Artificial Intelligence and Role in Bioremediation of Water Pollution: Article Review

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Abstract**—***Water pollution is still a major worldwide problem that endangers environmental balance and human health. Innovative strategies that make use of cutting-edge technologies are necessary to effectively handle this issue and combat pollution on a larger scale. Microbial-based bioremediation, which is well-known for its capacity to break down dangerous pollutants including petroleum hydrocarbons and other dangerous toxins, is one of the most promising techniques. However, because of differences in microbial populations and ambient variables, which frequently make outcome prediction difficult, bioremediation can be inconsistently successful.*

This review focuses on the revolutionary potential of artificial intelligence to address pollution in soil, water, and air environments while examining recent developments in microbial bioremediation. AI finds important trends and creates prediction models to improve bioremediation techniques by processing and analyzing large datasets. The use of artificial intelligence in water pollution control has great potential to increase the precision of contamination removal while facilitating more intelligent, real-time detection, monitoring, and remediation using sophisticated intelligent systems.

Artificial intelligence is essential for promoting sustainable practices by assisting proactive environmental management, in addition to improving pollution control strategies. Although the results demonstrate AI's remarkable potential to transform pollution mitigation and water conservation, successful adoption depends on the development of strong infrastructure, the promotion of interdisciplinary collaboration, and the application of responsible governance frameworks to direct innovation successfully and effectively.

Keywords**—** *Artificial intelligence, Healthy ecosystems, Microbial degradation, Water pollution, environmental sustainability, bioremediation.*

I. INTRODUCTION

The practice of utilizing microorganisms to break down pollutants is called bioremediation (1). Any type of pollution is a serious worldwide problem that negatively impacts the health of people, animals, plants, and the environment (2). To address environmental issues and their detrimental effects on human health, creative pollution-reduction techniques are needed. One promising method for environmental cleanup is the microbial breakdown of pollutants and poisons. (3,4). One of the main goals of environmental research is bioremediation process optimization. One of the best instruments for altering environmental conditions is artificial intelligence, or AI. Because AI algorithms can manage large and complex data, extract features, find trends, and produce timely suggestions to address environmental concerns, they have become increasingly popular in environmental research. (5,6). The potential of artificial intelligent can truly be assessed only through the incorporation of interdisciplinary research. However, it has already proven to be a cost-effective and practical solution for restoring polluted ecosystems. Heavy metal contamination, in particular, poses significant health risks, such as neurological conditions, reproductive issues, damage to the kidneys and possibly cancer. (7).

II. ENVIRONMENTAL SCIENCE: ADVANCES

Approximately 80% of wastewater globally is released into the environment untreated from economically developing nations, according to the United Nations Environment Program and the World Health Organization in 2021 (8-10) .

Algorithms for Artificial intelligence driven bioremediation optimization can be used to assess ecological data, predict pollutant behavior, streamline the procedure, and boost productivity. Despite years of use, conventional methods like bioaugmentations and bio-stimulation still have distinct drawbacks.

The technique of introducing microorganisms to degrade pollutants and boost the metabolic activity of the current bacterial community is known as bioaugmentation (11,12). In a similar vein, giving nutrition, oxygen, and other substances to enhance the capacity to degrade pollutants is known as bio-stimulation.(13, 14) These conventional bioremediation methods take a long time, don't take site heterogeneity into account, and can't predict microbial behavior.(15).Bioinformatics and computer models are being used to forecast how microorganisms will react to pollutants and environmental circumstances in order to get around the drawbacks of conventional bioremediation techniques.

Water pollution remains one of the most critical environmental crises of the 21st century. Rapid urbanization, industrial discharges, and agricultural runoff continuously introduce toxic heavy metals, hydrocarbons, microplastics, and emerging xenobiotics into global aquatic ecosystems. Traditional chemical and physical cleanup methods, while effective, are often expensive, energy-intensive, and prone to producing hazardous secondary waste. In response, bioremediation-the utilization of biological agents such as bacteria, fungi, algae, and plants to degrade or neutralize contaminants-has emerged as a highly sustainable, eco-friendly, and cost-effective alternative. (16).

