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Nature's Cleanup Crew: How Microbes Eat Pollution



BIOS4YOU
AR 2.0

BIO-INSPIRED STEM TOPICS FOR ENGAGING YOUNG GENERATIONS
THANKS TO THE USE OF AUGMENTED REALITY

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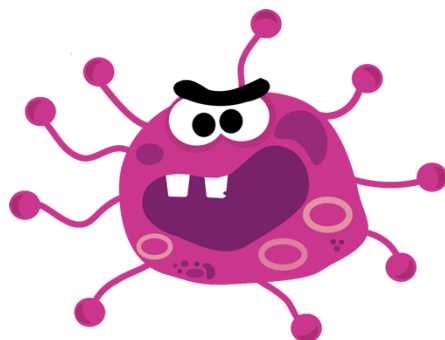




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General topic of the learning path	Microbial Bioremediation and Environmental Innovation
Specific name of the learning unit	Nature's Cleanup Crew: How Microbes Eat Pollution
Target user age	14–18 years
Learner prerequisites	Basic understanding of Biology, Chemistry, and Environmental Science
Description of the learning unit	This unit introduces the concept of bioremediation, showing how microbes are used to clean polluted environments. Learners will explore microbial diversity, pollution types, and cleanup methods through interactive content and AR simulations.
Subject involved	Biology, Chemistry, Environmental Science, Technology
Keywords	Microbes, Bioremediation, Pollution, Sustainability, AR, Innovation, Environmental Science
Key-skills, abilities, knowledge that can be acquired	Understanding microbial roles in pollution cleanup, evaluating real-world bioremediation cases, applying AR tools to visualize microbial actions, and developing solutions to environmental problems.
Resources and didactic tools used	Scientific articles, AR platforms (Assemblr EDU, Merge Cube), interactive simulations, case study documents, microbiological databases
Evaluation criteria and assessment	Assessment through interactive AR-based simulations, understanding of microbial functions, case analysis, and learner-created visual explanations or projects





Introduction

Bioremediation stands as a promising solution in the fight against environmental pollution. At its essence, it leverages the natural abilities of microorganisms to cleanse contaminated sites, offering an innovative and often economical approach to some of today's most critical ecological problems. By utilizing bacteria, fungi, or plants, bioremediation is reshaping how we handle pollutants, from oil spills to toxic heavy metals, as our understanding of these natural systems continues to grow.

The concept is relatively simple: microorganisms, tiny yet mighty life forms, possess unique metabolic pathways that allow them to break down or transform harmful substances into less toxic compounds. In polluted environments, these organisms can be encouraged or supplemented to accelerate the degradation of contaminants, thereby helping to restore ecological balance.

A well-known example is the cleanup of oil spills. The 1989 Exxon Valdez disaster highlighted the catastrophic effects of such incidents, while also sparking interest in bioremediation. Scientists have discovered that certain bacteria, such as *Alcanivorax borkumensis*, naturally feed on hydrocarbons found in crude oil. By introducing these microbes to spill sites or enhancing their growth with added nutrients, cleanup efforts can be significantly improved, reducing both the immediate and long-term environmental damage.

Beyond oil, bioremediation is also practical in addressing pollution from heavy metals. Industrial activities often leave behind hazardous elements, such as lead, mercury, and cadmium, which pose a threat to both ecosystems and human health. Certain bacteria and fungi, known as biosorbents, can bind these metals to their cell structures, making them less toxic and easier to extract from the environment (Hartman, 2024)

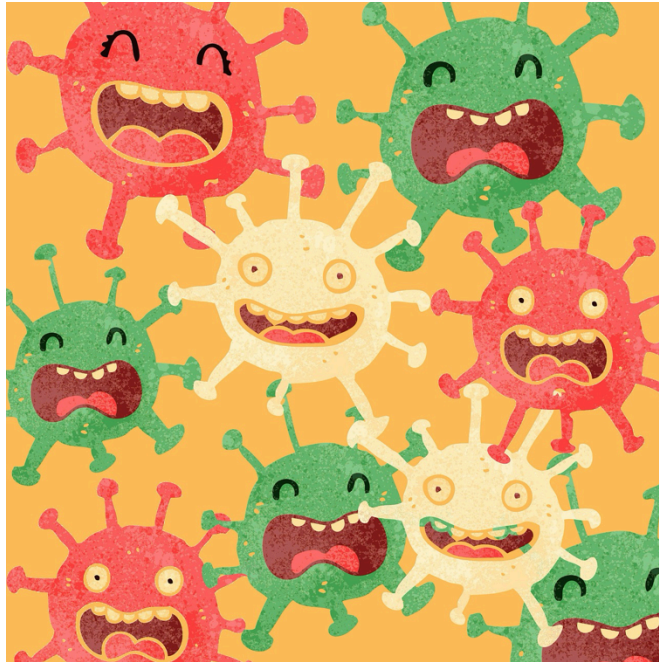
What Are Microbes?

Microbes, or microorganisms, are microscopic life forms that are typically invisible to the naked eye. They are incredibly diverse and inhabit virtually every environment on Earth, from deep-sea





vents to the human body. Microbes play essential roles in ecosystems, human health, and various industrial processes.



