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REVIEW

Bioengineered Materials for Soil and Water Remediation: Mechanisms, Effectiveness, and Global Applications

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ABSTRACT

Bioengineered materials are becoming more accepted as sustainable and efficient remedies towards the reduction of soil and water pollution caused by industrialization, agriculture, and urban development. This review is a synthesis of recent discoveries in bioengineered remediation materials, which range from microbial-based materials, biopolymer-derived sorbents, bio-inspired and biomimetic materials, and plant/biomass-derived hybrids. It focuses on the mechanistic principle of contaminant removal, such as adsorption, ion exchange, chelation, precipitation, biodegradation, and redox-mediated transformation and synergistic pathways facilitated by multifunctional hybrid designs. Commonly used metrics in performance evaluation include removal efficacy, kinetics, capacity, selectivity, stability, and reusability, with a specific focus on the differences between laboratory demonstrations and field-scale results in complex environmental matrices. The review also explains major constraints to large scale application, such as material fouling and degradation, inconsistency in changing pH and redox environments, biosafety and ecotoxicity (in particular in the case of living or genetically modified materials), cost and scale-up, and regulatory guidance and standardization lapses. Lastly, the future directions are described, based on opportunities in synthetic biology, smart and stimuli-responsive materials, integrated sensing and monitoring, and circular-economy organizing coupled with remediation and resource recovery. In general, bioengineered materials provide an attractive direction for the use of adaptable, low-impact remediation strategies, yet their global realization will demand

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balanced improvements in the material design, risk analysis, and scaled implementations.
Keywords: Bioengineered Materials; Soil Remediation; Water Treatment; Adsorption and Biodegradation; Environmental Safety

1. Introduction

Contamination of soil and water has become one of the most topical environmental problems of the twenty-first century, posing serious threats to the integrity of ecosystems, food security, and human health [1,2]. Rapid industrialization, urbanization, intensive agricultural practices, and poor waste disposal have caused extensive discharge of pollutants into the land, water, and atmosphere, including, but not limited to, heavy metals, persistent organic compounds, surplus nutrients, pharmaceuticals, and emerging contaminants. These contaminants have a long-lasting nature, bioaccumulate along food chains, and have a long-term and chronic toxic impact on the environment, thus necessitating effective and sustainable remediation measures [3,4].

Some of the conventional remediation technologies that have been frequently used to treat contaminated soils and waters are physical excavation, chemical oxidation, membrane filtration, and thermal treatment [5–9]. Although these methods may work well under controlled circumstances, they are subject to severe drawbacks regarding high costs of operation, secondary pollution, energy intensity, and low flexibility in changing a complex or heterogeneous environment. Specifically, most of the conventional approaches are ill-adapted to large-scale or on-site applications, particularly in resource-constrained areas. Such limitations have compelled the development of increasing interest in alternative remedial strategies that are environmentally smooth, economic, and compatible with innate biogeochemical activities. A conceptual overview of contamination sources and the role of bioengineered materials in soil and water remediation is shown in **Figure 1**.

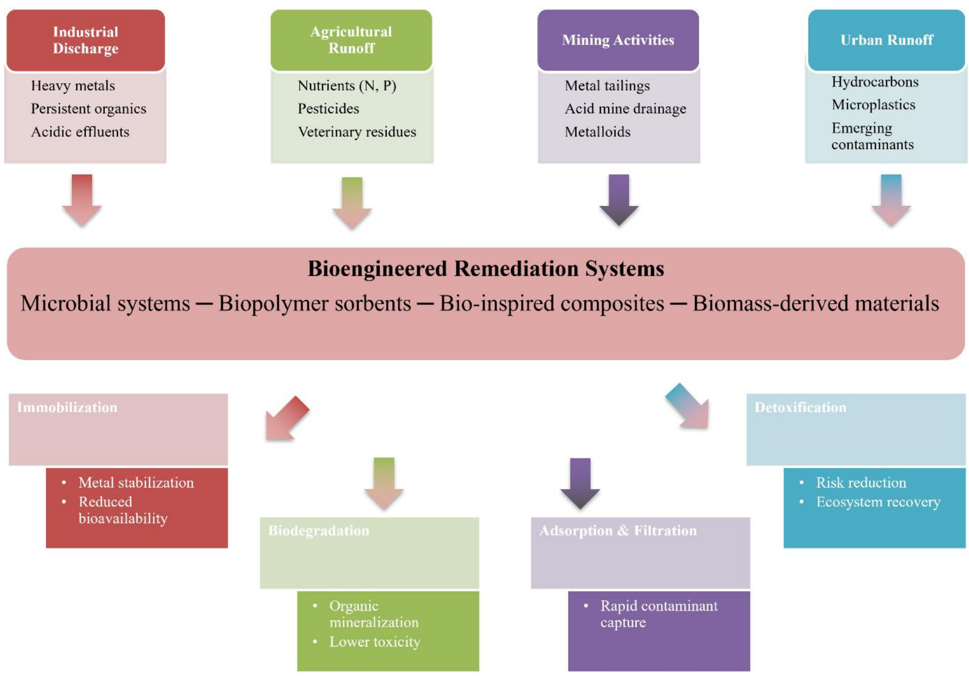

Figure 1. Conceptual overview of soil and water contamination sources and the role of bioengineered materials in remediation, illustrating major pollutant pathways and remediation outcomes.