Bioremediation, which includes both natural and artificial techniques, is critical for repairing water-polluted ecosystems (17).

III. AI IN MICROBIAL SELECTION AND OPTIMIZATION

For effective degradation processes, methods like clustering and classification aid in the identification and characterization of various microbial communities. As shown in Fig.1, ANNs and ensemble techniques can forecast microbial community dynamics and investigate the relationship between environmental factors and the microbial community for successful bioremediation tactics(18).

According to some research, functional profiling using AI allows for the identification of important enzymes and taxa responsible for degradation, which aids in the optimization of bioremediation processes, while machine learning can anticipate pathways involved in degradation by examining sequences. (1, 19).Genes, metabolites, and proteins are examples of biomarkers that can show the existence and activity of particular microbial populations that can break down contaminants.

By identifying connections between microbial activity and pollutant concentrations as demonstrated by two separate study groups operating at distinct timelines, algorithms such as SVMs, ANNs, and RF can find promising biomarkers (20,21). Fig. 2 illustrates these machine learning integration techniques with microbiome analysis.

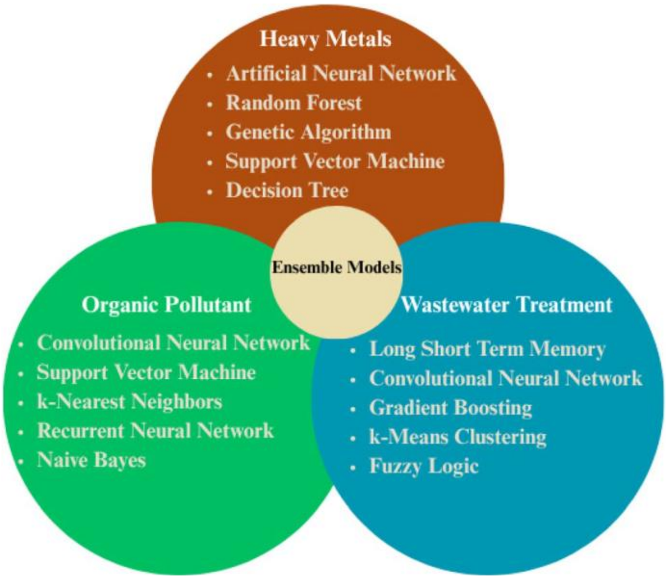

Fig. 1. Machine learning models for wastewater treatment, organic contaminants, and heavy metals, including ensemble models at the intersections

