malan et al., 2024). Together with the limited knowledge of complex interactions between several phytohormones produced by PGPR and plant endogenous pathways, this absence of systematic and large-scale field data poses a major obstacle in achieving the much-needed and desired beneficial use of PGPR bio-priming strategies in agriculture and bioremediation (Kudoyarova et al., 2019). However, the misaligning results of field observations to controlled lab experiments sow the seeds of doubt regarding the reliability of PGPR-based biofertilizers, and thorough protocols in agriculture are urgently needed to guarantee proper implementation (İkiz et al., 2024). Additional challenges comprise the high-throughput selection of PGPR strains, their intricate interplay with indigenous soil microbiota, and their environmental adaptability across distinct climate and edaphic conditions, as long-term effects are needed to predict potential outcome (Figure 6).

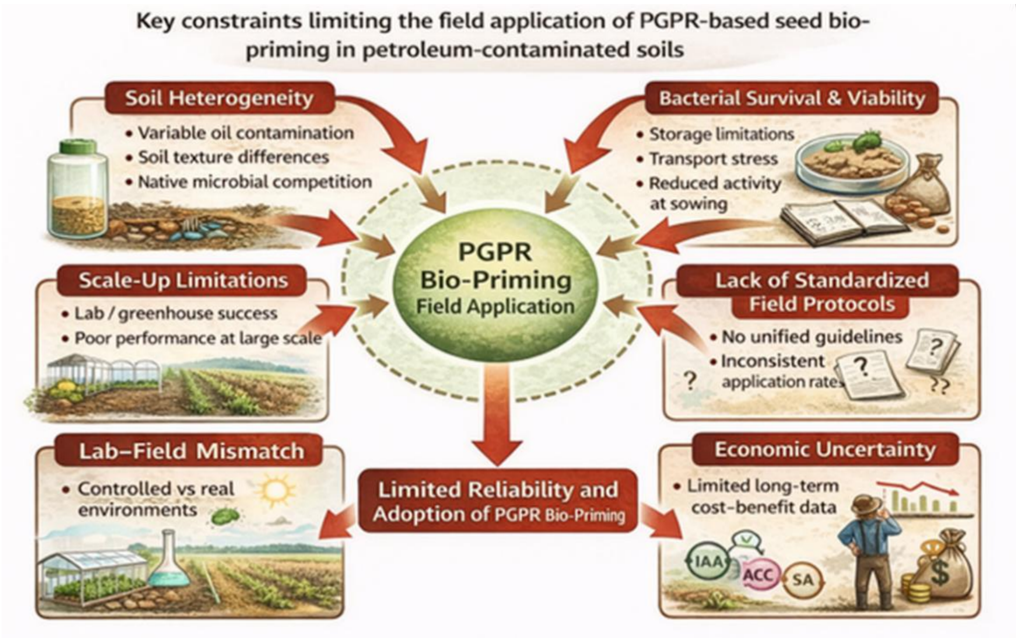

Figure 6. Key constraints limiting the field application of PGPR-based seed bio-priming in petroleum-contaminated soils.

Implications for Food Security

These microbial strategies, particularly related to PGPR-mediated bacterial activation, have far-reaching consequences on global food safety, enabling farming on marginal and contaminated lands. PGPR are known to alleviate the abiotic stresses such as salinity and drought, which decreases the need of expensive and environmentally damaging inorganic fertilizers (Rai et al., 2022). It provides opportunities to cultivate on lands that are unsuitable for agriculture, leading to an expansion of agrarian land and total food output. These advancement makes able to cultivate an area was previously unreceptive to cultivation (Ali et al., 2024). thus assisting both agricultural expansion and total food output. In addition, PGPR can bind cations and reduce harmful ionic bioavailability to the plant (Azam et al., 2025). Thus, alleviating salt stress, which poses a severe obstacle to the growth of non-halophytic plants in salinized soil by damaging nutrient absorption and raising osmotic pressure (Bhat et al., 2020). Since the development is a therapeutically important trait as salinity impacts around one third of the global farmland, reduces crop yield and worsens the global food insecurity menace, this capacity is utmost significant (Anon 2025). Activation the bacterial seeds by PGPR has also demonstrated that help crops to improve their resistance to various biotic and abiotic stresses including drought, salinity and heavy metal pollution which helps sustainable agriculture and food security (Shelar et al., 2024). This is a more sustainable type of agriculture compared to the traditional approaches, which are dependent on chemical inputs, which eventually reduce soil quality and exacerbate environmental problems (Singh et al., 2025). Bio-based shift represents the tenets of ecological intensification whereby factors of production target towards increasing sustained fertility of soil and resilience by utilizing biofuels over fertilizers, thus reducing reliance on the use of synthetic agricultural chemicals (Mahra et al., 2024). PGPR helps to facilitate the strong stability of crops under adverse conditions; they improve nutrient cycles, and promote plant tolerance to diverse forms of stress, and in turn, safeguard crop production (Kaushal et al., 2023). This multilayered enhancement in food production is elevated, in addition, by the combination of biotic technologies with genetically-eng-related crops that express PGPR traits (Tripathi et al., 2026). In addition, the deployment of PGPR-enabled plants in agroecosystems is a key strategy for lowering the environmental cost of agriculture through reduced chemical pest and fertilizer applications, ultimately supporting a healthy soil microbiome and sustainable ecosystems.