In this regard, bioengineered materials have received a lot of interest as potential agents of soil and water remediation. In a broad sense, bioengineered materials include materials that are of biological origin or materials that are engineered by incorporating some biological elements in the engineered framework with the aim of increasing the contaminant removal. The materials utilize the special functions of biological systems, such as specificity, versatility, and catalytic efficiency, and take advantage of the stability of structure and the versatility of engineered materials. Bioengineered materials have provided new avenues to dealing with situations of complex contaminations by amalgamating concepts in biotechnology, materials science, and environmental engineering [10,11].

Genetically engineered microorganisms, biofriendly polymers, immobilized performances of enzymes, bioinspired materials, and biomass-hybrid materials are some of the various forms that bioengineered materials in remediation might assume [12,13]. Such systems are microbial-based, such as the use of metabolic pathways that can be used to biodegrade or convert organic pollutants or immobilize or detoxify heavy metals. Innovations in genetic engineering and synthetic biology have enlarged the functional spectrum of microorganisms and can enable them to survive in extremely unfavorable conditions and achieve higher remediation rates. Likewise, materials made of biopolymers, including chitosan, alginate, and cellulose derivatives, have a high affinity to most contaminants and may be chemically altered to enhance selectivity, mechanical strength and reusability.

The peculiar feature of bioengineered materials is the versatile process of remediation. These materials are capable of working in several different pathways, unlike purely physical or chemical treatments, such as adsorption, ion exchange, chelation, biodegradation, and biotransformation. Synergistic behavior in hybrid systems. Synergistic interactions between physicochemical and biological processes can also be used to improve the performance in hybrid systems to be able to remove a variety of classes of contaminants simultaneously. Besides, the surface chemistry, porosity, and hierarchical structure of bioengineered materials can be manipulated to maximize contaminant accessibility and reaction kinetics, becoming very versatile to a wide range of environmental conditions [14,15].

Although the studies on this area have been rapidly growing, the capacity of bioengineered materials has been weakly linked to environmental and working conditions like pH, redox ability, temperature, contaminant speciation, and competing ions [16,17]. Laboratory work frequently lists high removals under a controlled environment, but the process of translating the results into the real world encounters some serious problems. The problems of material stability, long-term functioning, regeneration, and possible ecological consequences should be assessed in detail in order to guarantee the feasibility. As a result, evaluating the performance measures on laboratory, pilot, and field levels is critical to the next step in developing the technology into a common practice.

Besides technical performance, there is also a significant concern that bioengineered materials inspire the use of bioengineered materials in environmental safety and regulatory acceptance [18]. The issue of engineered microorganisms release, the possible transfer of genes, and the subsequent disposal of spent materials in the natural environment have become the more problematic issues that regulatory bodies and stakeholders started to pay more attention to. The solution to these issues demands a definitive insight into the life cycles of materials, ecotoxicological effects, and risk management techniques. Simultaneously, an economic factor such as the cost of material synthesis, scalability, and compatibility with existing infrastructure is a determining factor of large-scale application feasibility [19].

Due to interdisciplinarity and dynamic, fast-changing nature of the field, systematic and integrative reviews, synthesizing the recent developments, comparing the remediation mechanisms, and critically assessing the effectiveness and limitations, are increasingly in demand. Although particular studies have been conducted targeting particular material classes or target pollutants, there has not been a holistic view that encompasses material design, remediation mechanisms, performance assessment, and future issues. This way is necessary to determine the gaps in knowledge and direct future research to the practical and sustainable solutions.

This review aims to offer a broad synopsis of bioengineered materials used in soil and water remediation, particularly the mechanisms behind it, the effectiveness of these materials, and their existing limitations. Unlike previous reviews that focus on single material classes or contaminant types, this work systematically compares physicochemical and biological mechanisms across material categories and critically evaluates performance from laboratory to field scales. This paper is a systematic review of significant categories of biogenic engineered materials, which clarifies their different physicochemical or biological mechanisms of action and performance regarding a variety of contaminants and application size [10,20,21].

Through a combination of the latest developments in the field of bioengineering and environmental remediation, this review will become a valuable source of information which the researchers, engineers, and policymakers will use to find sustainable solutions to soil and water contamination. The synthesis above shows the possibility of bioengineered materials playing a crucial role in the restoration of the world environment and also illustrates the key processes involved in making the best use of them.