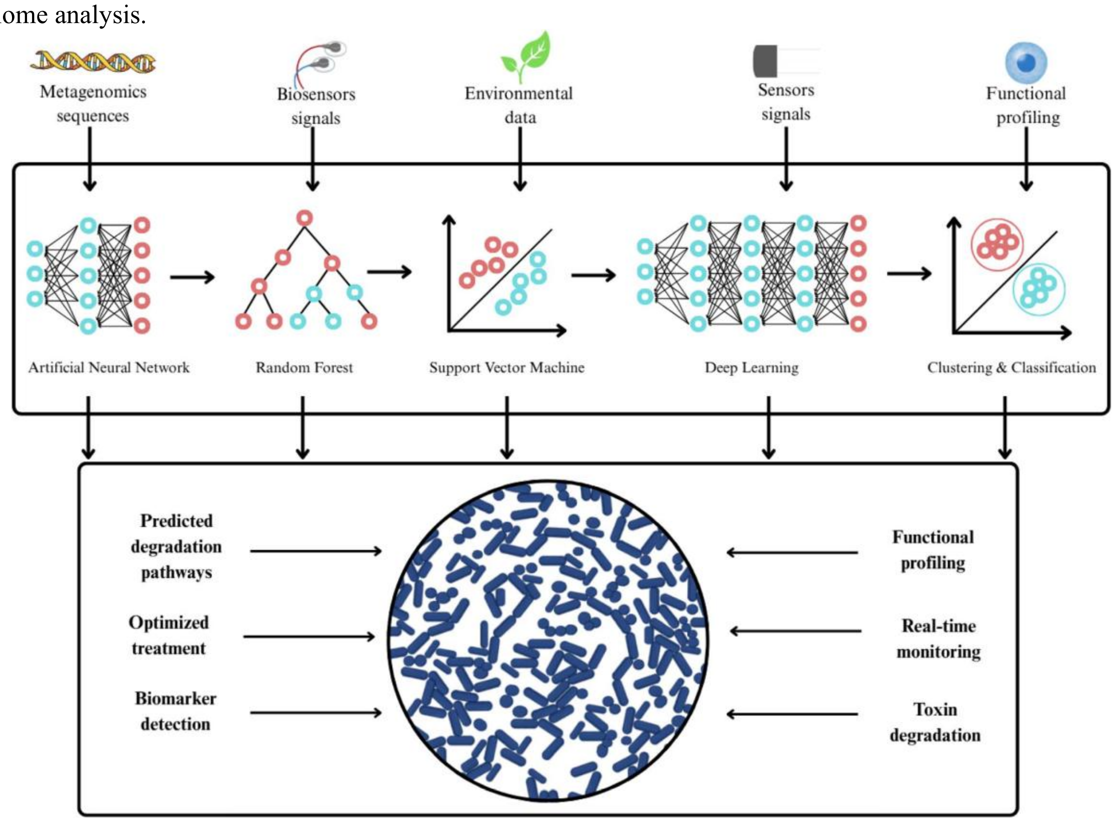

Fig. 2. incorporating machine learning methods into microbiome analysis for use in clinical and environmental settings.

Machine learning models, particularly those based on supervised and unsupervised learning, can improve the performance of bioaugmentation by predicting microbial activity, optimizing strain consortia, and fine-tuning environmental conditions to maximize degradation efficiency (22). The adoption of ML in bioaugmentation enables a more data-driven approach, where microbial consortia are selected based on not only their intrinsic capabilities but also their interactions with one another and the surrounding environment (23).

IV. THE SIGNIFICANCE OF BIOREMEDIATION

In contemporary environmental management, bioremediation is highly relevant because several key advantages over traditional physicochemical remediation methods. Firstly, it is often more cost-effective since treatments can typically be implemented directly on-site, requiring minimal energy and infrastructure in contrast to energy-intensive methods similar to burning and soil washing. Secondly, bioremediation offers the potential for complete pollutant breakdown (mineralization), as opposed to merely transferring contaminants to another part of the environment, such as moving pollutants from soil to landfills or from activated carbon to water.

Bioremediation is a more environmentally responsible choice since it makes use of natural biological processes, where Its ecological friendliness and environmental sustainability provide another important benefit which often result in less secondary waste or byproducts. It is particularly well-suited for large-scale or remote contaminated sites since it can frequently be carried out on-site with little disturbance to the nearby ecology or local residents.

To promote ecosystem restoration and improve soil health, bioremediation can also be paired with phytoremediation, a technique that makes use of plants and rhizosphere bacteria. This integration fits very nicely with the general goals of sustainable development. These notable strengths position bioremediation as a pivotal technology for addressing inheritance contamination and reducing the negative effects of industrial activities on the environment. (24).