Major Types of

Microbes:

1. **Bacteria:** Single-celled organisms without a nucleus (prokaryotes). They exhibit a vast range of shapes and metabolic capabilities. Bacteria are ubiquitous, found in soil, water, and as part of the human microbiome. While some bacteria are pathogenic, many are beneficial, aiding in processes like digestion and nutrient cycling.
2. **Archaea:** Also single-celled prokaryotes, archaea differ from bacteria in their genetic makeup and membrane composition. They are known for thriving in extreme environments, such as hot springs and salt lakes, but are also present in more common habitats, including the human gut. Archaea play roles in processes like methane production and nitrogen cycling (https://en.wikipedia.org/wiki/Archaea?utm_source=chatgpt.com).
3. **Fungi:** This group includes yeasts, molds, and mushrooms. Fungi are eukaryotic organisms (with a nucleus) that can be unicellular or multicellular. They are crucial decomposers in ecosystems, breaking down organic matter, and have applications in food production and medicine.
4. **Protists:** A diverse group of mostly unicellular eukaryotic organisms. Protists include protozoa and certain types of algae. They inhabit various environments, from freshwater to marine systems, and play roles in nutrient cycling and as part of the food web.
5. **Viruses:** Acellular entities composed of genetic material (DNA or RNA) encased in a protein coat. Viruses require a host cell to replicate and are known for causing diseases in humans, animals, and plants. Despite not being considered "alive" by all definitions, they are studied extensively in microbiology (https://www.britannica.com/science/microbiology/Types-of-microorganisms?utm_source=chatgpt.com).





Importance of Microbes

Microorganisms are fundamental to life on Earth, playing critical roles in environmental processes, human health, and biotechnology.

1. Environmental Significance

- **Nutrient Cycling:** Microbes are essential in biogeochemical cycles, including nitrogen, carbon, and sulfur cycles, facilitating the transformation and movement of these elements through ecosystems(preprints.org).
- **Bioremediation:** Certain microbes can degrade environmental pollutants, such as hydrocarbons and heavy metals, making them invaluable in cleaning up contaminated sites.

2. Human Health

- **Microbiome Function:** The human microbiome, comprising trillions of microbes, is integral to digestion, immune system development, and protection against pathogens. Disruptions in this microbial community are linked to various diseases(pmc.ncbi.nlm.nih.gov).
- **Disease Prevention and Therapy:** Advances in understanding the microbiome have led to novel therapeutic approaches, including microbiome modulation to treat or prevent diseases(nature.com).

3. Biotechnological Applications

- **Industrial Processes:** Microbes are harnessed in biotechnology for the production of antibiotics, enzymes, biofuels, and fermented foods. Their metabolic capabilities are exploited in various industries.
- **Genetic Engineering:** Genetically modified microbes are developed for specific tasks, such as producing therapeutic compounds or degrading environmental pollutants, showcasing their versatility in biotechnology.





Pollution Problems

Types of Environmental Pollution



Fig 1. Environmental pollution, source:

https://gosharpener.com/blogs/710991/Environmental-Pollution?lang=de_de

Air Pollution

Air pollution refers to the presence of harmful substances in the Earth's atmosphere, including gases, particulates, and biological molecules that can endanger human health and the environment. Common pollutants such as carbon monoxide, nitrogen oxides, sulfur dioxide, ozone, and particulate matter often originate from fossil fuel combustion in transportation, industry, and power generation. The consequences range from respiratory illnesses and cardiovascular problems to environmental degradation like acid rain and global warming.

Water Pollution

Water pollution is the contamination of water bodies including rivers, lakes, oceans, and groundwater, making them unsafe for human use and harmful to aquatic life. It is typically caused by the discharge of pollutants such as industrial waste, sewage, pesticides, plastics, and heavy metals into water sources. This pollution leads to a range of issues including waterborne diseases, ecosystem destruction, and the reduction of potable water availability.

Soil Pollution

Soil pollution involves the degradation of land quality through the presence of toxic chemicals,





heavy metals, and waste materials that disrupt soil health and productivity. Sources include industrial activities, agricultural chemicals, improper waste disposal, and mining operations. Contaminated soil can affect food safety, plant growth, and groundwater quality, while also posing direct risks to human and animal health.

Noise Pollution

Noise pollution is the excessive or disturbing level of noise in the environment that interferes with normal activities and well-being. It originates mainly from traffic, construction, industrial processes, and urban development. Chronic exposure to high noise levels is associated with a range of health issues, including hearing loss, sleep disturbances, increased stress levels, and impaired cognitive performance, especially in children.

Light Pollution

Light pollution refers to the excessive or misdirected artificial light that brightens the night sky and disrupts natural darkness. It arises primarily from street lighting, advertising signs, buildings, and public spaces in urban areas. Light pollution not only obscures the visibility of stars but also disturbs wildlife behavior and human circadian rhythms, leading to ecological imbalance and sleep-related health problems.

Thermal Pollution

Thermal pollution occurs when industries discharge heated water or air into natural environments, especially aquatic systems, altering the temperature balance. Power plants, manufacturing units, and refineries are typical contributors. The elevated temperatures reduce oxygen levels in water, harm sensitive aquatic organisms, and can lead to biodiversity loss and algal blooms, disrupting aquatic ecosystems.

Radioactive Pollution

Radioactive pollution is the contamination of the environment by radioactive substances, either through accidental releases, improper waste disposal, or natural events. Common sources include nuclear power plants, medical and research facilities, and past nuclear weapons testing. This type of pollution poses long-term risks to human health and ecosystems, with effects including cancer, genetic mutations, and persistent environmental contamination.

Microbial Role in Cleaning Environmental Pollution

Microorganisms play a vital and natural role in mitigating environmental pollution through a process known as bioremediation, where bacteria, fungi, algae, or archaea break down, transform, or immobilize





harmful pollutants. These microbes are highly adaptable and can thrive in diverse environments, including contaminated air, water, and soil. In aquatic systems, bacteria such as *Pseudomonas* and algae like *Chlorella vulgaris* can degrade oil compounds, remove heavy metals, and absorb excess nutrients, helping restore water quality (UNEP, 2021). In soil remediation, certain microbes degrade complex hydrocarbons, pesticides, and even heavy metals, while fungi like *Phanerochaete chrysosporium* break down persistent organic pollutants (FAO, 2021). Air purification systems, including biofilters and bioscrubbers, employ microbial communities to remove volatile organic compounds and ammonia from industrial exhausts (EPA, 2023). Furthermore, advancements in microbial biotechnology have enabled the engineering of microbial strains that target specific pollutants with enhanced efficiency. The ecological benefits of microbial cleanup not only reduce reliance on chemical or mechanical interventions but also promote sustainable environmental management. As such, microbes are increasingly recognized as crucial allies in combating pollution and achieving long-term ecological restoration.

