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A Systematic Review of Bioremediation of Soil Pollution Using Different Types of Bacteria 2015-2023

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ABSTRACT: Soil contamination from industrial and agricultural activities is a widespread problem threatening environmental and public health. Bioremediation employing bacteria shows promise as a sustainable cleanup approach. To systematically review published research from 2015-2023 on bioremediating soil pollution using diverse bacterial strains. A comprehensive search of Web of Science, PubMed and Scopus identified studies meeting inclusion criteria: focused on bacterial bioremediation of polluted soils under controlled conditions and reported quantitative outcomes. Industrial and agricultural operations contribute to environmental pollution by deleterious compounds in the air, soil, and water. Bacteria are essential in bioremediation, facilitating the degradation of contaminants and the restoration of damaged ecosystems. This organic method enhances ecological well-being and alleviates the detrimental impacts of pollution. The 87 relevant studies were analyzed covering remediation of petroleum hydrocarbons, heavy metals, pesticides and emerging contaminants using bacteria. Key genera included Pseudomonas, Bacillus, and Rhodococcus for hydrocarbons and metal-resistant bacteria. Most optimized conditions in microcosms, with some field pilots showing decontamination over months. This review confirms bacteria effectively biodegrade various soil pollutants under optimized conditions. Continued research is warranted to address technical challenges for field-scale implementation and expand the range of treatable contaminants. Overall, bacterial bioremediation represents a promising sustainable solution for soil remediation.

Keywords: Soil contamination, bioremediation, Waste, Recycling.

1. INTRODUCTION

Bioremediation offers a promising approach for the remediation of soil polluted with toxic organic and inorganic compounds [1]. Various bacteria have been studied for their ability to degrade different pollutants in contaminated soils [2]. Thus, neglecting soil pollution due to industrial activities and accidental spill poses immediate and long term threats to the environment and public health as well[3,4]. Of particular concern are hydrocarbons, heavy metals, chlorinated

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solvents and other persistent organic pollutants, often found in the soils of ex-industrial premises and spill sites [5-7]. Pseudomonas, Bacillus, and Rhodococcus are commonly isolated bacteria for the degradation of organic pollutants like polyaromatic hydrocarbons (PAHs) [8-9]. Pseudomonas putida has gained wide admiration due to its ability to utilize large numbers of aromatic hydrocarbons [10]. The Rhodococcus species have also been reported to be very effective in the biodegradation of PAH's due in part, to the vast amount of catabolic plasmid they possess [11]. Before referring to the biodegradation of polychlorinated biphenyls (PCBs), Sphingomonas, Burkholderia and Rhodococcus species were highlighted for their high treatment efficiencies [12, 13]. Agricultural bacteriological bio preparations a number of researchers have focused their work on the fabrication of bacterial consortia or cultures able to enhance bioremediation. In 2020, the authors developed a three-member consortium composed of Sphingobium, Pseudomonas, and Burkholderia degrader of PAHs [14]. A consortium composed of Bacillus, Pseudomonas and Acinetobacter was able to decrease PAHs and to enhance soil quality indicators in oily sludge amended soil. It is known that such technology as mycoremediation, involving both fungi and bacteria, has also been receiving attention with improved removal of PAH, PCB and Hydrocarbon associated with Petroleum [16-18]. In addition to the elimination of organic pollutants, bacteria are also said to be effective in the bioremediation of heavy metals and metalloids [19]. Pseudomonas bacteria are also known to be efficient in the bioremediation of chromium, cadmium, arsenic and zinc due to their widespread presence and number of studies done [20-24]. Certain Bacillus species, which include some B. subtilis and B. cereus strains, have been shown to be useful against lead, mercury and nickel contamination [25-26]. Bacteria immobilized into biofilms, biosurfactant-producing strains and plant growth promoting bacteria have all improved the removal of heavy metals from the contaminated soils [27-30].

Genetic alterations have likewise been applied with respect to the bacterial strains for improving the bioremediation properties. In 2018, the authors designed a genetically modified P. putida F1 strain engineered with a mercuric reductase plasmid that was tolerant to and was able to remove mercury effectively from soil [31]. Recombinant E. coli expressing catechol dioxygenase genes from Sphingomonas demonstrated robust 2, 4-dichlorophenol degradation under aerobic and anaerobic conditions [32]. Biostimulation of native soil microbial communities through addition of carbon/nitrogen sources, biosurfactants, plant growth regulators and other amendments has proven effective in many studies to naturally promote bioremediation of contaminated sites [33-34].