2. Types of Bioengineered Materials for Soil and Water Remediation

Bioengineered materials are an eclectic and developing category of remediation agents that combine engineered materials design and biological functionality [22,23]. They are developed under the requirement of high remediation efficiency and environmental compatibility, structural stability, and the capacity to adapt to contaminated systems of complex systems. Based on the biological component utilized and mechanism of creating material to fabricate it, bioengineered soils and water remediation materials can be broadly divided into microbial-based materials, biopolymer-based materials, bio-inspired and biomimetic composites, and plant- and biomass-based engineered materials. Both categories also have a different structure and are unique in their remediation behavior, thus suitability to various contaminants and environmental conditions.

2.1. Microbial-Based Bioengineered Materials

Bioengineered materials derived from microorganisms utilize the natural metabolic and biochemical functions of a microorganism to eliminate, convert, or adsorb contaminants in soil and water surfaces. The microorganisms that have been studied extensively are bacteria, fungi, and algae because these microorganisms have the capacity to degrade organic pollutants, lower toxic metal ions, and sequester nutrients by way of assimilation or precipitation. During the last few years, genetic engineering and synthetic biology have made it possible to modify microbial strains to increase their resistance to adverse environmental factors and increase their specificity and efficiency against a particular contaminant [15,24].

Microorganisms are frequently confined to engineered matrices to either enhance operational stability or to allow a practical application, often in the form of hydrogels, biofilms, or porous carriers [25,26]. Immobilization not only shields microbial cells against environmental stressors but also permits increased cell densities and extended activity in vivo. Microbial consortia that have been engineered have also been getting some attention because cooperative interactions between various species may permit simultaneous elimination of several contaminants as well as enhanced resistance to changing environmental conditions. The microbial-based systems are especially effective with the biodegradation of petroleum hydrocarbons, pesticides, and pharmaceutical residues and the bioremediation of metal-contaminated soils by redox-mediated reactions.

2.2. Biopolymer-Based Engineered Materials

One of the most common categories of bioengineered remediation materials that are currently under investigation is biopolymer-based materials owing to their abundance, biodegradability, and chemical versatility. Polymers of natural origin, like chitosan, alginate, cellulose, and starch, contain functional groups that are able to bind a large variety of contaminants, including heavy metals, dyes, and organic molecules. These biopolymers can be modified through chemical modification, crosslinking, or grafting with functional moieties to acquire a better adsorption capacity, selectivity, and mechanical strength [27,28].

Biopolymers are commonly used in the remediation of soil and water, where they are prepared in the form of a bead, membrane, fibre, or porous scaffold to enhance surface area and mass transfer [29]. The use of inorganic fillers, nanoparticles, or bioactive molecules into biopolymer matrix has also widened the functionality of biopolymers to allow hybrid materials, wherein adsorption is combined with catalytic or antimicrobial properties. Due to their low toxicity and biodegradable nature, materials based on biopolymers are of special interest for use in applications where environmental safety or post-treatment disposal is a paramount factor. Nevertheless, the issues of long-term stability and performance in changing environmental conditions still lead to research on more robust formulations.

2.3. Bio-Inspired and Biomimetic Composite Materials

Bio-inspired and biomimetic materials are developed by imitating some structure, functions, or processes in natural biological systems [30]. These materials in soil and water remediation may also include biological substances, including enzymes, peptides, or biomolecules, in conjunction with artificial supports, so as to obtain great specificity and catalytic capability. The enzyme immobilized materials, e.g., can be used to selectively degrade the organic contaminants in favorable environmental conditions with a limited number of damaging by-products.

Biomimetic composites are often biological and are often coupled with high material architecture, e.g., hierarchical porosity or surface patterning, to improve accessibility of contaminant and reaction kinetics [31]. These systems can be designed to respond to environmental effects such as pH or redox potential, so as to be activated or deactivated in a controlled manner to control remediation processes. Even though bio-inspired materials have immense potential as far as efficiency and selectivity is concerned, their mass utilization is frequently limited due to enzyme stability, manufacturing prices, and their disposition to environmental changes. Consequently, there is continuous study to enhance durability and come up with economical fabrication techniques.

2.4. Plant- and Biomass-Derived Engineered Materials

Plant- and biomass-based materials constitute a promising and economically viable category of bioengineered remediation agents, as they can be based on renewable resources and frequently can be based on agricultural or industrial wastes [32,33]. Plant biomass-derived materials, such as lignocellulosic fibers and biochar, and plant-based polymers, have been shown to possess high potential in contaminant adsorption and immobilization. By physical activation or chemical functionalization, these materials may be designed to increase surface area, pore structure, and affinity with a certain pollutant.

Biomass-derived materials are commonly employed in stabilizing contaminants and enhancing the quality of soil in the soil remediation process, and therefore, they can be employed in the restoration processes of agriculture and ecology [34]. Engineered biochar and plant-based composites, when used in water treatment, can be effective in removing heavy metals, nutrients, and organic contaminants. Biomass-derived matrices have been further extended in terms of remediation capacities by the integration of biological agents, e.g., microorganisms or enzymes, with them, which add biodegradation and transformation routes. Although they have their benefits, inconsistency in the composition of the raw material, as well as uniformity in performance, is a problem, and hence, standardized processing and quality control are a necessity.