Air Pollution Cleanup Methods

Air pollution is mitigated using mechanical filtration, chemical neutralization, and increasingly, biological methods. Technologies such as electrostatic precipitators and scrubbers remove particulates and gases from industrial emissions, while catalytic converters reduce vehicular pollutants. Biofiltration systems, which use microbial communities to metabolize airborne toxins like VOCs and sulfur compounds, offer a sustainable alternative to chemical treatments. These biological systems are especially effective in treating odorous emissions from wastewater and composting facilities (Deshusses, 1997).





Water Pollution Cleanup Methods

Water pollution cleanup involves multi-stage treatment processes combining physical separation, chemical disinfection, and biological degradation. Sedimentation and membrane filtration remove solids, while ozonation and coagulation eliminate pathogens and heavy metals. Biological treatments such as activated sludge and biofilm reactors rely on microbial activity to digest organic matter and nutrients. Microbial fuel cells have also been explored to simultaneously treat wastewater and generate electricity, showcasing innovative dual-purpose applications (Logan et al., 2006).

Soil Pollution Cleanup Methods

Soil pollution remediation employs strategies such as excavation, chemical immobilization, and biological processes. Bioremediation techniques are particularly effective, using indigenous or introduced microbes to degrade petroleum hydrocarbons, solvents, and pesticides. Phytoremediation, enhanced by rhizosphere-associated microbes, offers a green solution by promoting contaminant uptake or degradation via plant-microbe interactions. Recent studies highlight the success of microbial consortia in degrading polycyclic aromatic hydrocarbons (PAHs) in complex contaminated soils (Meckenstock et al., 2015).

Noise Pollution Mitigation Methods

Noise pollution, unlike chemical pollutants, cannot be removed but must be mitigated through planning and engineering. Strategies include acoustic barriers, sound-absorbing building materials, and urban green buffers that reduce ambient noise levels. Vegetation and soil, which benefit from healthy microbial communities, play a passive but supportive role in noise reduction by softening surfaces and absorbing sound energy. A study on urban forest design showed that integrating dense vegetation can reduce noise by up to 10 dB in city environments (Fang & Ling, 2003).

Light Pollution Reduction Methods

Reducing light pollution involves smart lighting design and community planning to minimize unnecessary artificial illumination. Techniques such as using full cutoff fixtures, motion sensors, and warm-colored LEDs help limit skyglow and glare. Although microbial action does not directly reduce light pollution, minimizing artificial light benefits nocturnal ecosystems that rely on microbial-rich soils and natural light cycles. Research shows that artificial lighting disrupts nocturnal pollination networks and microbial activity in soil crusts (Knop et al., 2017).





Thermal Pollution Mitigation Methods

Thermal pollution, particularly from industrial discharges into water bodies, is managed through engineered cooling systems like cooling ponds and towers. Emerging natural systems such as constructed wetlands utilize thermally tolerant microbes to not only regulate temperature but also break down pollutants in heated effluents. A study by Vymazal (2011) emphasizes the use of constructed wetlands for combined removal of nutrients and temperature reduction in wastewater treatment.

Radioactive Pollution Cleanup Methods

Remediation of radioactive contamination involves containment, vitrification, and, increasingly, biological stabilization. Some microbes, such as *Deinococcus radiodurans* and uranium-reducing *Geobacter* species, exhibit resistance to radiation and can alter the solubility or mobility of radionuclides. These organisms are being studied for their role in long-term bioremediation at nuclear waste sites. Recent research by Fredrickson et al. (2004) has shown promising microbial reduction of uranium under anaerobic conditions, limiting its groundwater mobility.

Table 1. Environmental Pollution Types and Associated Treatment Techniques

Pollution Type	Microbial Cleanup Method	Example Microbes
Air	Biofiltration, Bio scrubbers	Pseudomonas, Bacillus, Aspergillus
Water	Activated Sludge, Bioaugmentation, Algae	Nitrosomonas, P. putida, Chlorella
Soil	Bioremediation, Mycoremediation	Phanerochaete, Bacillus, Rhizobium
Noise	No direct role	—
Light	No direct role	—
Thermal	Indirect (thermophilic microbes)	Thermus aquaticus, B. stearothermophilus
Radioactive	Experimental (radioresistant microbes)	Deinococcus radiodurans, radiotrophic fungi