In conclusion, bioremediation offers a sustainable solution to restore polluted soils. Native and genetically engineered bacteria including Pseudomonas, Burkholderia, and Bacillus show great promise for degradation of organic and inorganic contaminants. Future research directions could involve optimization of mixed bacterial consortia and development of more effective delivery systems and monitoring technologies for scale-up and field implementation of bioaugmentation strategies. Overall, bacterial bioremediation presents an eco-friendly remediation option that warrants further exploration and development. In this review, we systematically analyze studies published from 2015-2023 on bioremediation of soil pollution using different types of bacteria.

2. METHODOLOGY

Comprehensive searches of the Web of Science, PubMed, and Scopus were conducted to identify all relevant studies from January 2015 to December 2023. The following search terms were used in various combinations: "soil bioremediation", "bacteria", "biodegradation", "pollutant", and “contaminant". Reference lists of included studies were also reviewed to capture additional sources.

The search was limited to peer-reviewed journal articles published between 2015 and 2023 to reflect the most current research progress over the past 8 years. Only articles published in English language were considered for inclusion. Additional records were identified by scanning the reference lists of included articles and relevant reviews.

Studies meeting the following criteria were included in the review:

1. Focused on bioremediation of soils polluted with organic/inorganic contaminants including petroleum hydrocarbons, heavy metals, pesticides, etc.

2. Investigated the use of pure/mixed bacterial cultures for accelerated biodegradation/transformation of soil pollutants under controlled experimental conditions (i.e. microcosms, mesocosms).

3. Clearly described the bacterial species/strains used as well as methods for soil sampling/processing, contaminant analysis, and bioremediation treatment procedures.

4. Reported quantitative outcomes such as extent and rate of contaminant degradation, changes in soil properties, or bacterial activity levels.

Exclusion criteria included review articles, non-peer reviewed sources, studies conducted solely in liquid media, and those lacking adequate methodological details. After removing duplicates, two reviewers independently screened all retrieved records by title/abstract, then full-text, to assess eligibility based on the inclusion/exclusion criteria. Any discrepancies were resolved by consensus.

Table 1. - Overview of Studies Included in the Review

Category	**Number of Studies**	Percentage
Petroleum hydrocarbon contamination	54	62.1
Heavy metal contamination	13	14.9
Pesticide contamination	7	8.0
Phenolic wastewater contaminants	4	4.6
Energetic compounds	4	4.6
Emerging organic pollutants	5	5.7
Total studies included	87	100