2.5. Hybrid and Multifunctional Bioengineered Systems

Bioengineered systems Hybrid and multifunctional bioengineered systems integrate materials classes that are complex and interdependent to meet multi-contamination complexities and co-occurring situations that commonly arise in the real world [21,35]. Through incorporation of microbial activity with biopolymer supports or bio-inspired catalysts into biomass-derived matrices, such systems can realize synergistic remediation effects, which are even more effective than the corresponding single-component materials. With these types of hybrid designs, a multi-contaminant elimination is possible at the same time, and increased material stability and reusability are achieved.

The progress in multifunctional bioengineered materials is indicative of a greater trend towards holistic approaches to remediation in terms of environmental complexity and sustainability [19]. Such systems are progressively being developed to work in in situ conditions, which minimize the necessity of vast infrastructure and other effects on the environment. The emergence of hybrid bioengineered products will have a central role to play in further development of soil and water remediation technologies to useful and scalable solutions as the research continues. The major classes of bioengineered materials employed in soil and water remediation, along with their representative forms and target contaminants, are summarized in **Table 1**.

Table 1. Classification of major bioengineered materials used for soil and water remediation, including representative forms, functional components, target contaminants, and typical application media.

Material Class	Representative Forms	Functional Components	Primary Target Contaminants	Typical Application Media
Microbial-based materials	Free cells, immobilized cells, biofilms, consortia	Engineered/native microbes; EPS; metabolic pathways	Petroleum hydrocarbons, chlorinated organics, nutrients, some metals via redox	Soil, groundwater, wastewater, sediments
Biopolymer-based materials	Beads, membranes, fibers, hydrogels	Chitosan, alginate, cellulose; modified functional groups	Metals, dyes, polar organics, nutrients	Water, wastewater, soil amendments
Bio-inspired/biomimetic composites	Enzyme-immobilized carriers, peptide-functional surfaces	Oxidoreductases, hydrolases, biomolecules on supports	Phenolics, dyes, pharmaceuticals, pesticides	Water/wastewater; engineered reactors
Plant/biomass-derived engineered materials	Biochar hybrids, lignocellulosic sorbents	Activated/functionalized biomass; mineral additives	Metals, organics, nutrients; mixed contaminants	Soil stabilization; water treatment
Hybrid multifunctional systems	Microbe–polymer, enzyme–biochar, multi-layer composites	Coupled sorption + catalysis + biodegradation	Complex mixtures and co-contaminated sites	In situ soil and groundwater; treatment trains

3. Remediation Mechanisms of Bioengineered Materials

The successful use of bioengineered materials in soil and water remediation is due to their capacity to work in different mechanisms and often simultaneously at the same time[36]. Bioengineered materials combine physicochemical interactions with biological and biochemical functionality, unlike traditional remediation agents, which generally use only one physical or chemical process. This mechanistic diversity enables them to respond to complicated contamination situations with multiple classes of pollutants and changing environmental situations. These mechanisms are critical to understand to design material rationally, optimize performance, and be able to apply it in the field efficiently.

3.1. Physicochemical Interaction Mechanisms

Several bioengineered remediation systems, such as but not limited to biopolymers, biomass-based materials, and hybrid composites, are built upon physicochemical mechanisms. One of the most overwhelming processes involves adsorption, which is an electrostatic pulling force, the Van der Waals force, the Hydrogen bonding, and the surface complexation between contaminants and functional groups of the material surface. Amino, hydroxyl, carboxyl, and sulfhydryl functional groups are important functional groups that help in the binding of heavy metals, dyes, and organic pollutants[37].

The exchange of ions and the chelation process are particularly applicable in the extraction of metal ions in polluted soils and waters[38]. Metal ions may be swapped out by the protons or other cations available on the surface of the material in biopolymer-based and plant-derived materials, or may be held together in stable chelate complexes that decrease the mobility and bioavailability of metal. Precipitation can also take place when bioengineered materials change the local chemical conditions, e.g., pH or redox potential, and cause the formation of insoluble contaminant phases. These physicochemical interactions are usually fast and reversible, and hence they are very suitable in areas that need instant contaminant fixation.

3.2. Biological Degradation and Transformation Processes

The remedies of microbial-based and biologically functionalized materials have a central role in biological mechanisms[39]. Microorganisms can break down a great variety of organic pollutants (hydrocarbons, pesticides, and pharmaceutical compounds), and use them as a source of carbon or energy. Complex and persistent pollutants are gradually broken down to simpler and less toxic compounds through complex and persistent enzymatic pathways or broken down to carbon dioxide and water through complete mineralization.