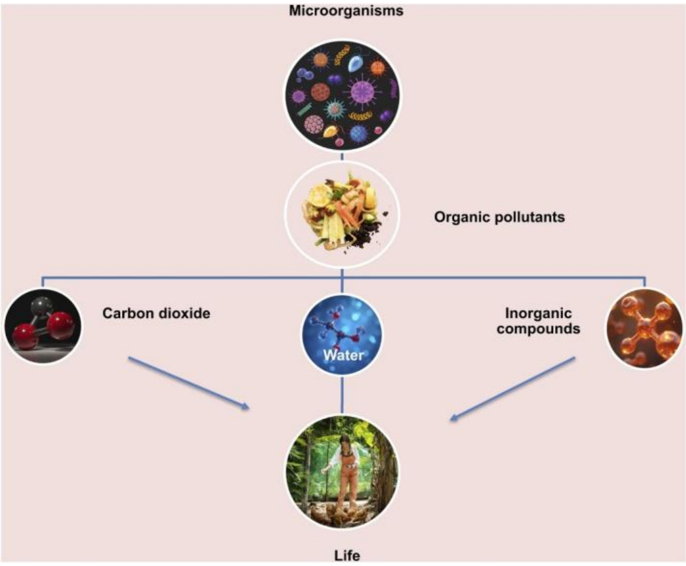

Fig. 3. Microorganisms' function in organic contaminants' biodegradation. The picture depicts the natural metabolic processes by which microorganisms degrade organic contaminants, including pesticides and hydrocarbons. Carbon dioxide (CO_2), water (H2O), and inorganic chemicals are among the simpler, non-toxic end products that result from the breakdown of organic contaminants. In addition to cleaning up contaminated environments, this microbial activity maintains microbial survival and growth. Bacteria, fungus, and archaea are important microbial organisms that use pollution as sources of carbon and energy.

V. APPLICATION OF BIOREMEDIATION

Increasing the rate of soil and groundwater purification through biostimulation requires removing biodegradation bottlenecks or drastically reducing the threshold for active biodegradation. Supplementing inadequate nutrients won't assist if oxygen isn't there, or vice versa; any obstacles preventing relevant microbial activity must be removed. This means that a detailed analysis of the local circumstances must be carried out in order to determine the best course of action in each instance. Surveys conducted in polluted areas may not always take into account all relevant elements, despite the fact that this may appear apparent. Physical treatments, chemical oxidation or reduction, bioaugmentation, biostimulation, natural attenuation, and combinations of these methods are all potentially useful methods for the in-situ remediation of contaminated sites. However, bioremediation using biostimulation is almost often combined with other methods. Consequently, the final option—a combination of techniques—is the most widely used strategy in bioremediation.

1-Remediation of Soil

The term "soil organic pollutants" refers to a wide variety of materials, some of which share traits. Explosives, flame retardants, surfactants, dioxins, halogenated hydrocarbons, polyaromatic hydrocarbons, insecticides, and medical waste/pharmaceuticals are among them. It's crucial to remember that some of these classifications overlap, thus a single contaminant may fit into more than one category. This intricacy emphasizes the necessity of having a solid grasp of certain pollutants and the possible hazards they pose to the environment.(25,26).

Cleaning up soil organic contaminants usually starts with a comprehensive assessment. This entails assessing the stability of hazardous substances, identifying the particular pollutants present, quantifying their concentrations, and assessing the degree of contamination. Characterizing the soil itself, taking into account its physical, chemical, and biological characteristics, is also essential. Conditions related to water flow are also crucial to take into account. Furthermore, eliminating the source of contamination is essential, and the effect of doing so on the pollutant's lifespan should be evaluated while accounting for its rate of deterioration (27). The creation of novel techniques for cleaning up contaminated places has advanced significantly.

The pore area where bacteria and clay particles interact is comparatively rich in organic materials, including leftover EPS. Particles of sand and silt limit this pore space. Fungal hyphae are affixed to the outside of an aggregate. (28).

2- Remediation of Water

The pharmaceutical industry is a major source of emerging organic pollutants because it releases a lot of waste water that may contain organic pollutants, inorganic pollutants, and inorganic compounds that are either biodegradable or non-biodegradable depending on how strict national regulations are. (29). Due to the use of numerous dangerous chemicals in the production of dyes, the textile industry is a major source of pollution. The textile sector frequently releases untreated effluent into the environment. Many physicochemical techniques have been widely used to remove pollutants from the environment, however these techniques are often unfeasible because to factors including high operating and maintenance costs and the production of extremely dangerous secondary contaminants. Figure 4: One approach that shows promise for getting rid of pollutants is biological remediation. It has a number of advantages over alternative methods, including as low operating and maintenance costs, environmental friendliness, and an effective removal procedure. The bioremediation technique uses microorganisms like fungi and bacteria to change or remove pollutants.(30). Furthermore, research on microalgal technology has shown that it has the potential to be a sustainable way to manage pollutants (31).