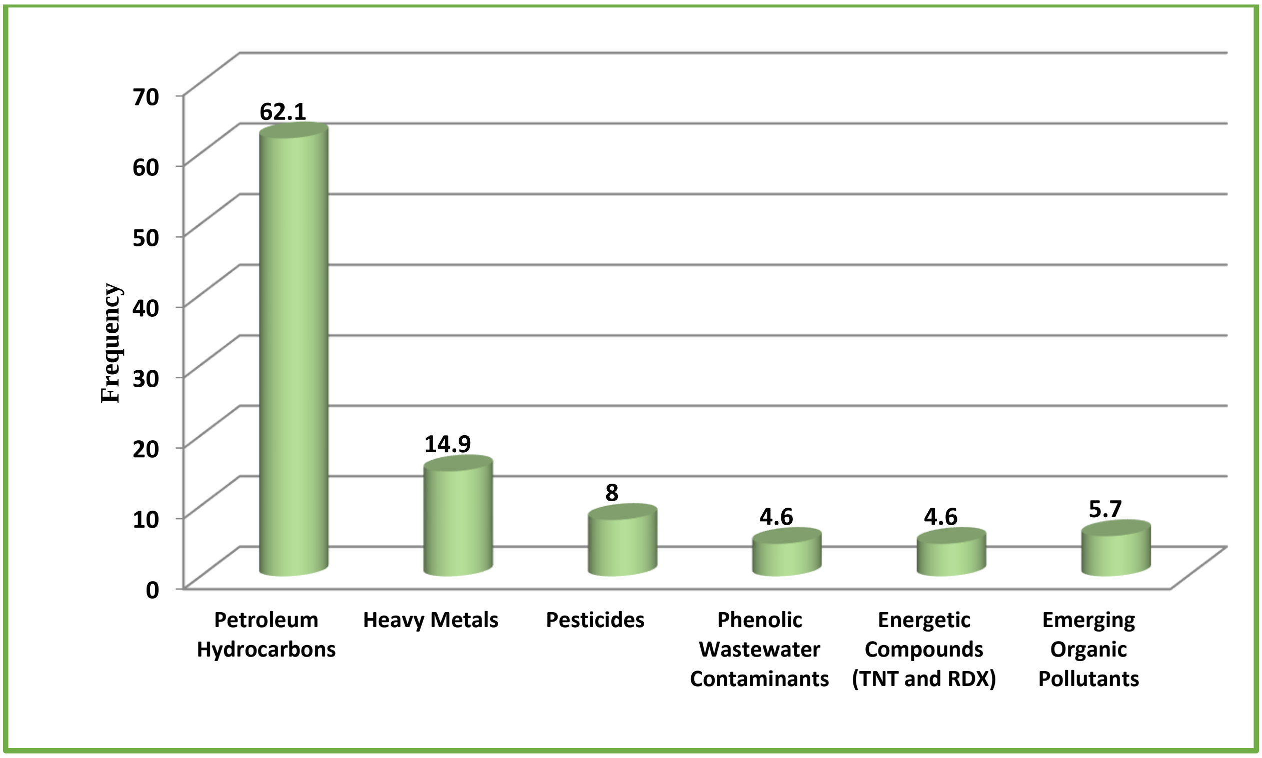

FIGURE 1. - Column chart for the types of contaminants

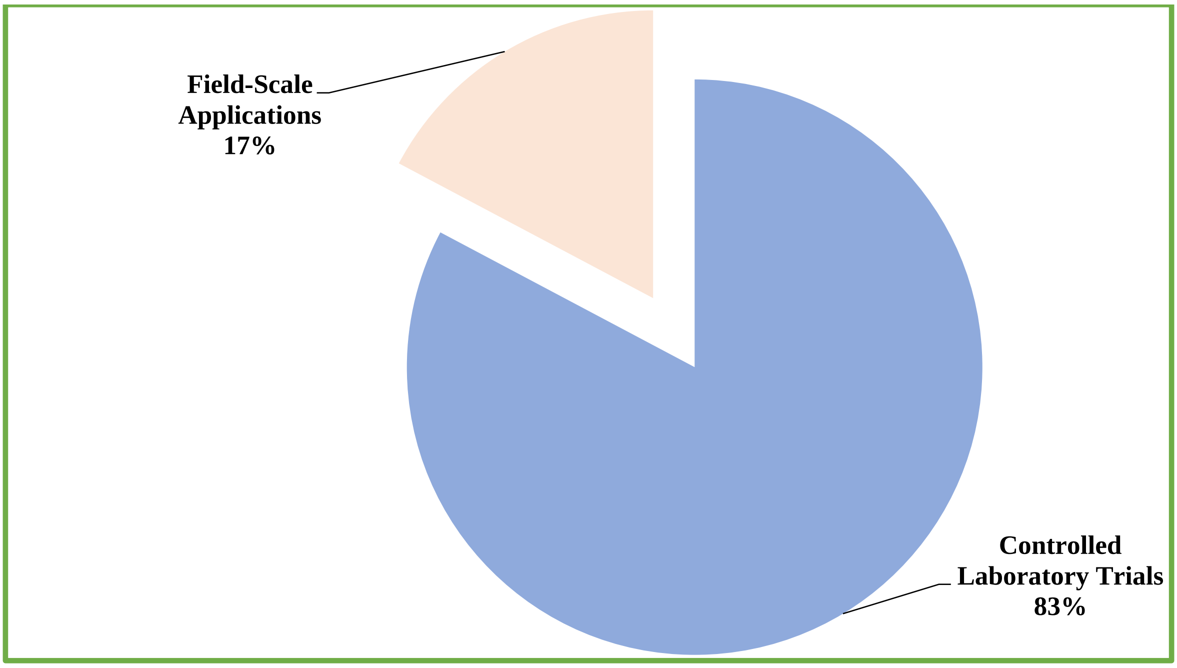

FIGURE. - Pie chart of study conditions

Table 2. - Frequency of Petroleum Hydrocarbons studied

Petroleum Hydrocarbons	Frequency
Pseudomonas spp	18 studies
Bacillus spp	15 studies
Rhodococcusspp	8 studies