Introduction to Bioremediation

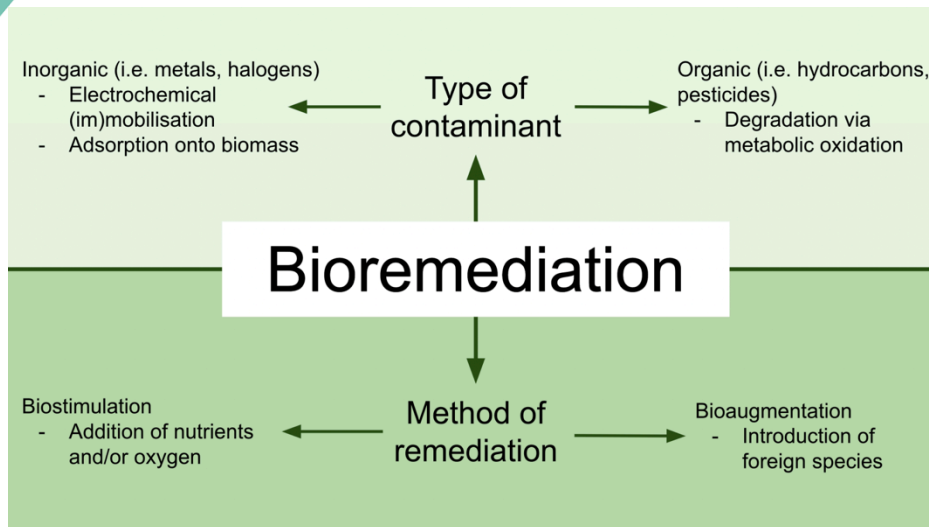


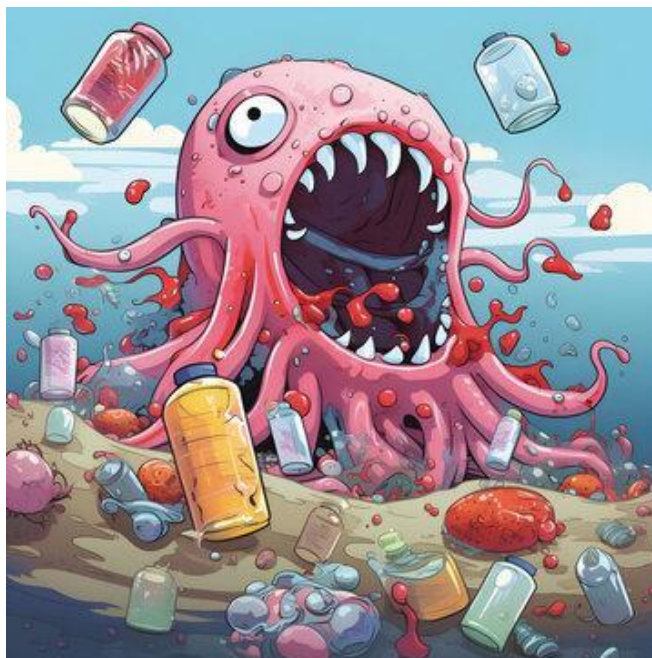
Fig 2. Bioremediation, source: <https://tinyurl.com/pbdykp7a>

Bioremediation is a sustainable and biologically driven approach that uses living microorganisms, primarily bacteria, fungi, algae, and archaea, to degrade, detoxify, or transform environmental pollutants into less harmful forms. While traditionally associated with soil pollution, bioremediation has proven effective across a broad spectrum of environmental contexts, including contaminated water, polluted air, and even radioactive waste sites. In water systems, for instance, oil-degrading bacteria and nutrient-consuming algae are employed to clean up petroleum spills and eutrophic lakes. In air purification, biofilters utilize microbial biofilms to capture and biodegrade volatile organic compounds (VOCs) and sulfurous gases from industrial exhausts. Moreover, radioactive bioremediation is an emerging frontier, with extremophilic microbes like *Geobacter* and *Deinococcus radiodurans* being studied for their ability to immobilize or transform radioactive elements. The increasing application of microbial consortia and genetically engineered strains has further expanded the potential of bioremediation for complex and recalcitrant pollutants. According to Singh and Strong (2022), the integration of omics technologies and bioinformatics tools has significantly enhanced the specificity, speed, and scalability of microbial interventions in environmental cleanup. As global challenges of pollution intensify, bioremediation offers a low-cost, low-energy, and ecologically restorative alternative to conventional chemical and mechanical remediation methods.





How Microbes "Eat" or Break Down Pollutants



Microorganisms break down pollutants through processes in which sources of energy, biological microbes secrete alter toxic them into simpler, For example, bacteria such

are capable of breaking through metabolic the contaminants serve as carbon, or nutrients. This degradation occurs when enzymes that chemically substances, converting less harmful compounds. hydrocarbon-degrading

as *Pseudomonas*, *Alcanivorax*, and *Mycobacterium* can metabolize oil components by oxidizing them into carbon dioxide and water during aerobic respiration. In anaerobic conditions, certain bacteria can also use pollutants as alternative electron acceptors, allowing them to degrade compounds like nitrates, chlorinated solvents, or heavy metals.

Fungi such as *Phanerochaete chrysosporium* are capable of degrading persistent organic pollutants like pesticides and dyes by producing ligninolytic enzymes that break complex molecules into smaller fragments. Some microbes even transform heavy metals into insoluble forms through redox reactions, immobilizing them in soil or sediment. Environmental factors, including pH, temperature, oxygen availability, and the presence of co-substrates, influence these processes. According to recent findings by Ghosal et al. (2016), microbial communities often function more effectively as consortia, where different species work synergistically to degrade complex mixtures of pollutants more efficiently than single strains. These biological mechanisms are central to both natural and engineered bioremediation systems, making microbes indispensable agents in the sustainable treatment of environmental contamination.

