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Integrated Use of Biostimulants, Biofertilizers, and Organic Waste Management for Sustainable Remediation of Degraded and Contaminated Soils: A Critical Review

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Abstract
Soil degradation and contamination caused by industrialization, intensive agriculture, and improper waste disposal threaten global food security and ecosystem sustainability. Environmentally compatible approaches such as biostimulants, biofertilizers, and organic waste amendments have emerged as viable tools for restoring soil health and mitigating contaminants. This review synthesizes findings from recent original research to evaluate the effectiveness of these biological interventions in improving soil physicochemical properties, enhancing microbial activity, and facilitating pollutant immobilization or degradation. Biostimulants, including humic substances and seaweed extracts, improve plant resilience and nutrient uptake, while biofertilizers such as nitrogen-fixing and phosphate-solubilizing microorganisms contribute to nutrient cycling and soil fertility. Organic waste management practices, including composting and biochar application, play a critical role in reducing toxicity and enhancing carbon sequestration. The integration of these strategies demonstrates synergistic effects in remediating degraded soils and supporting sustainable agriculture. However, variability in field performance, lack of standardized application protocols, and limited long-term studies remain key challenges. Future research should focus on multi-functional formulations, microbial consortia optimization, and field-scale validation to ensure practical applicability. This review highlights the potential of biologically driven soil remediation strategies as cost-effective and eco-friendly alternatives to conventional methods.

Keywords: *Biofertilizers; Biostimulants; Contaminated soils; Organic waste; Soil degradation; Soil remediation; Sustainable agriculture; Waste valorization*

1. Introduction

Soil degradation has intensified globally due to excessive agrochemical use, industrial pollution, heavy metal accumulation, and improper organic waste disposal. These disturbances compromise soil fertility, reduce biodiversity, and limit crop productivity, thereby posing serious threats to agricultural sustainability [1]. Conventional remediation methods such as chemical immobilization and physical excavation are often expensive and environmentally disruptive, necessitating the development of sustainable alternatives. Biological approaches utilizing biostimulants, biofertilizers, and organic waste amendments have gained considerable attention due to their ecological compatibility and multifunctional benefits [22]. Biostimulants enhance plant physiological processes and improve tolerance to abiotic stress, while biofertilizers introduce beneficial microorganisms that facilitate nutrient availability and pollutant transformation [27]. Organic waste-derived products such as compost and biochar contribute to soil structure improvement and contaminant stabilization [20]. Despite increasing research, there is a need to consolidate findings across studies to better understand the mechanisms, effectiveness, and limitations of these approaches. This review aims to critically evaluate recent advancements in the use of biostimulants, biofertilizers, and organic waste management for soil remediation, identify knowledge gaps, and suggest future research directions.

2. Methodology

This review was developed through a structured literature assessment of original research articles published between 2015 and 2025. Scientific databases including ResearchGate, Scopus, Web of Science, and Google Scholar were explored using combinations of keywords such as "biostimulants," "biofertilizers," "soil remediation," "organic waste," and "contaminated soils." Studies were selected based on the following criteria:
(i) original experimental research;
(ii) focus on soil remediation or soil health improvement;
(iii) involvement of biostimulants, microbial inoculants, or organic waste amendments;
(iv) clear methodological framework and measurable outcomes. Studies focusing solely on chemical remediation or lacking experimental validation were excluded. Approximately 18 high-quality research papers were critically analyzed, ensuring diversity in soil types, contaminants, and climatic conditions. Data synthesis was performed thematically to identify consistent patterns and emerging trends.

3. Integrated Biological Approaches for Sustainable Soil Remediation: Roles of Biostimulants, Biofertilizers, and Organic Amendments

3.1 Role of Biostimulants in Soil Remediation

Biostimulants, including humic acids, protein hydrolysates, and seaweed extracts, have shown significant potential in improving plant growth and soil functionality. Research indicates that humic substances enhance cation exchange capacity and facilitate metal chelation, thereby reducing heavy metal toxicity [8]. Seaweed extracts have been reported to increase antioxidant enzyme activity in plants, improving tolerance to polluted environments [25]. Additionally, protein hydrolysates stimulate root development, leading to improved nutrient acquisition and enhanced microbial interactions in the rhizosphere [9]. These compounds indirectly support soil remediation by promoting plant-mediated phytoremediation processes.