Limitations and Knowledge Gaps

Even though the PGPR holds an innovative potential to revolutionize sustainable agriculture and food security, some of the limitations and knowledge gaps need attention for further research (Ghosh et al., 2024). Perhaps the most important of these gaps was the lack of knowledge about the factors that regulate the roots-induced recognition of the root zone, which modulates the enhancement of the whole plant growth and stress tolerance (Robert et al., 2025). Recently it has become clearer that more studies will be needed to resolve the exact molecular and genetic basis by which PGPR interact with the plant, particularly since soils are such complex environments and plants are generally exposed to various forms of stress (Alturki et al., 2023). In agreement, interactions of PGPR with other soil microorganisms and their combined roles in nutrient cycles and pathogen suppression, involve complicated communication networks which remain enigmatic (Jalmi and Sinha, 2022; Alturki et al., 2023). Because these results are limited to the short-term, releasing external PGPR strains into natural microbial communities would need extensive study to prevent potentially unanticipated perturbations in the stability of ecosystems (Ghosh et al., 2024). One of the greatest difficulties in transferring the molecular advantages afforded by PGPR from the lab to the field is the interaction of multiple factors (e.g. gene x microbe x environment interactions) that differ significantly between lab and field environments for a wide range of strains as well (Azam et al., 2025). Building predictive models with these components would help to enhance the predictability with reliability of PGPR application effectiveness in crop systems. Since knowledge on which factors drove the establishment of the plant microbiome in response to bio-stimulants and whether these responses are host-or environment-associated is key for a robust application of beneficial bacteria in sustainable agriculture. In addition, the stability and effectiveness of microbial vaccines in seed coats, and the varieties of seeds and conditions under which they may be used are major obstacles to success under field conditions (González-Guzmán et al., 2021). Thus, further refinements of preparation formulations and delivery methods are needed to promote the successful transfer of these microbial organisms from bench to field (Anon 2025). In addition, Figure 7 application of 'omics' techniques like genomics proteomics and metabolomics can play a significant role in comprehensively elucidating PGPR-plant interactions and producing better strains conditions (Anon., 2025).

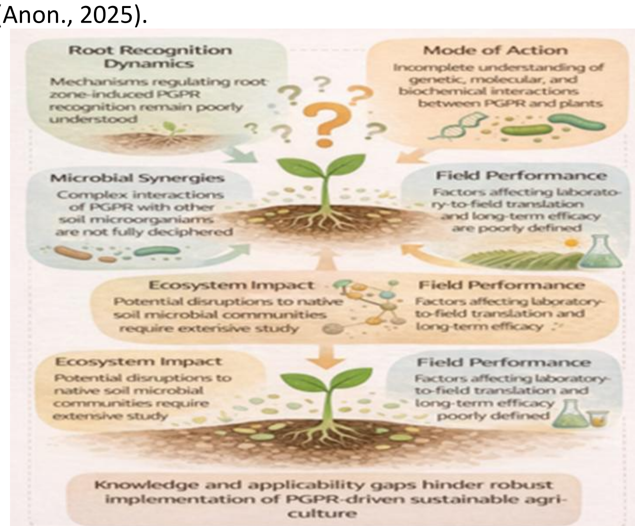

Figure 7. Knowledge gaps and implementation challenges in PGPR-mediated enhancement of seed germination and plant establishment.