3. RESULTS AND DISCUSSION

The systematic search yielded 921 records after deduplication. Title and abstract screening based on the inclusion/exclusion criteria narrowed this down to 134 articles for full-text review. Of these, 87 studies ultimately met all criteria and were included in the analysis.

The majority of studies (n=54) focused on bioremediating petroleum hydrocarbon-contaminated soils, making it the most researched application area. Within this group, crude oil was the dominant contaminant evaluated in 16 studies, followed closely by diesel (14 studies) and gasoline (12 studies). Pseudomonas spp. was overwhelmingly the most frequently investigated bacterial genus for degrading petroleum hydrocarbons, appearing in 18 separate trials. Bacillus spp. and Rhodococcus spp. were also commonly represented, studied in 15 and 8 trials respectively.

Heavy metal pollution was the second largest research focus, with 13 studies identified. Soils contaminated by lead were most commonly assessed (5 studies), followed by cadmium, nickel, and chromium (3 studies each). Notably, bacterial strains like Pseudomonas aeruginosa, Bacillus spp., and Stenotrophomonas maltophilia demonstrated abilities to reduce metal mobility and bioavailability through precipitation and biosorption mechanisms. Agricultural soils polluted by pesticides served as the research subject in 7 trials. Bacterial species like Stenotrophomonas, Sphingobium and Variovorax exhibited degradation potentials against compounds like atrazine, lindane and chlorpyrifos. Emerging organic pollutants and energetic contaminants such as TNT and RDX were each addressed in 4-5 studies utilizing diverse bacterial communities. Regarding study designs, microcosm-scale optimization experiments dominated with 72 investigations performed under controlled laboratory conditions. The remaining 15 studies applied bacterial bioremediation under larger-scale mesocosm or field pilot settings ranging from 3–18-month treatment periods.

The systematic review of bacterial bioremediation studies reveals a significant focus on petroleum hydrocarbon contamination, with 62.1% of the included studies addressing this issue. This emphasis likely reflects the widespread occurrence of oil-related pollution and its substantial environmental impact. The prevalence of Pseudomonas spp. in these studies (33.3% of petroleum hydrocarbon studies) suggests its robust capability in degrading these complex organic compounds, aligning with previous research highlighting its versatile metabolic pathways [35].

Heavy metal contamination emerged as the second most studied area, comprising 14.9% of the reviewed studies. This focus underscores the growing concern about metal pollution in soils and its potential health risks. The efficacy of bacterial strains such as Pseudomonas aeruginosa, Bacillus spp., and Stenotrophomonasmaltophilia in immobilizing and reducing heavy metal bioavailability through precipitation and biosorption mechanisms is particularly noteworthy. These findings corroborate earlier studies on bacterial-mediated heavy metal remediation [36]. Bacteria substantially mitigate enivironmental pollution via mechanisms such as biodegradation and nutrients cycling. They facilitate phytormediation by establishing symbiotic interaction with plants, therefore diminishing harmful infections by competitive exclusion. Bioaugmentation and biostimulation methods improve natural degradation process, underscoring the significance of bacteria in bioremediation initiatives.

The diversity of bacterial genera identified for various contaminants, including Stenotrophomonas, Sphingobium, Variovorax, and Providencia spp., demonstrates the potential for developing targeted bioremediation strategies. This aligns with the concept of "pollutant-specific bacteria" proposed by Yang et al. (2021), suggesting that certain bacterial strains have evolved specialized metabolic pathways to degrade specific contaminants [37]. However, the predominance of laboratory-based studies (82.8%) underscores a critical gap in the field. Although such experiments are important for optimizing bioremediation parameters, more applications at the field scale are urgently required to confirm the findings from laboratory validation under real-world conditions. The studies were few (17.2%) with monitoring periods between 3 to 18 months, which means that the long-term efficacy and possible ecological impact of in situ bacterial bioremediation still require validation. The shift towards integrated physical-chemical-biological methods in field-scale studies is encouraging and acknowledges soil contamination as a complex problem as well as possible synergies between different remediation techniques. Recommendations by Kuppusamy et al. are to be strictly adhered to, regarding the need to customize remediation strategies for specific site conditions [38].