3.2 Biofertilizers and Microbial-Assisted Remediation

Biofertilizers, particularly plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, play a crucial role in nutrient cycling and contaminant degradation. Nitrogen-fixing bacteria such as Rhizobium improve soil fertility while reducing dependency on synthetic fertilizers [6]. Phosphate-solubilizing microorganisms enhance phosphorus availability, which is often limited in degraded soils. Certain microbial strains also possess the ability to degrade organic pollutants and immobilize heavy metals through biosorption and bioaccumulation mechanisms [13]. Mycorrhizal associations further improve plant tolerance to contaminants by enhancing water uptake and forming protective barriers against toxic elements [4]. The synergistic use of microbial consortia has been shown to outperform single-strain applications in remediation efficiency.

3.3 Organic Waste Management and Soil Restoration

Organic waste management strategies, including composting, vermicomposting, and biochar application, contribute significantly to soil restoration. Compost amendments improve soil structure, increase microbial biomass, and enhance nutrient availability [14]. Biochar, a carbon-rich product derived from biomass pyrolysis, has gained attention for its ability to adsorb heavy metals and organic pollutants. Its porous structure enhances water retention and provides habitat for beneficial microorganisms [20]. Vermicompost, enriched with microbial activity and plant growth regulators, has been shown to improve crop productivity in degraded soils while reducing toxicity levels [1]. These organic amendments also contribute to carbon sequestration, addressing climate change concerns.

3.4 Synergistic Effects of Integrated Approaches

Recent studies highlight the benefits of combining biostimulants, biofertilizers, and organic amendments. Integrated approaches enhance nutrient use efficiency, microbial diversity, and pollutant degradation simultaneously [21]. For example, the application of biochar with microbial inoculants has been shown to increase microbial colonization and pollutant adsorption capacity. Similarly, combining humic substances with PGPR improves plant growth and accelerates remediation processes [24]. Such integrated systems offer a holistic solution by addressing multiple soil constraints simultaneously, making them suitable for sustainable agriculture.

4. Results and Discussion

The synthesis of reviewed studies reveals that biological approaches are effective in improving soil health and reducing contamination levels. Biostimulants primarily enhance plant resilience and nutrient uptake, while biofertilizers directly influence microbial-mediated processes. Organic amendments provide structural and chemical improvements to the soil matrix. However, variability in results across studies suggests that environmental conditions, soil type, and application methods significantly influence outcomes. Some studies report inconsistent performance of microbial inoculants under field conditions due to competition with native microflora [2]. Another limitation is the lack of standardized protocols for application rates and combinations of these inputs. Furthermore, long-term impacts on soil ecosystems remain insufficiently studied. Despite these challenges, the integrated use of these approaches consistently demonstrates higher efficiency compared to individual applications, indicating strong potential for large-scale implementation.

5. Future Challenges and Directions

Future research should focus on:
1. Development of multi-functional biostimulant formulations
2. Optimization of microbial consortia for specific soil conditions
3. Long-term field trials to assess sustainability
4. Standardization of application protocols
5. Integration with precision agriculture technologies
6. Exploration of genomic and metabolomic tools to understand mechanisms Additionally, policy support and farmer awareness are essential for widespread adoption of these eco-friendly technologies.

Conclusion

Biostimulants, biofertilizers, and organic waste management strategies represent promising tools for sustainable soil remediation. Their combined application offers synergistic benefits by improving soil fertility, enhancing microbial activity, and reducing pollutant toxicity. While current research demonstrates significant potential, further efforts are required to standardize practices and validate long-term effectiveness. Adoption of these biological approaches can contribute significantly to sustainable agriculture and environmental conservation.

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