Besides degradation of organic pollutants, the biological processes are also central to the remediation of inorganic pollutants[40]. Redox reactions of microbes have the ability to change the oxidation state of metal ions, thus decreasing their toxicity or mobility. As an illustration, the decrease in the solubility and toxicity of hexavalent chromium to trivalent chromium is caused by the microbial reduction of the hexavalent compound. Equally, biologically-controlled sulfate or phosphate precipitation can fix metals on the stable mineral phases. By entrapping microorganisms into engineered matrices, long-term remediation can be improved by maintaining the metabolic activity of the microorganism over a prolonged duration.

3.3. Enzymatic and Biochemical Mechanisms

Enzyme-based processes are a more specific and manageable remediation method, especially when used in bioinspired and biomimetic materials [41]. Oxidoreductases, hydrolases, and peroxidases are enzymes with high specificity to some types of organic pollutants and can be selectively degraded under mild environmental conditions. On solid supports, enzymes are able to maintain their activity and have the advantages of enhanced stability, reusability, and environmental resistance.

The biochemical interactions are not confined to direct transformations of the contaminant but also to the formation of the extracellular polymeric substances, biosurfactants, and organic acids by the microorganisms [42]. These compounds are capable of increasing the solubility of contaminants, bioavailability, and degradation or adsorption. The biochemical processes in the soil also affect the soil structure and the nutrient cycling in the soil system, which in turn leads indirectly to contaminant fixation and recovery of the ecosystem.

3.4. Synergistic Mechanisms in Hybrid Systems

Perhaps the greatest benefit of bioengineered materials is that they can be used to facilitate synergistic remediation processes [43]. Hybrid systems comprising biological components and physicochemical matrices can also be used concurrently to utilize adsorption processes, degradation processes, and transformation processes. As an example, a contaminant can be quickly adsorbed onto a biopolymer-based support or biomass-based support, which can be biodegraded or enzymatically changed at the surface of the material. This type of connection improves the final removal rate and minimizes the chances of desorption of contaminants or secondary contamination.

The synergistic processes are especially useful in conditions that are poisoned with combined pollutants, when various contaminants demand various remediation pathways [44]. Adaptive responses to varying contaminant loads and environmental conditions can be achieved through the integration of a number of mechanisms into one material system. This multifunctional behavior is becoming more and more considered as needed in practice, in situ remediation applications. **Table 2** provides an overview of the relationships between dominant remediation mechanisms, material types, and classes of contaminants.

Table 2. Relationship between dominant remediation mechanisms, representative bioengineered materials, target contaminant classes, and key environmental controlling factors.

Mechanism Category	Dominant Processes	Typical Bioengineered Material Examples	Contaminants Most Impacted	Controlling Factors
Physicochemical capture	Adsorption, ion exchange, chelation, surface complexation	Functionalized biopolymers; biochar composites	Pb, Cd, As, Cr; dyes; hydrophobic organics	pH, ionic strength, competing ions, surface area
Immobilization/mineralization	Precipitation, co-precipitation, stabilization	Phosphate-modified matrices; microbe-induced mineral formation	Metals/metalloids; some radionuclides	Redox, alkalinity, phosphate/sulfide availability
Biodegradation	Metabolic breakdown and mineralization	Engineered microbes; immobilized consortia	Hydrocarbons, pesticides, solvents	Electron acceptors, nutrients, toxicity, temperature
Redox transformation	Reduction/oxidation altering toxicity/mobility	Metal-reducing bacteria; bioelectroactive materials	Cr(VI) → Cr(III), nitrate reduction; some organics	Redox potential, donor availability, reactor/soil oxygen
Enzymatic catalysis	Enzyme-mediated oxidation/hydrolysis	Immobilized laccase/peroxidase/esterase systems	Phenolics, dyes, pharmaceuticals	Enzyme stability, inhibitors, pH/temperature

3.5. Influence of Environmental and Operational Factors

Environmental and operational parameters have a significant impact on the performance of remediation mechanisms of bioengineered materials. The adsorption capacity, microbial activity, and enzyme stability may be strongly influenced by factors, including pH, temperature, redox conditions, ionic strength, and the presence of other competing substances. Moisture content, organic matter, and soil texture also mediate material contaminant interactions in soil systems [45].

The predominant remediation pathways are also dictated by the operational factors such as dosage of materials, contact time, and deployment strategy [46]. As an example, short-term applications can be based on physicochemical adsorption, and long-term in situ treatments can take advantage of long-standing biological and biochemical processes. The thorough comprehension of these controlling aspects is thus essential to the customization of bioengineered materials to different situations of remediation and also to achieve consistent behavior of the material under field conditions.

4. Effectiveness and Performance Evaluation of Bioengineered Materials

The functional utility of bioengineered materials in soil and water remediation is not only based on the mechanism underlying the process, but also on the actual functionality in terms of laboratory and field performance [47]. Effectiveness is normally determined in the form of removal efficiency, kinetics, selectivity, stability, and environmental safety. Since bioengineered material systems and contamination situations are quite diverse, the performance assessment needs to be holistic to attach importance to both short-term results of remediation and long-term operational perspectives.