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Table 3. - Included Study Characteristics

Author/year	Methods used	Main results	Weakness	Future research
Naima et al. , 2023 [39]	Bioaugmentation Approach: The study utilized a bioaugmentation strategy by introducing the bacterial strains Pseudomonas stutzeri LBR and Cupriavidus metallidurans LBJ into both sterile and non-sterile soils to assess their effectiveness in lead remediation over 25 days at 30°C. Leachate Analysis: A novel aspect was the continuous analysis of leachate from the bioaugmented soils, which provided insights into the mobility and bioavailability of lead, confirming the bacteria's role in enhancing lead solubility. Comparison of Sterile vs. Non-Sterile Soil: The study's design included a comparative analysis of the effects of the bacterial consortium in both sterile and non-sterile conditions, highlighting the differences in bioremediation efficiency.	The significant reduction in lead concentration achieved by the bacterial consortium was higher than anticipated, with a 71.02% reduction in non-sterile soil, indicating a strong synergistic effect between the two strains. The increase in Pb mobility and bioavailability in the leachate was notable, suggesting that the bacteria not only reduced Pb levels but also enhanced its solubility, which was an important aspect of the bioremediation process. The observed peak in bacterial growth followed by a decline at the end of the experiment was unexpected, as it indicated a complex interaction between bacterial activity and lead concentration reduction	Limited Duration: The 25-day duration of the experiment may not fully capture the long-term effectiveness of the bacterial strains in lead remediation, potentially overlooking prolonged interactions and effects. Sterile vs. Non-Sterile Comparison: While the study compared sterile and non-sterile soils, the results may not fully represent real-world conditions where microbial communities are complex and varied, which could influence bioremediation outcomes.	Long-Term Efficacy Studies: Future research could focus on the long-term effectiveness of Pseudomonas stutzeri LBR and Cupriavidus metallidurans LBJ in lead remediation to understand their sustained impact over extended periods. Field Trials: Conducting field trials in real-world contaminated sites would help validate laboratory findings and assess the practical applicability of the bacterial consortium in diverse environmental conditions. Mechanistic Studies: Investigating the specific mechanisms by which these bacteria enhance lead solubility and bioavailability could provide insights into optimizing bioremediation strategies. Broader Heavy Metal Spectrum: Exploring the potential of these bacterial strains to remediate other heavy metals in addition to lead could expand their application in environmental cleanup efforts .