Future Perspectives

While targeted improvement of these traits through enhanced packaging or more environmental-stress tolerant microbial assemblages (Darriaut et al., 2025). is an area for larger future study. Unsurprisingly, future research will help identify strong soil health indicators of microbial community structure and function based on technologies underpinning soil reclamation techniques and sustainable management such as metagenomics and metabolomics (Ejaz et al., 2024). We shall integrate bioinformatics with machine learning algorithms to allow these data to guide us on complex patterns and key taxa and microbial metabolic pathways for ecosystem services (Anon 2025).The performance of the co-interaction of nanoparticles and plant growth regulators is highly dependent on the crops, thus future research needs to be targeted for determining the obscurity of co-interaction of nanoparticles and plant growth regulators on beneficial food crops containing stress-tolerant crops and the practicality under diverse stress conditions in order to augment the viabilities of nanomaterials to activate sustainable agriculture. Research answering this question will necessitate not only considerable molecular might, but also representational muscle around what we do (and do not) know about the synergistic interaction of these factors and the gaps in our knowledge between them (Khan et al., 2024). Ongoing research is needed to develop microbial interventions, their utilitarian risks, and agricultural systems that can support their sustainability in the long-run (Zhang, 2024). Therefore, a data-driven approach that combines genomic and environmental assessments with improved delivery systems is needed for the rational selection of isolated strains and the manipulation of agricultural practices to promote crop health and productivity (Hanif et al., 2024). Although not yet explored, the intersection of seed coat-penetrating nanotechnology with biological seed activation based on fungi appears particularly plausible and promising for sustainable agriculture and biotic stress-protective crops by supporting stress tolerance to increase the quality and yield of crops as a result (Geetha et al., 2022, Zaim et al., 2023; Shelar et al., 2024; Panda et al., 2025). Furthermore, synergistic utilization of nanoparticles and plant probiotics on agricultural systems can help attain increased crop yield, boosted quality of food, and elevated food nutritional value for resolving global food safety issues (Figure 8).

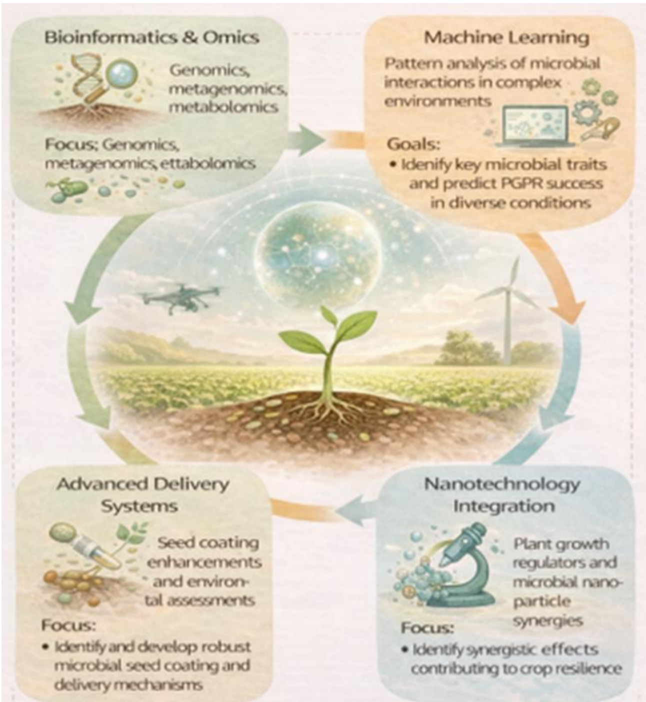

Figure 8. Conceptual roadmap of future perspectives in PGPR research for sustainable agriculture