4.1. Removal Efficiency and Contaminant Specificity

The removal efficiency is still the main measure of remediation performance and it is usually referred to as the percentage of a reduction in contaminant level in soil or water. Bioengineered materials have been proven to be very efficient to a broad category of contaminants, which include heavy metals, organic pollutants, nutrients, and novel contaminants. Material composition, surface chemistry and biological functionality are highly specific to removal. Biomass-based and biopolymer-based materials tend to have high affinity with metal ions, and polar organic compounds, whereas microbial- and enzyme-derived systems are especially good at the degradation of complicated organic pollutants [48].

Performance also depends on the presence of other substances in the real environmental matrices, which are contaminants [49]. Comparable effects of competitive adsorption, inhibitory turning on the metabolism of microorganisms, and the complexity of the matrices may decrease apparent removal efficiency relative to particular lab conditions. Consequently, multiple contaminant systems and real-world environmental samples are given more focus in the research to offer more realistic performance measurements. **Table 3** summarizes some of the most commonly used performance measures and suggested reporting considerations of bioengineered remediation materials.

Table 3. Performance evaluation metrics are commonly used to assess the effectiveness, stability, scalability, and environmental safety of bioengineered remediation materials.

Performance Dimension	Core Metric(s)	How It Is Commonly Reported	Why It Matters for Translation	Recommended Additions for Comparability
Removal efficiency	% removal; residual concentration	C_0 and C_t; % reduction	Indicates immediate effectiveness	Report matrix type, background ions/organics
Capacity	q_max; mg g^{-1} (or mmol g^{-1})	Isotherms (Langmuir/Freundlich)	Determines material demand and cost	Report equilibrium time and fitting uncertainty
Kinetics	k values; t_1/2; rate laws	Pseudo-first/second order models	Governs reactor size and treatment time	Provide model selection rationale and bounds
Selectivity	Selectivity coefficients; competition tests	Target vs. interferents	Predicts performance in real matrices	Include multi-contaminant and real-sample tests
Stability & reusability	Cycles retained (%); leaching	Regeneration cycles	Controls lifecycle cost and waste	Track structural changes and leachate composition
Field relevance	Pilot/field removal; durability	Before/after monitoring	Captures realistic constraints	Include seasonal variability and maintenance needs
Safety	Ecotoxicity indices; by-products	Bioassays; transformation products	Ensures true risk reduction	Add life-cycle considerations and fate of spent media

4.2. Kinetics and Treatment Capacity

The remediation kinetics are important factors that can be used to establish whether bioengineered materials can be viable in practice [50]. The fast initial removal is commonly related to processes like adsorption and ion exchange, but the slower but sustained removal is more commonly related to biological processes of degradation and transformation.

Balances between these processes define the total time of treatment and operating needs.

Another important parameter is treatment capacity, which is the highest amount of contaminant that is capable of being removed per unit mass or volume of material [51]. Large-capacity materials minimize the consumption and costs of materials, especially where they are used on a large scale. Nevertheless, values of capacity used in the literature may be quite diverse as a result of experimental differences, concentrations of contaminants, and methods of assessment. Testing protocols should also be standardized to be able to make meaningful comparisons across the studies.

4.3. Stability, Reusability, and Longevity

The structural and functional stability of bioengineered materials under environmental conditions is closely associated with the long-term performance of materials. Deterioration, filtration, loss of the active sites, and microbial inactivation may cause the decline in performance with time. The biopolymer-based materials, such as could be, could be affected by swelling or mechanical degradation, whereas the enzyme-based systems could experience the loss of activity because of denaturation or inhibition [36,52].

Sustainable remediation should consider reusability by means of regeneration or recycling [53]. Other bioengineered materials may be regenerated by mild chemical or biological treatment, and repeat remediation can be carried out with little performance deterioration. Nevertheless, the regeneration process can be repeated, causing the secondary waste streams or undermining the materials. Testing longevity under cyclic and long-term conditions is thus vital in testing the viability in the real world.

4.4. Laboratory-Scale vs. Field-Scale Performance

One issue that has continued to plague the production of bioengineered remediation materials is a disparity between laboratory-scale performance and the scale of operation in the field [21]. The laboratory studies are generally conducted in controlled conditions, which may optimize the material performance but the field conditions provide variations in temperature, pH, hydrology and distribution of contaminants. Such factors may have an important impact on physicochemical interactions, as well as biological activity.

Field and pilot-scale demonstrations give vital information concerning the behavior of the materials in actual circumstances, such as transportation, deployment, and interaction with the local ecosystem. Although field studies usually have lower removal efficiency rates than laboratory experiments, they also indicate some significant positive benefits of bioengineered material, including flexibility, less environmental disturbance, and compatibility with on-site remediation efforts. The improvement of the gap between laboratory and field performance is one of the key challenges of the existing research [54].