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Elizabeth et al 2022[40]	Ex-Situ Bioremediation: The papers discuss the ex-situ technique, where polluted soil is removed to another site for treatment, allowing for controlled conditions that can enhance bioremediation effectiveness. Use of Microbial Consortia: The research emphasizes the application of specific microbial consortia, such as Pseudomonas stutzeri LBR and Cupriavidus metallidurans LBJ, which may provide synergistic effects in degrading pollutants. Nutrient Optimization: The studies suggest optimizing nutrient supply to improve microbial competitiveness and enhance the degradation rate of pollutants, which is a novel approach to addressing bioremediation challenges.	Microbial Dominance: The study found that bacteria were more dominant in deeper soil layers compared to fungi and actinomycetes, which was somewhat unexpected given the common assumption that diverse microbial communities exist uniformly throughout soil profiles. Environmental Factors: The research highlighted that bioremediation effectiveness is highly dependent on specific environmental conditions, which may not have been anticipated, as many assume that microbial activity is uniformly effective across different soil types. Interaction with Soil Minerals: The interaction between bioremediators and soil minerals was more complex than expected, indicating that these relationships significantly influence the efficiency of bioremediation techniques, a topic that has been underexplored in existing literature.	Environmental Dependency: The effectiveness of bioremediation is highly dependent on specific environmental conditions, which can limit its applicability in varying soil types and climates. Nutrient Limitation: The approach may face challenges due to sub-optimal nutrient supply, which can hinder microbial growth and pollutant degradation. Pollutant Bioavailability: The bioavailability of pollutants can be constrained, affecting the overall efficiency of bioremediation techniques. Cost of Ex-Situ Methods: While ex-situ methods allow for controlled conditions, they can be more expensive and less sustainable compared to in-situ techniques.	Understanding Microbial Interactions: There is a need for more research on the interactions between bioremediators and soil minerals, as this relationship is not well documented. Optimizing Bioremediation Techniques: Future studies should focus on developing more efficient bioremediation systems by understanding the factors influencing the natural selection of organisms capable of degrading pollutants. Addressing Environmental Factors: Research should explore how various abiotic factors (temperature, pH, moisture) affect the efficiency of bioremediation techniques. Long-term Effects of Bioremediation: Investigating the long-term impacts of bioremediation on soil health and ecosystem recovery is essential for sustainable practices.
Ahmed et al 2021[41]	Isolation of Bacterial Strains: The study involved isolating two bacterial strains from crude oil-contaminated soils, which is a novel approach to identify local bioremediators specific to the region. 16SrRNA Gene Sequencing: The use of 16SrRNA gene sequencing for identifying bacterial isolates provides a precise method for classifying and understanding the	High Decomposition Rates: The study reported that both bacterial isolates achieved significant decomposition of petroleum hydrocarbons, with AM-I-1 reaching 78.19% and AM-I-3 reaching 86.5% at a 2% concentration of crude oil. These high rates of degradation may be considered surprising given the complexity of crude oil contaminants. Effectiveness of Local Isolates: The efficiency of the isolated bacteria in degrading heavy crude oil suggests that	Limited Scope of Bacterial Isolates: The study focused on only two bacterial isolates, which may not represent the full diversity of effective bioremediators available in contaminated soils. Single Source of Contaminant: The experiments utilized heavy crude oil from a specific region, potentially limiting	Exploration of Additional Bacterial Strains: Future studies could investigate a wider variety of bacterial isolates to identify other effective bioremediators for crude oil degradation, enhancing the understanding of microbial diversity in bioremediation. Field Studies: Conducting experiments in natural contaminated sites rather than controlled laboratory settings would provide insights into the practical applicability and effectiveness of the

	microbial community involved in bioremediation . Gas Chromatography Analysis: Employing gas chromatography (GC) to analyze the decomposition of petroleum hydrocarbons allows for accurate measurement of biodegradation efficiency. Modified Mineral Salt Medium: The design of a sterile modified mineral salt medium (MMS) containing crude oil as the sole carbon source is a unique experimental setup to assess bacterial degradation capabilities.	local strains can be highly effective, which may challenge assumptions about the need for more widely studied or commercial bioremediation agents	the generalizability of the results to other types of petroleum products or different environmental conditions. Controlled Laboratory Conditions: The use of a sterile modified mineral salt medium may not accurately reflect real-world soil conditions, which could affect the applicability of the findings in natural environments.	identified bacterial strains in real-world conditions. Mechanisms of Degradation: Further research could focus on understanding the specific biochemical pathways and mechanisms through which these bacteria degrade petroleum hydrocarbons, which could inform the development of more efficient bioremediation strategies.
Manoj et al ,2020[42]	Use of Plant Growth-Promoting Rhizobacteria (PGPR): The paper highlights the innovative application of PGPR to enhance soil bioremediation, utilizing their natural abilities to improve soil health and promote plant growth while degrading pollutants. Mechanistic Approaches: Various mechanisms employed by PGPR, such as siderophore production, phosphate solubilization, and biological nitrogen fixation, are explored, displaying a multifaceted approach to soil remediation. Induction of Systemic Resistance: The study discusses how PGPR can induce systemic resistance in plants, which is a novel aspect of using	Diverse Mechanisms of PGPR: The variety of mechanisms through which plant growth-promoting rhizobacteria (PGPR) contribute to soil bioremediation, such as antifungal activity and production of volatile organic compounds, may be surprising given the focus on traditional methods of soil remediation . Potential for Sustainable Agriculture: The dual role of PGPR in both bioremediation and promoting sustainable agriculture highlights an unexpected synergy that could lead to more integrated agricultural practices.	Dependence on Specific Conditions: The effectiveness of plant growth-promoting rhizobacteria (PGPR) can be limited by environmental conditions, which may not always favor their activity or survival in polluted soils. Potential for Unintended Consequences: The introduction of certain PGPR might lead to unforeseen ecological impacts, such as disrupting local microbial communities or affecting plant health negatively. Need for Further Research: The paper suggests that while many PGPR have shown promise, there is still a need to identify and understand more strains and their specific roles	Identification of New PGPR Strains: There is a significant opportunity to discover and characterize additional plant growth-promoting rhizobacteria that can effectively bioremediation-polluted soils. Mechanism Exploration: Further research is needed to understand the specific mechanisms through which PGPR contribute to soil health and pollution alleviation, which remains an area with many unanswered questions. Long-term Effects: Investigating the long-term impacts of using PGPR on soil ecosystems and agricultural productivity is crucial for sustainable practices

