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REVIEW

Bioremediation using genetically modified microorganisms for the degradation of environmental pollutants

Biorremediación mediante microorganismos modificados genéticamente para la degradación de contaminantes ambientales

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ABSTRACT

Introduction: the study addressed the environmental problems caused by soil and water contamination due to the excessive use of agrochemicals and industrial wastes. It was pointed out that intensive agricultural production and population growth have increased the accumulation of pollutants, generating negative impacts on biodiversity and human health. In the face of this environmental crisis, remediation methods were explored, highlighting bioremediation as a sustainable and efficient strategy based on microorganisms for the elimination of pollutants.
Development: different bioremediation strategies were analyzed, differentiating between in situ and ex situ techniques. Processes such as biospraying, biostimulation and bioaugmentation, which allow the degradation of contaminants through microbial activity, were described. In addition, the impact of biotechnology on bioremediation was discussed, highlighting the use of omics tools and the application of genetically modified microorganisms to improve the efficiency of these processes. It was emphasized that genetic engineering and genome editing have made it possible to optimize the metabolic capacities of bacteria and fungi to transform toxic substances into less hazardous compounds.
Conclusion: it was concluded that bioremediation represents a viable and ecological alternative for dealing with environmental contamination. However, its large-scale application still faces challenges, such as the regulation of genetically modified microorganisms and the need for more detailed studies on its long-term impact. The integration of new biotechnological technologies could optimize environmental remediation and ensure its sustainability in the future.

Keywords: Bioremediation; Environmental Contamination; Microorganisms; Biotechnology; Genetic Engineering.

RESUMEN

Introducción: el estudio abordó la problemática ambiental causada por la contaminación del suelo y el agua debido al uso excesivo de agroquímicos y residuos industriales. Se destacó que la producción agrícola intensiva y el crecimiento de la población han incrementado la acumulación de contaminantes, generando impactos negativos en la biodiversidad y en la salud humana. Ante esta crisis ambiental, se exploraron métodos de remediación, resaltando la biorremediación como una estrategia sostenible y eficiente basada en microorganismos para la eliminación de contaminantes.
Desarrollo: se analizaron diferentes estrategias de biorremediación, diferenciando entre técnicas in situ y

ex situ. Se describieron procesos como la bioaspersión, la bioestimulación y la bioaumentación, los cuales permiten la degradación de contaminantes mediante la actividad microbiana. Además, se discutió el impacto de la biotecnología en la biorremediación, resaltando el uso de herramientas ómicas y la aplicación de microorganismos genéticamente modificados para mejorar la eficiencia de estos procesos. Se destacó que la ingeniería genética y la edición del genoma han permitido optimizar las capacidades metabólicas de bacterias y hongos para transformar sustancias tóxicas en compuestos menos peligrosos.
Conclusión: se concluyó que la biorremediación representa una alternativa viable y ecológica para enfrentar la contaminación ambiental. Sin embargo, su aplicación a gran escala aún enfrenta desafíos, como la regulación de microorganismos modificados genéticamente y la necesidad de estudios más detallados sobre su impacto a largo plazo. La integración de nuevas tecnologías biotecnológicas podría optimizar la remediación ambiental y garantizar su sostenibilidad en el futuro.

Palabras clave: Biorremediación; Contaminación Ambiental; Microorganismos; Biotecnología; Ingeniería Genética.

INTRODUCTION

The scarcity of agricultural land, population growth, the loss of food to natural disasters and pests, and the water crisis all limit developing countries' economic development. Increasing agricultural yields in the future will be difficult under these restrictions. Farmers have adopted advanced technologies such as hybrid seeds, systematic irrigation, chemical fertilizers, and pesticides to achieve food objectives. However, these agricultural advances have generated environmental threats such as decreased soil fertility, increased acidification, nitrate leaching, weed resistance to herbicides, and decreased soil biodiversity. The excessive and inappropriate use of pesticides affects the entire ecosystem, as their residues contaminate the food chain, the soil, the air, and the water. These chemicals have also been shown to be hazardous to health (Gangola et al., 2023).

The European Union and the United States have seen a significant increase in hazardous and non-hazardous waste production in recent years. Annual municipal solid waste production in China is also expected to grow considerably (El Asri et al., 2022). In addition, industrial activities, especially mining, have contributed to contaminating surface water and groundwater systems with various chemical compounds, such as chlorinated hydrocarbons and radon. This pollution represents a significant environmental challenge that requires attention. Arsenic contamination in groundwater is considered the worst mass poisoning in the world. It is estimated that more than 100 million people in 70 countries are affected by this problem (Paul et al, 2019).

In addition, the World Bank report "What a Waste 2.0" indicates that the world produces 2,01 billion tons of municipal solid waste per year, of which at least 33% is not managed in an environmentally responsible manner. For example, the plastic waste choking our oceans represents 90% of all marine debris (Kaura et al., 2023).