Examples of Microbial Bioremediation

Pseudomonas and Oil Degradation

Species of the genus *Pseudomonas*, particularly *Pseudomonas aeruginosa*, are renowned for their ability to degrade hydrocarbons found in crude oil. These bacteria produce biosurfactants that emulsify oil, increasing its bioavailability for microbial degradation. Recent studies have demonstrated that co-culturing *P. aeruginosa* with *Bacillus subtilis* enhances crude oil degradation efficiency, achieving up to 63.05% removal of oil components. [pmc.ncbi.nlm.nih.govfrontiersin.org](https://pubmed.ncbi.nlm.nih.gov/frontiersin.org)





Ideonella sakaiensis and Plastic-Eating Capabilities

Ideonella sakaiensis is a bacterium capable of degrading polyethylene terephthalate (PET), a common plastic used in bottles and packaging. It secretes an enzyme called PETase, which breaks down PET into its monomers, terephthalic acid and ethylene glycol, which the bacterium then utilizes for growth. Recent research has focused on enhancing the efficiency of PETase through genetic engineering to improve plastic degradation rates. en.wikipedia.org

Geobacter Species and Metal Cleanup

Members of the genus *Geobacter*, such as *Geobacter metallireducens*, are known for their ability to reduce and immobilize heavy metals, including uranium and chromium, in contaminated environments. These bacteria transfer electrons to metal ions during their metabolic processes, converting soluble toxic metals into insoluble forms that precipitate out of solution, thereby reducing their mobility and bioavailability.

Diverse Bioremediation Techniques

There are many ways to use bioremediation, each for different pollutants and places:

- Phytoremediation – Plants help clean pollutants from soil, water, and air.
- Microbial Remediation – Microbes work to break down and change pollutants into safer substances.
- Mycoremediation – Fungi are used to clean up many kinds of pollutants.
- Biomanipulation – Animals, like fish, help clean polluted water.

These methods offer many ways to solve environmental problems. They show how nature can help us clean up (<https://editverse.com/bioremediation-using-nature-to-clean-up-pollution/>).

Table 2. Bioremediation Techniques

Bioremediation technique	Description	Examples
Phytoremediation	Plants help clean pollutants from soil, water, and air.	Rhizofiltration, Phytoextraction, Phyto stimulation, Phyto stabilization
Microbial Remediation	Microbes break down and change pollutants into safer stuff.	Bio stimulation, Bioaugmentation, Intrinsic Bioremediation





Mycoremediation	Fungi are used to clean up pollutants like heavy metals and oil.	Fungal degradation of heavy metals, hydrocarbons, and organic compounds
Biomanipulation	Animals, like fish, help clean polluted water.	Using fish to control algal blooms and improve water quality

Microbial Remediation

Microbes are microscopic organisms classified within two significant life domains: Archaea and Eubacteria. They encompass a wide range of life forms, including primary producers that convert light or chemical compounds into energy, as well as heterotrophs and decomposers that rely on external sources for sustenance. Ubiquitous in nature, microbes are found in virtually every environment on Earth.

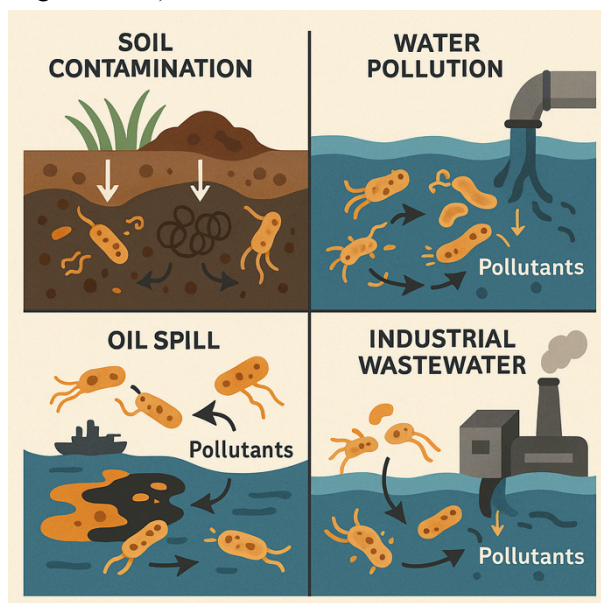
These tiny organisms play a significant role in human life. They help clean up pollutants, enrich soil fertility, contribute to advancements in food technology, and synthesize essential nutrients that support our health. In most cases, we coexist with microbes without being aware of their presence.

While many microbes provide protective functions, such as shielding us from harmful pathogens, others can have adverse effects. They may cause disease outbreaks, spoil food, or contribute to material decay and decomposition (Postgate, 2003).

Microbial and technologies

Microbial remediation natural functions render and it typically and of their tiny degrading ability, are constantly toxicity in a environment. combining bacteria with

several heavy metals (HMs) to eliminate target contaminants (Fig. 3). Biostimulation enhances soil quality by introducing growth hormones and nutrients to promote the development of local microflora. However, various microbial technologies for remediation are discussed below.



remediation strategies

remediation is a type of method that utilizes the of microbes in the soil to contaminants nontoxic, involves bioaugmentation biostimulation. Because quantity and low indigenous microbes restricted by pollutant co-contaminated Bioaugmentation involves obligatory degrading strains that can withstand