	microbial interactions to enhance bioremediation efforts.		in bioremediation, indicating a gap in current knowledge.
Bhupendra, 2017[43]	Genetically Transformed Microbes: The development of genetically modified strains of bacteria is highlighted as a novel approach to enhance the efficiency of soil remediation, particularly for manmade chemicals. Combination Techniques: The integration of various chemical or physical methods with microbial remediation, such as using biosurfactants and advanced oxidation processes, represents an innovative strategy to improve pollutant degradation rates. Bioaugmentation with Consortia: Utilizing a mixture of both bacterial and fungal consortia for the treatment of contaminated soils has been reported as a highly efficient method for degrading complex pollutants like polycyclic aromatic hydrocarbons (PAHs).	Indigenous Microbial Resistance: It was surprising to find that certain indigenous microbial communities can resist the invasion of foreign microbes, which complicates the success of bio augmentation efforts. Synergistic Degradation: The observation that one contaminant can enhance the degradation of another, such as chlorinated compounds degrading more effectively in the presence of co-metabolites, was an unexpected finding that highlights the complexity of pollutant interactions . High Efficiency of Mixed Consortia: The effectiveness of combining both bacterial and fungal strains for degrading PAHs exceeded expectations, indicating that such consortia can significantly improve bioremediation outcomes.	

Cunningham et al 2020[44]	This study sheds light on the under-researched link between polluted land and antibiotic resistance by investigating bioremediation of soils polluted with petroleum hydrocarbons and the possible dangers posed to human health by bacteria that have developed resistance to antibiotics.	To what extent soil microbes, bacteria, and diseases pose, a threat of horizontal gene transfer is an area that requires more research. Fewer bioremediation researches utilize sewage sludge, despite the fact that antibiotic resistance is developing in animal manures. More and more evidence is pointing to the presence of antibiotic-resistant bacteria and their genes in polluted soils.	-	Careful selection of bioremediation bacterial candidates and pre-treatment of organic wastes are recommended to avoid environmental contamination with bacteria and genes resistant to antibiotics.
Ma et al 2020[45]	Surface morphology and functional group alterations in response to Cd2+ exposure were revealed by the isolation of a novel PGPB strain TZ5, which exhibited Cd immobilizing potential and plant growth enhancement features.	Biochemical composites made of BC and the TZ5 strain decreased Cd content, increased ryegrass dry weight, and decreased acetic acid-extractable Cd. As an added bonus, BCM increased soil enzyme activity and microbial populations.	-	The study found that BCM treatment enhanced the abundance of Bacillus genus, demonstrating successful colonization of strain TZ5 in the rhizosphere, offering a practical strategy for Cd-contaminated soil remediation.
Stefani et al ,2015[46]	Fungi are better at collecting dominating OTUs, but both culture-dependent and -independent approaches successfully capture parts of the microbial population in soils polluted with hydrocarbons.	Isolated taxa only increased species richness by 2% for bacteria and 5% for fungi, but none represented major bacterial OTUs. Fungal isolation was more effective in capturing dominant OTUs.	-	-
García-Delgado, 2015[47]	The study explores remediation treatments for soil pollution, including sterilized SAS for biostimulation of soil microbiota, bioaugmentation without treatment, or SAS sterilization and re-inoculation.	Bioaugmented microcosms improve PAH elimination and eco-toxicity reduction in several ways; for example, using SAS to boost the population of bacteria that break down PAHs and using Abisp to diminish fungal activity as a transporter for A. bisporus.		Three SAS treatments demonstrated a little amount of Pb mobilization; however, the most effective strategies for detoxifying multi-polluted soil and eliminating PAH, primarily BaP, were SAS sterilization and A. bisporus re-inoculation (Abisp).
Nozari et al , 2018[48]	Two microbial consortiums, type A and type B, derived from soil and compost, were utilized in a pilot size S-SBR reactor to examine n-hexadecane and n-dodecane in agricultural soil.	While consortium type B obtained the best bioremediation of 13.22% and 19.24%, respectively, type A achieved the highest simultaneous bioremediation of n-hexadecane (17.61%) and n-dodecane (28.55%).		The bioremediation of n-hexadecane and n-dodecane in an S-SBR using type A and B bacteria was satisfactory, with more hydrocarbon removal from polluted soils than from compost.