Methods such as pyrolysis, recycling, backfilling of contaminated land, and incineration are used to reduce soil contamination and toxicity in agricultural fields. However, these physical and chemical methods are not economical or suitable for environmental remediation. Using microbiological agents would be a promising option because of their ability to clean up pollutants at affected sites. This alternative could be more effective, profitable, less dangerous for organisms, and more ecological. Biodegradation, carried out with the help of algae, fungi, bacteria, and actinomycetes, is a natural process that does not produce harmful intermediate metabolites and is an effective technique for eliminating toxic substances. Various microorganisms in different habitats, such as fresh and seawater, wastewater, and soil, can metabolize foreign compounds and convert them into natural minerals used by plants (Gangola et al., 2023).

Environmental remediation usually resorts to chemical methods such as reduction, washing, ion exchange, adsorption, and filtration. However, biotechnological methods for eliminating pollutants exist, such as hemofiltration, biosorption, land cultivation, and phytoremediation. Biological processes are the most widely used because they do not require toxic chemicals or a lot of energy (Naik et al., 2023).

Bioremediation could be an innovative and effective alternative for remedying the accumulation of heavy metals. Unlike other methods, biological strategies are environmentally friendly and socially acceptable. In addition, there is a wide diversity of organisms with capacities that have not yet been fully exploited, and these can be genetically modified to accelerate the environmental clean-up process (Mathew et al., 2023).

Given the importance of the context outlined, the main objective of the present research was to analyze the effectiveness of bioremediation using genetically modified microorganisms as an innovative strategy for the degradation of environmental pollutants.

DEVELOPMENT

Bioremediation is a process that uses living organisms, such as bacteria and fungi, to remove pollutants from contaminated sites. Microbes can transform heavy metals into less toxic or water-soluble states, reducing their bioavailability. These microorganisms use different strategies, such as oxidation, immobilization, transformation, binding, and volatilization, to remove heavy metals from the contaminated site. Some microbes can even reduce the toxicity of metals through enzymatic metabolic processes (Khan et al., 2023).

Bioremediation is considered adequate when an efficient bacterial strain can degrade many contaminants to a minimum amount of harmless or non-toxic degradation products at an adequate rate and in a limited time (Patil et al., 2019).

Recent advances in metabolic engineering and systems biology tools have opened up new opportunities to improve the efficiency of microbial strains and increase their biodegradation potential. Biological engineering is not the only solution, but it is unique among the various approaches needed to address the climate crisis. Biological solutions designed in a safe and responsible manner can be more sustainable, integrable in natural environments, and durable (Aurand et al., 2024).

In situ bioremediation involves the treatment of contaminated material on site. Some of the in situ bioremediation technologies include:

1. Bio-spraying: Native microorganisms degrade pollutants in the saturated zone. Air (or oxygen) and nutrients are injected to increase their biological activity.
2. Bioventing: Native microorganisms degrade contaminants in the unsaturated zone. Bioventing systems supply air from the atmosphere to the soil above the water table through injection wells.
3. Biostimulation: Electron acceptors and donors, nitrogen, oxygen, and carbon are added to stimulate the native microbial populations.
4. Bioaugmentation: Selected bacteria are added to a contaminated area.

Ex-situ bioremediation techniques involve excavating and piling up the contaminated soil and adding organic materials and waste. Pipes that allow air to circulate for microbial respiration facilitate bacterial growth. Compared to other methods, bioremediation in suspension in a bioreactor is a faster process, as the contaminated soil is mixed with water, nutrients, and oxygen to create the ideal environment for microorganisms to degrade the contaminants (Debbarma et al., 2023).

Biotechnology in bioremediation

In recent years, advances in genomics, metagenomics, proteomics, bioinformatics, and high-throughput analysis have allowed for the detailed study of ecologically important microbiota, identifying key pathways for pesticide biodegradation and the capacity of microbes to adapt to unfavorable environments.

Advances in metagenomics and sequencing have opened opportunities to search for new catabolic genes and their regulatory mechanisms in culturable and non-culturable microbes in diverse ecosystems. Exploring the molecular mechanisms of pollutant biodegradation by microbes and their interaction with the environment is important for successfully applying these techniques in situ remediation studies (Gangola et al., 2023).

Nanoparticles manufactured using biological methods are a more ecological and efficient alternative to the physical or chemical processes traditionally used for wastewater treatment. These nanoparticles, whether bimetallic or enzyme-functionalized, can be used in multimodal effluent treatment, eliminating metals and degrading dyes. On the other hand, omic technologies, which study complete sets of molecules such as genes, proteins, and metabolites, have proven efficient and profitable bioremediation methods. The use of omic techniques, such as metagenomics, functional genomics, proteomics, and metabolomics, has allowed for a better understanding of the physiology and genetics of microbial communities. These tools have facilitated studying individual organisms and explained how environmental factors affect microorganisms. In addition, fluxomics, which evaluates metabolic flux using isotopic tracers, has helped identify the metabolic processes that underpin essential microbial functions (Patil et al., 2023), (Wani et al., 2023).