4.5. Environmental Safety and Ecotoxicological Assessment

In addition to contaminant removal, environmental safety of bioengineered materials is also a basic element of performance consideration [53,55]. The possible threats encompass the emission of secondary pollutants, unintentional ecological relationships, and the possible accumulation of spent products in the long run. Ecological impacts, especially the possibilities of gene transfer, and the impact of microbial systems on native microbial communities, need careful consideration in microbial-based systems.

Performance evaluations are increasingly being done in ecotoxicological studies to demonstrate the impact of treated soils and waters on plants, microorganisms, and aquatic organisms [56]. These types of testing give a more detailed understanding of the success of remediation as the removal of contaminants is correlated to the actual reduction of risk. The cycle consideration, such as the material synthesis, deployment, and recycling, also adds to the total assessment of the environmental sustainability. A schematic framework illustrating performance evaluation and scale transition for bioengineered remediation materials is shown in **Figure 2**.

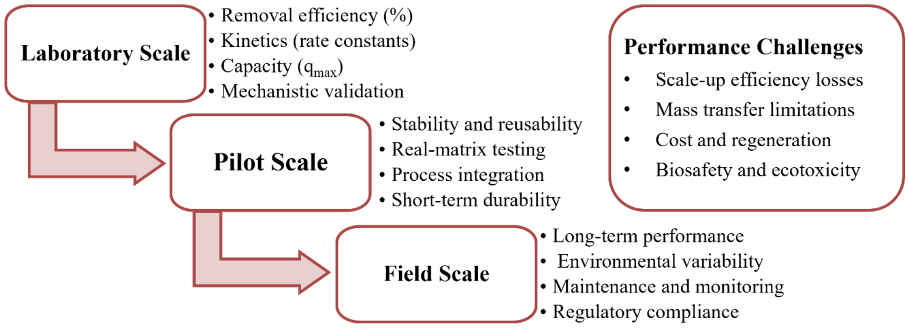

Figure 2. Performance evaluation framework for bioengineered remediation materials across laboratory, pilot, and field scales, highlighting key metrics and scale-dependent challenges.

5. Limitations and Future Perspective

Although there have been many advancements in the production of bioengineered materials in the remediation of soil and water, there are still numerous limitations that limit their extensive use. These issues are caused by technical, environmental, economic, and regulatory aspects, and it is crucial to overcome them to move laboratory-scale innovations to real and viable remediation technologies. Simultaneously, the new trends in bioengineering, materials science, and environmental monitoring also hold some bright opportunities to address the existing obstacles and inform further research trends [57].

5.1. Technical and Material-Related Limitations

The stability of bioengineered materials in complex and variable environmental conditions is one of the main technical issues in relation to bioengineered materials. The performance or activity of many biologically functional materials can be affected by changes in pH, temperature, redox potential, and contaminant composition, resulting in reduced performance or loss of activity with time. Materials based on biopolymers can degrade or be fouled, whereas enzyme and microbial systems can be deactivated by toxicity, nutrient deprivation, or competition with indigenous organisms [58].

The other weakness is associated with performance consistency. Batches or location of application of the remediation process may vary significantly in effectiveness due to variability in quality of raw materials, biological or fabrication processes. This is something inconsistent, which makes it difficult to predict performance and restricts trust in large-scale deployment. Moreover, the broad use of bioengineered materials, when beneficial, may also become a problem in design and optimization because of the multifunctionality of many of these materials, as they may not be easily adapted to particular contaminants or environmental conditions [59].

5.2. Scale-Up and Economic Challenges

There are significant economic and logistical issues associated with scaling bioengineered materials used in the laboratory to the field scale. Most techniques of fabrication that work well on a small scale, including precision functionalization or biological immobilization with control, are economically not viable or technically unfeasible at a large scale. Raw biological materials and conditions of the controlled processing are also factors that contribute to the economic attractiveness [60].

Deploying and maintenance fees are also a vital factor in deciding to be practically applicable. The in-situ remediation usually involves material application, monitoring, and possible regeneration, which is repeated and is involved in the overall project expenses. When compared to traditional remediation technologies, bioengineered materials need to not only be just as effective, but also have obvious economic benefits that can be associated with their use. Life-cycle cost analysis has increasingly become a significant part of the future performance analysis [61].

5.3. Environmental and Biosafety Considerations

The safety of the environment is one of the key issues in the use of bioengineered materials, especially those that include living or genetically modified organisms [62]. The risks involved may include unnecessary ecological interactions, horizontal gene transfer, and the long-term survival of engineered biological parts in nature. Non-living bioengineered materials, even in their non-living state, can also cause a secondary effect on the environment through degradation products or spent materials.