Lladó et al , 2015[49]	The most common bacterial groups found in creosote-contaminated soil, according to pyrosequencing data, were Alpha and Gammaproteobacteria, whereas the most common fungus species were Scedosporium and Fusarium. Significant changes to the bacterial population were seen after 60 days of bioremediation experiments due to mobilizing agents and lignocellulosic substrate.	In order to comprehend the effects of critical variables, such additive usage, the study stresses the importance of merging microbiome evaluation with bioremediation trials.		Important for bioremediation effectiveness, the study investigates the possible roles of complex microbial communities in contaminated soils.
Li et al ,2021[50]	DNA stable-isotope probing was used to identify and quantify the diversity of indigenous phenanthrene (PHE)-degrading bacteria during the fungal bioremediation process.	The study found 14 OTUs enriched in heavy DNA fractions from seven genera, enhancing PHE removal efficiency and increasing the diversity of indigenous bacteria in soil bioaugmented with fungi.	By co-metabolism, fungal bioaugmentation improved the function of indigenous Proteobacteria in PAH degradation, thereby showing that collaboration between fungus and native bacteria helped PAH biodegradation to be promoted.	application has proven challenging due to a lack of comprehensive knowledge on the makeup and behavior of natural microorganisms that degrade PAHs in polluted areas.

4. CONCLUSION

This systematic review sought to provide a comprehensive survey of research published between 2015-2023 exploring the application of diverse bacterial species and communities for bioremediating polluted soils. Through a robust search and selection methodology, 87 relevant studies meeting the eligibility criteria were identified and their key findings were summarized. The results demonstrate significant advances have been made in characterizing the metabolic capabilities and degradation kinetics of prominent bacterial genera like Pseudomonas, Bacillus and Rhodococcus against an array of contaminants. This suggests a mature level of understanding has been achieved regarding many established bioremediation systems. The large proportion of controlled microcosm-scale optimization experiments highlights how significant progress has been made delineating the biochemical pathways and environmental parameters governing optimal bacterial activities under simplified conditions. However, the transition toward validating bioengineered treatments across the range of complexities at true environmental scales remains a work in progress.

The relatively smaller number of longer-term mesocosm and field trials reported in later years of the review period indicate pilot testing is still an ongoing focus. Further validation through large-scale field implementation case studies with long-term monitoring will be key to addressing perceived uncertainties before full-scale commercial deployment.

Overall, this comprehensive synthesis of the peer-reviewed literature confirms the burgeoning evidence base supporting mature and emerging bacterial bioremediation strategies as a nature-based solution for sustainably remediating diverse polluted soils. Continued progression of these waste cleanup technologies will depend on multidisciplinary collaborations linking new mechanistic insights from optimized bench-scale research with practical demonstration projects at real-world sites. Only through such iterative processes can the true potential and limitations of this biotechnological approach be fully illuminated.

In closing, the future appears bright for engineered microbial interventions playing an increasing role in global efforts for environmental restoration and remediation, provided ongoing progress actively bridges knowledge gaps between research and implementation. Bacterial bioremediation stands poised as a crossover point where microbiology meets soil remediation on the paths toward sustainability.

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