Bioinformatics is a field of biology that uses computational and statistical tools to solve biological problems. It includes phylogenetic analysis, data mining, determination of the closest molecular phylogeny, and systems biology, all of which help to simplify the bioremediation process (Raj et al., 2023).

Genetic engineering applied to bioremediation

Genetic engineering is a modern technology that allows the creation of microorganisms designed to treat specific pollutants. The genes of these microorganisms are modified to achieve the desired effect. Studies show that genetically modified microorganisms can degrade specific compounds. This is achieved by altering the specificity and affinity of enzymes, constructing and regulating metabolic pathways, developing and controlling bioprocesses, and using bioinformatic sensors. Furthermore, the application of genetic engineering techniques, such as recombinant DNA technology, has made it possible to improve the capacity of microorganisms to generate more energy, increase redox activity, eliminate limiting pathways, and modify the genes responsible for metabolic routes, resulting in more significant degradation of pesticides and other chemical pollutants

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(Patel et al., 2022), (Debbarma et al., 2023).

Genome editing is a revolutionary technique that uses specially designed molecular tools to modify DNA sequences. These tools have various applications in animal, plant, and microorganism research. Genetic editing involves identifying the sequence of the target gene, generating a specific break at that site, and then repairing the break through a process of homologous recombination, resulting in the modification (insertion or deletion) of the desired gene or a fragment of the sequence. These gene editing tools have great potential for improving the efficiency of bioremediation processes, such as eliminating harmful substances, transforming toxic compounds into less dangerous forms, and degrading pesticides. The primary gene editing tools are zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the CRISPR-Cas system.

Recently, genome editing tools such as CRISPR-Cas9 and CRISPR-Cpf1 have demonstrated their potential to improve agricultural characteristics and phytoremediation efficiency by strengthening the interaction between plants and microorganisms. Several microbial genes have been reported to contain phytoremediation attributes, such as those encoding enzymes that degrade pollutants such as 2,4-dinitrotoluene, arsenate, chlorobenzoic acid, or trichloroethylene. These genes have shown great potential for reducing soil pollutants, and their overexpression can be achieved using genome editing tools in microorganisms that promote plant growth.

Genetically modified organisms (GMOs) can affect the growth and sustainability of other species, including plants, animals, and humans. Some of these risks could be mitigated by using genetic "kill switches" that quickly eliminate GMOs from the environment once they have fulfilled their purpose or by applying specific chemicals (Barooah et al., 2023).

Genetic engineering and molecular biology have proven fundamental in eradicating environmental pollution caused by human negligence. Oxygenase protein engineering is a molecular technique used to improve the oxidative degradation of contaminated sites. Oxygenase enzymes participate in the degradation process, catalyzing the reduction of oxygen and incorporating monooxygenases or dioxygenases into the oxidizing substrate. These oxygenase catalysts are often effective in the degradation of many aromatic compounds.

Toluene (an aromatic hydrocarbon) and mercury in ionic form can be degraded more safely and ecologically through genetic engineering compared to traditional methods (Wilgince Apollon et al., 2023).

Using genetically modified organisms (GMOs), including Pseudomonas aeruginosa, Neurospora crassa, and Escherichia coli, is an innovative strategy for remediating water and soil contamination. These desirable properties, such as tolerance to metals, overproduction of metal-chelating proteins and peptides, and metal accumulation, have made GMOs effective for bioremediating a wide range of pollutants.

Advances in biotechnological techniques such as recombinant DNA and natural gene transfer can facilitate the production of specific enzymes that improve the degradation of hazardous organic compounds, both by endophytic and rhizospheric bacteria of plant origin, thus helping to improve the decomposition of these pollutants in contaminated areas. Furthermore, it has been demonstrated that strains of Pseudomonas can biodegrade total petroleum hydrocarbons (TPH) with a significant increase in dehydrogenase activity in the soil, which increases their capacity to decompose oil up to 100 times more than wild (natural) isolates found in extrachromosomal plasmids (Nath et al., 2023).

CONCLUSIONS

It is essential to study the relationship between the environmental effect, the behavior and the fate of pollutants, and the efficiency of the different bioremediation technologies. The horizontal gene transfer from modified microorganisms to native microorganisms, the use of antisense RNA and suicide genes, and antibiotic resistance markers, which other selectable markers can replace to prevent the unintended transfer of resistance genes, should be avoided. The regulatory problems and risks associated with genetically modified micro-organisms (GMMs) significantly impede their use. However, this can be resolved by developing and implementing suicide GMMs. Suppose detailed information is obtained on bioremediation tools, their genomes, biochemical pathways, and functions and mechanisms. In that case, this will be the most efficient technology in the future to enable the use of GMMs in large-scale bioremediation approaches.

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