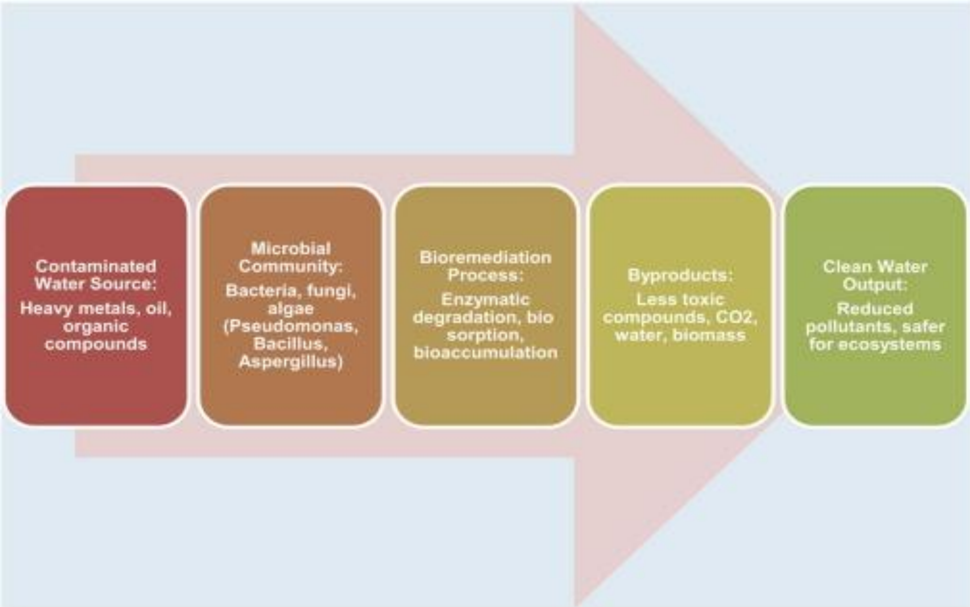

Fig. 4. Microorganisms play a crucial role in the bioremediation of contaminated water, transforming polluted sources into cleaner outputs. The process, illustrated step by step in the image, involves utilizing various microorganisms such as bacteria (e.g., Pseudomonas and Bacillus), fungi (e.g., Aspergillus), and algae to detoxify water containing heavy metals, oils, and organic chemicals. These microbes employ several remediation methods, including bioaccumulation (active uptake and internal storage of contaminants), biosorptions(passive adherence of pollutants to cell wall structures), and enzymatic degradation (breakdown of organic pollutants through microbial enzymes). The byproducts generated during this process include water, microbial biomass, carbon dioxide (CO_2), and less harmful compounds. The outcome is water with significantly reduced pollution levels, enhancing its safety for aquatic life and its potential for reuse.

VI. MICROBE-ASSISTED BIOREMEDIATION

The main foundation of bioremediation is the production of enzymes, which are necessary for effectively decomposing the dangerous pollutants. Numerous microorganisms, including bacteria, fungus, and archae, have the metabolic capacity to transform hazardous substances into less harmful or innocuous forms. Numerous bacterial taxa, including *Pseudomonas, Dehalococcoides, Rhodococcus, Comamonas, Burkholderia, Alcaligenes, Bacillus subtilis, Deinococcus radiodurans, Acidithiobacillus ferrooxidans, Mesorhizobium huakuii,* and *Sphingomonas*, have been widely documented to be capable of bioremediation. (32).

Last but not least, there is a toxicity threshold limit that microorganisms may tolerate; in extreme, high-concentration pollution scenarios, bacteria may die before they can perform their functions, which would completely fail the bioremediation process. Understanding these limitations is the first step towards developing more reliable and effective field application strategies (33).

VII. CONCLUSION

It is increasingly clear how AI may revolutionize daily living, from environmental bioremediation to medical surgery. The use of AI to improve the microbial breakdown of water contamination is an important advancement in environmental management. We can accomplish more precise, successful, and economical restoration procedures by combining AI-driven predictive models with conventional bioremediation methods. To solve the intricate problems caused by water contamination, there is an urgent need for ongoing study, strong interdisciplinary cooperation, and the incorporation of AI into bioremediation procedures. By adopting these advancements, we can guarantee safe and clean water for future generations, enhance the effectiveness of remediation efforts, and foster a cleaner, healthier environment. Beyond enhancing the precision of pollution management, such progress can also support the creation of a more sustainable future while aiding in the preservation and restoration of our environment.

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