These risks need to be evaluated and controlled using elaborate biosafety systems and strategies of long-term monitoring. Existing ecotoxicological researches tend to be short or narrow in its scope, and so, it is hard to determine long-term effects on an ecosystem. The creation of materials that degrade with control, have low ecological footprints, and can be predicted to have at the end of their usefulness is one of the critical research priorities of environmental acceptability [63].

5.4. Regulatory and Standardization Barriers

Biological engineering of remediation materials is still poorly regulated, and in certain instances, not well-developed. Current environmental policies are also not geared towards the use of hybrid materials of biological and engineered materials, thus creating confusion in the approval and permitting procedures. Such a lack of clear regulatory channels may slow down the implementation process and deter the use of new remediation technologies [36].

The issue of standardization also complicates the transfer and communication of technology between studies. Variations in testing procedures, performance measures, and reporting procedures are obstacles to effective assessment of material performance and safety. It is necessary to develop standard requirements to define material characterization, performance tests, and risk testing to enable easier regulatory acceptance and wider adoption [64].

5.5. Future Research Directions and Technological Outlook

In the future, synthetic biology, nanotechnology, and novel designs of smart materials will continue to advance with the next generation of bioengineered remediation materials [65]. Growth of responsive and self-regulating mechanisms that are sensitive to environmental conditions has great potential in the enhancement of performance and resilience. The integration with digital monitoring solutions and data-driven optimization methods can also help to improve the control and predictability of the field applications.

Multifunctionality, system integration, remediation and resource recovery, ecosystem restoration, and circular economy are also likely to be the focus of future research [66,67]. The cross-disciplinary and cross-regional collaboration will be essential to overcome the site-specific problems and provide equal opportunities to achieve sustainable remediation methods. Through a systematic course of action concerning the present constraints and exploiting new technologies, bioengineered materials will become much more significant in the process of soil and water remediation at the global level. **Table 4** presents the main constraints that prevent the large-scale use of bioengineered materials, with a description of the reasons and possible ways to address them.

Table 4. Limitations affecting the deployment of bioengineered remediation materials, underlying causes, practical impacts, and future mitigation strategies.

Limitation Domain	Typical Manifestation	Root Cause(s)	Practical Impact	Future Perspective/Mitigation Pathway
Material durability	Fouling, swelling, mechanical breakdown	Biofilm growth, particulates, weak crosslinking	Declining efficiency, higher O&M	Anti-fouling surfaces; robust crosslinking; layered designs
Performance variability	Unstable removal across sites	pH/redox shifts; heterogeneity; competition	Poor predictability	Site-specific tailoring; adaptive/stimuli-responsive materials
Biological stability	Loss of microbial/enzyme activity	Toxicity, inhibitors, nutrient limits	Reduced long-term treatment	Protective immobilization; engineered tolerance; consortium design
Scale-up economics	High synthesis cost or low throughput	Complex functionalization, bioprocess constraints	Limits adoption	Green manufacturing; low-cost feedstocks; modular production
Biosafety/ecotoxicity	Potential ecological impacts	Living/engineered organisms; leachables	Regulatory and public barriers	Containment strategies; kill-switches; degradable, low-leaching media
Regulatory/standardization	Inconsistent testing & approval	Lack of shared protocols	Slow deployment	Standard test matrices and reporting; harmonized risk frameworks

6. Conclusion

Genetically engineered organisms have become a promising and effective category of remediation technology that can overcome the increasing problems of soil and water pollution. These systems have unique values compared to traditional methods of remediation in that they combine biological functionality with engineered material design, such as increased specificity, adaptability to multi-faceted environmental conditions, and increased compatibility with the environment. The variety of bioengineered materials, including microbial and biopolymer-based systems, bio-inspired composites, and hybrids of biomass, is a versatile set of tools to address a wide range of contaminants.

The review has identified the basic remediation processes, which are the basis of bioengineered materials, and has shed light on the interaction between physicochemical interactions and biological or biochemical reactions. With this form of mechanistic integration, contaminants can be removed efficiently by adsorption, degradation, transformation, and immobilization, often in the same material platform. Laboratory and field experimentation of the evaluation of performance indicates high remediation potential, and also reveals the effects of environmental conditions, material stability, and operational factors on performance.

Despite these developments, many issues still restrain large-scale adoption. The problems to be considered are material durability, scalability, economic viability, environmental safety, and regulatory acceptability, to be dealt with systematically to achieve dependable and accountable deployment. Not only the optimization of technologies but also the standardization of evaluation systems and interdisciplinary cooperation are needed to provide the transition of laboratory innovation to practical application.

In the future, further advances in bioengineering, materials science, and environmental monitoring will respond to the creation of more robust, multifunctional, and adaptable remediation systems. Bioengineered materials can also be used to transform the world in the context of the global battle against soil and water pollution by incorporating sustainability concepts and site-specific needs in the design of the materials. Their effective incorporation into environmental management plans will do a great deal in reducing pollution, restoring ecosystems, and protecting human and environmental health in the long-run.

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