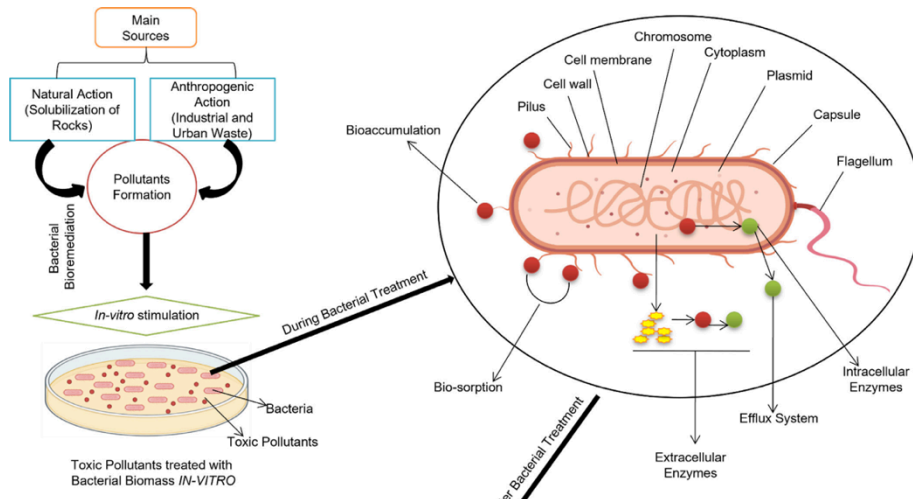
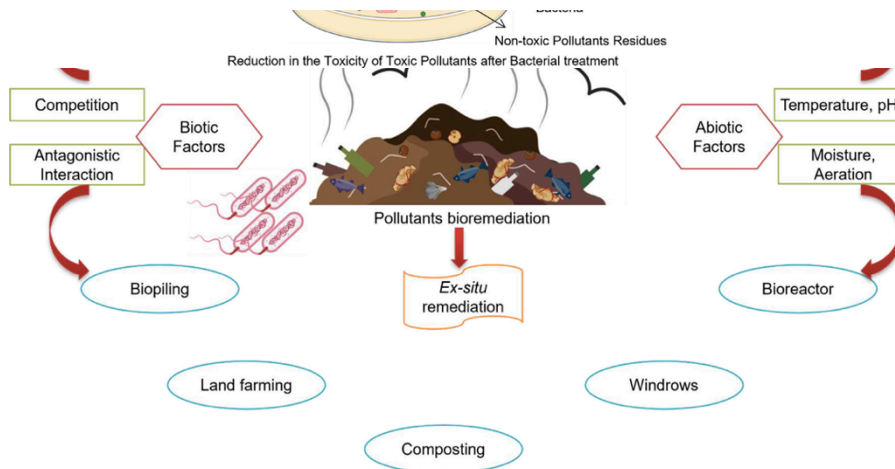


Figure 3-In vitro mechanisms of bacterial bioremediation in the polluted environment, source: Sharma et al., 2022



• In situ techniques for

bioremediation

This remediation eliminates the need for polluted soil to be extracted and transported to off-site treatment facilities, thereby reducing the disruption to the soil, minimizing exposure to toxins for helpers and the community, and potentially lowering the costs of treatment. Soil permeability, pollution depth, temperature, and probable chemical deep leaching are all important field characteristics to consider (Fasani et al., 2018). In-situ clean-up of pollutants is depicted in Figure 4.





Figure 4. Microbial bioremediation for the restoration of the contaminated sites via *in-situ* and *ex-situ* remediation, source: Sharma et al., 2022

Microbes do not degrade significant pollutants, but instead affect their physicochemical characteristics (Sharma et al., 2021f; Sharma et al., 2021g). The remediation component includes intracellular accumulation, further cell complex formation, and oxidation-reduction or precipitation calculations. Hazardous heavy metals are widely present in industrial processes and are significant environmental pollutants. Molecular filtration for extracting metals from low-grade materials was simple and successful (Dhaliwal et al., 2020). *Pseudomonas* sp., *Bacillus* sp., *Torulopsis bombicola*, *Desulfuromonas palmitatis*, and other microorganisms may detoxify mechanical waste, sewage sludge, and remediate residues and soils polluted with heavy metals (HMs) (Priya and Nagan, 2015). Microbial biomass has diverse biosorption capabilities, and fundamental alterations occur between species. Their extraordinary biosorption ability is attributed to higher volume-to-surface ratios and the probable sites of complex chemical adsorption, primarily on cellular membranes (Li et al., 2019). Microorganisms are frequently more resilient and last longer in mixed cultures. Crop consortia are therefore metabolically dominant for biosorption of metals and are thus suited for large-scale applications. However, because the biosorption capacity of each microorganism cell varies, it is dependent on the specific treatment and testing conditions (Dhaliwal et al., 2020).

Natural attenuation

Contaminants are converted into a less hazardous form or immobilized throughout biodegradation (natural attenuation). These transformation and immobilization mechanisms are primarily caused by microorganism biodegradation and, to a lesser extent, by interactions with naturally occurring chemical and geologic media sorption. This mechanism is specific to the contaminant and has been approved as an approach for treating components of fuel, such as BTEX (benzene, toluene, ethylbenzene, and xylene), but not for numerous other classes (Ganiyu et al., 2022). The period required for natural attenuation varies greatly depending on the site circumstances. Many contaminated sites may not necessitate an extensive clean-up





strategy, and bioattenuation is both cost-effective and efficient. In reality, the United States has successfully employed a range of bioremediation approaches at prices that are roughly 80–90% cheaper than alternative cleaning technologies based on chemical and physical principles. Post-clean-up expenditures are significantly decreased with minimum site disruption. Industrial and environmental biotechnologies also favor novel approaches, leading to processes that utilize clean technologies to maximize output while generating fewer residues (Rhea and Clark, 2022). Because the majority of soils are oligotrophic or lack the necessary microbes, bio attenuation alone becomes insufficient and time-consuming in many circumstances.

These genetic and metabolic engineering techniques can aid in the bioremediation process (Liang et al., 2020). For editing of the gene as well as metabolic engineering, pollutant-inhabiting bacteria are a major ideal candidate as they are employed to survive and shelter in stressful circumstances of diverse toxic, refractory, and non-degradable xenobiotics. Furthermore, understanding the metabolic pathway appears to be crucial in analyzing microbial bioremediation (Plewniak et al., 2018). Figure 5 illustrates the role of metabolic reconstruction in synthetic bioremediation, employing both in situ and ex-situ routes for the treatment of hazardous pollutants.