Environmental Monitoring Indicators

To understand whether petroleum-contaminated soils are truly recovering, it is important to measure more than plant growth alone. Environmental monitoring indicators help evaluate the overall improvement in soil health. These indicators include the reduction in total petroleum hydrocarbons (TPH), which shows how much of the oil pollution has been degraded (Zuzolo et al., 2021). Reduced soil toxicity can be illustrated by improved seed germination and more vigorous seedlings (Sun et al., 2024). Elevation in microbial activity and soil enzymes confirms the activity of good soil microbes. Even soil properties, such as pH balance and organic matter content, represent another indicator of ecological recovery (Rivera et al., 2014). In aggregate, these pieces of evidence suggests that bio-priming by PGPR not only enhances seed performance, but it also aids in recovery of contaminated soils (Anon 2025). Although the effect of beneficial microbes on crop yield and soil health has been studied extensively, this approach needs to be complemented with well-designed manipulative experiments to fill the existing knowledge gaps about the complex interplay between multifunctional microbes, plant genotypes, soil conditions, and the resulting rhizo-microbiome (Sharma et al., 2025). An example of this would be the incorporation of multi-omic approaches (e.g., genomics, transcriptomics, metabolomics, and proteomics) to elucidate the molecular and biochemical pathways that this complexity interacts with (Kaushal and Pati, 2025). Moreover, by unraveling intricate plant-microbiota interactions such as nitrogen fixation and mycorrhizal associations, multi-omics techniques are also essential for increasing antioxidant content and phytohormone production in plants, even in interest soils (Minello et al., 2025). Moreover, investigating the impact of plant growth-promoting rhizobacteria on catabolic biological activities that utilize contaminants as energy sources can further elucidate their role in phytoremediation (Oubohssaine et al., 2025). The genetic engineering of plants for enhanced tolerance to pollutants, coupled with bioaugmentation using plant growth-promoting rhizobacteria, presents a promising avenue for amplifying phytoremediation efficacy and improving crop yield in contaminated soils (Anwar-ul-Haq et al., 2022). In addition, the plant growth-promoting rhizobacteria effect on the catabolic biological activities using contaminants as energy can also be studied related to phytoremediation (Ahmad, 2024). A deeper understanding of the plant-microbe synergy at the genomic level through technologies such as CRISPR can further enhance phytoremediation prospects and reclaim deteriorated soil and water systems (Salum et al., 2026). However, the genetic engineering of plants by introducing the necessary biochemical pathways to enhance their tolerance to specific pollutants on the phytoremediation front and the possibility of bioaugmentation with plant growth-promoting rhizobacteria are two innovative approaches to overcome the current bottlenecks of poor phytoremediation efficiency and low crop yields grown in contaminated soils (Poria et al., 2022). In addition, although some studies have begun to explore these aspects for potential efficient approaches to rhizoremediation, more studies are needed to confirm the viability of these strategies in the context of plant biochemical responses (Trapp et al., 2017). Tools like CRISPR, on the other hand, can provide insights into plant-microbe synergy at the genomic level, which can be useful to improve phytoremediation possibilities, in addition to restoring damaged soil and water systems (Wentzell, 2025). A holistic exploration of how plants and microbes interact with contaminants is imperative, utilizing omics tools and genetic tools for this purpose, in order to establish effective plant-based strategies for bioremediation (Basu et al., 2018; Salum et al., 2026). The bio securing approach can be included in the future research direction by formulating rhizoremediation that is flexible with specific environmental stressors and thus sustainability in terms of biosafety and nutritional cycling dynamics for more efficiencies in microbial degradation (Kuri et al., 2018). This encompasses the application of current molecular techniques such as genomics, metabolomics, metabolomics, and proteomics as they relate to the biochemistry of degrading microbes and identification of possible genes and enzymes related to the degradation process(Mishra et al., 2021).

Conclusion

In conclusion, bacterial seed priming could serve as a novel and sustainable strategy targeting key issues in seed germination, degradation of petroleum hydrocarbon contaminated agricultural soils, and global food security. Under this strategy heathy microorganisms which provide the ability for seeds to adapt, improve plant resilience and help in bioremediation of hydrocarbon pollutants allow degrees of freedom to reconstitute keystone species and maximize yield (Dudeja et al., 2025; Ptaszek et al., 2023). They will elucidate the proximal molecular mechanisms that underlie these beneficial interactions, ultimately allowing for more targeted and refined applications (Alturki et al., 2023). Integrating bacterial seed activation with high-throughput genomic and proteomic analyses will provide the contextual information to be used for the development of bioprotective agents Advancements in synthetic biology and microbial engineering are anticipated to facilitate the engineering of bespoke bacterial populations with improved properties for tailored solutions to agricultural and environmental challenges. Nonbiological seed activation, as a recent seed treatment technique, offers a practical advantage in crop development and resistance to different biotic and abiotic stresses that gives stronger attention on its function in sustainable agriculture. Combining nanotechnology with microbial solutions represents an eco-friendly option to traditional chemical inputs to improve plant performance under extreme conditions (Alturki et al., 2023; Anwar-ul-Haq et al., 2022). Always, Nano activation materials are helpful to improve seed viability and germination, the efficiency of photosynthesis and the accumulation of biomass and to activate the antioxidant enzyme system that lowers the oxidative damage of reactive oxygen species. Nanotechnology technology given plants significant physiological and morphological advancements during germination and growth against diverse stressors through unique properties of nanoparticles, for instance, high surface area to volume ratio.

Sustainability Statement

This review highlights the environmental potential of plant growth-promoting rhizobacteria (PGPR)-based seed bio-priming as a sustainable and eco-friendly strategy for the remediation of petroleum-contaminated soils. By integrating microbial biotechnology into soil restoration practices, this approach supports the reduction of petroleum-derived pollutants, enhances soil biological activity, and contributes to long-term ecosystem recovery and sustainable land management in contaminated environments.

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Data Availability Statement

This is a review article. All data discussed in this manuscript are derived from publicly available published literature.

Author Contributions (CRediT)

First author: Conceptualization, Literature review, Writing – original draft. Second author: Supervision, Validation, Writing – review & editing. Third author: Resources, Critical revision, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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