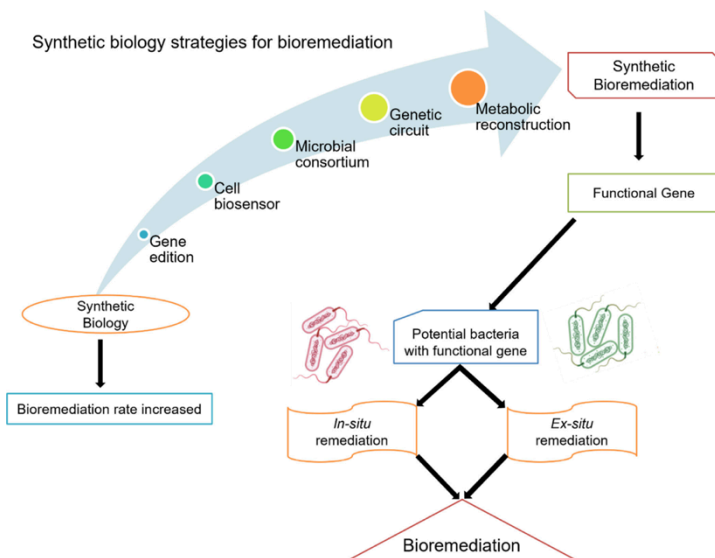


Figure 5. Role of metabolic reconstruction in synthetic bioremediation via in-situ and ex-situ routes to bioremediation of hazardous pollutants.

Case Studies

Deepwater Horizon Oil Spill (2010, Gulf of Mexico)

The Deepwater Horizon disaster released approximately 134 million gallons of crude oil into the Gulf of Mexico, marking one of the most significant marine oil spills in history. In the aftermath, indigenous marine bacteria,





notably *Alcanivorax* and *Cycloclasticus* species, proliferated and played a crucial role in degrading hydrocarbons. These microbes utilized the oil as a carbon source, effectively reducing the environmental impact of the spill. Research funded by the Gulf of Mexico Research Initiative (GoMRI) provided insights into microbial genomics and hydrocarbon bioremediation responses in marine ecosystems.

Plastic Pollution in Oceans

Plastic waste, particularly microplastics, has become pervasive in marine environments, posing threats to marine life and human health. Innovative bioremediation approaches are being explored to address this issue:

Community-Led Initiatives: In Kerala, India, the Munambam fishing community initiated the Drive to Recover Ocean Plastic (DROP) project. Over 600 fishing boats participate by collecting plastic waste during their trips, leading to the recovery of 22,000 kg of plastic in 2024–25 alone. timesofindia.indiatimes.com

Microbial Solutions: Research has identified plastic-degrading fungi capable of breaking down synthetic polymers like polyurethane. These fungi could be utilized in controlled environments, such as sewage treatment plants, to mitigate plastic pollution. reuters.com+l1bassconnections.duke.edu+1

Heavy Metal Contamination in Mining Sites

Mining activities often lead to heavy metal contamination in surrounding soils and water bodies. Bioremediation strategies employing microbes have shown promise in mitigating these pollutants: **Qixia Mountain Lead–Zinc Mine, China:** Studies revealed severe heavy metal pollution in soils around the mine. Microbial communities, including *Sphingomonas* and *Pseudomonas* species, demonstrated resistance to heavy metals and contributed to soil remediation efforts. pubs.rsc.org

Tar Creek Superfund Site, USA: An innovative bioremediation system was implemented to treat groundwater contaminated with lead, zinc, cadmium, and iron from abandoned mines. The system utilizes a series of ponds with aerobic and anaerobic bacteria treatments, significantly reducing heavy metal concentrations in the water.

Biotechnology and the Future

Enhancing Microbes for Environmental Cleanup

Advancements in biotechnology have enabled scientists to genetically engineer microorganisms to enhance their ability to degrade environmental pollutants. Techniques such as CRISPR-Cas9 allow precise modifications to microbial genomes, enhancing their metabolic pathways for the breakdown of complex contaminants. For instance, *Pseudomonas putida*, *Bacillus subtilis*, and *Escherichia coli* have been engineered to overexpress enzymes like cytochrome P450 and dioxygenases, resulting in accelerated degradation of organic pollutants. mdpi.com/researchgate.net

Moreover, tools like XenoBug, developed by researchers at IISER Bhopal, utilize machine learning to predict bacterial enzymes capable of breaking down various pollutants, streamlining the identification of effective microbial strains for bioremediation efforts. timesofindia.indiatimes.com

Ethical and Ecological Considerations

While genetically modified microbes offer promising solutions for pollution remediation, their deployment raises several ethical and ecological concerns:

- **Ecological Impact:** The release of engineered organisms into the environment could disrupt existing ecosystems, potentially leading to unintended consequences such as the displacement of native microbial communities or horizontal gene transfer to non-target species. pollution.sustainability-directory.com





- **Biocontainment Challenges:** Ensuring that genetically modified microbes do not persist beyond their intended application areas is crucial. Strategies for intrinsic biocontainment are still under development, and their effectiveness in real-world settings remains uncertain. [nature.com](https://www.nature.com)
- **Equity and Access:** The benefits of bioremediation technologies must be accessible to all communities, especially those disproportionately affected by pollution. There is a risk that proprietary technologies could limit access for underprivileged regions, exacerbating environmental injustices. [pollution.sustainability-directory.com](https://www.pollution.sustainability-directory.com)
- **Defining Restoration Goals:** Determining what constitutes a "clean" or "restored" environment is subjective and may vary among stakeholders. It's essential to engage communities in setting remediation goals to ensure that bioremediation efforts align with local values and needs. [pollution.sustainability-directory.com](https://www.pollution.sustainability-directory.com)

Future Potential in Green Technologies

The integration of biotechnology into environmental remediation holds significant promise for developing sustainable and efficient cleanup strategies:

- **Synthetic Biology and Directed Evolution:** By harnessing synthetic biology and directed evolution, scientists can design microbes with enhanced capabilities to degrade pollutants, offering tailored solutions for specific contamination scenarios.
- **Nanobioremediation:** Combining nanotechnology with microbial remediation can improve the delivery and effectiveness of bioremediation agents, allowing for more precise targeting of pollutants. [prism.sustainability-directory.com](https://www.prism.sustainability-directory.com)
- **Microbial Fuel Cells (MFCs):** MFCs utilize the metabolic activities of microbes to generate electricity while simultaneously degrading organic pollutants, presenting a dual benefit of energy production and environmental cleanup. en.wikipedia.org
- **Microbial Electrolysis Carbon Capture (MECC):** This technology employs microbes to capture carbon dioxide during wastewater treatment processes, converting it into stable mineral forms and contributing to carbon sequestration efforts. en.wikipedia.org

As these technologies advance, interdisciplinary collaboration among microbiologists, environmental scientists, ethicists, and policymakers will be essential to ensure that biotechnological solutions for pollution are effective, ethical, and equitable.

Augmented Reality in Action: Exploring Microbial Cleanup

Imagine being able to visualize microscopic microbes, observe how they interact with pollutants, and witness them in action as they clean up oil spills or plastic waste, all within your immediate environment. This immersive experience is made possible through Augmented Reality (AR), a technology that superimposes digital content onto the real world via devices like smartphones, tablets, or AR glasses. Recent studies have highlighted the efficacy of AR in enhancing science education. Research by Arici (2024) demonstrated that AR technology supports environmental sensitivity and positive behavior, making it a valuable tool in science education.

In the realm of microbiology, AR has been effectively utilized to facilitate the learning of intricate processes. A study by Herlina et al. (2024) developed an AR-based microbiology practicum guide, which significantly improved students' comprehension and engagement by allowing them to interact with 3D models of viruses and other microorganisms.

In this section, you will not only learn about the remarkable capabilities of microbes in environmental cleanup but also interact with them through augmented reality (AR) experiences. These activities are designed to make abstract scientific concepts tangible, enhance your understanding of microbial processes, and inspire innovative thinking about sustainable solutions to pollution.

"Augmented Reality in Action: Exploring Microbial Cleanup" is an educational concept that integrates emerging technologies with environmental science to make the invisible processes of microbial bioremediation visible and interactive. Microbial cleanup, also known as bioremediation, refers to the use of microorganisms, such as bacteria, fungi, and algae, to degrade or transform hazardous pollutants into





less harmful forms. This process plays a critical role in addressing environmental challenges like oil spills, heavy metal contamination, and plastic pollution. For example, *Pseudomonas* and *Bacillus* species are commonly used to degrade hydrocarbons, while *Deinococcus radiodurans* has shown remarkable potential in cleaning up radioactive waste (Gadd, 2010; Varjani, 2017). Integrating augmented reality (AR) into this context provides a novel pedagogical tool for visualizing complex biological interactions that are otherwise imperceptible to the naked eye. AR can simulate polluted environments, display microbial activity in real time, and allow learners to interact with different bioremediation strategies, enhancing both comprehension and engagement. Research by Bacca et al. (2014) and Dunleavy et al. (2009) demonstrates that AR supports experiential learning by making abstract scientific processes more accessible and memorable. Educational AR applications such as Unity with Vuforia, JigSpace, or Assemblr EDU can be leveraged to create dynamic simulations of microbial responses to environmental toxins. This approach not only enriches scientific literacy but also encourages students to think critically about sustainable solutions and the role of biotechnology in environmental protection. The combination of AR and microbial bioremediation offers a powerful interdisciplinary learning experience, grounded in the principles outlined by Singh and Chandra (2019) in their exploration of pollution control biotechnology and supported by the foundational framework provided in Crawford and Crawford's work on bioremediation principles and applications.

Implementing AR in Microbial Bioremediation Education

Designing AR-Based Learning Activities

Augmented Reality (AR) offers immersive experiences that can enhance the understanding of microbial bioremediation processes. By overlaying digital information onto real-world environments, AR can make abstract concepts tangible. For instance, students can visualize how specific microbes interact with pollutants, observe the breakdown process, and understand the environmental impact.

Recent studies have demonstrated the effectiveness of AR in science education. A systematic review highlighted that AR applications in environmental education significantly improve students' understanding of complex concepts, increase engagement, and foster environmental awareness. Similarly, research in microbiology education has shown that AR-based tools can enhance student comprehension and interest in the subject matter. matter.ejmste.comacademic.oup.com

Scientific Rationale, Educational Integration, and Tools

Microbial bioremediation is the process of using microorganisms to degrade, transform, or remove contaminants from the environment, including soil, groundwater, and marine ecosystems. While bioremediation is essential to addressing pollution sustainably, teaching it poses significant challenges due to the invisible and complex microbial interactions involved. Augmented Reality (AR), as an immersive technology, provides a unique opportunity to enhance the understanding and communication of microbial bioremediation processes. Through interactive visualizations, spatial overlays, and real-time data integrations, AR bridges the gap between abstract microbiological knowledge and experiential learning (Bacca et al., 2014; Beck et al., 2022).

One of the core advantages of AR is its ability to visualize invisible microbial activity. Using 3D simulations, learners can observe how bacterial strains such as *Alcanivorax borkumensis* or *Pseudomonas putida* respond to contaminants like hydrocarbons or heavy metals (Vidali, 2001). These simulations can demonstrate the progression of bioremediation over time, showcasing how environmental factors (e.g., temperature, nutrient levels, oxygen availability) affect microbial performance (Dunleavy & Dede, 2014). This interactivity enhances conceptual retention and learner engagement, enabling active experimentation within virtual environments.

Additionally, AR offers significant benefits in spatial learning. By projecting microbial processes onto real-world spaces, such as cross-sections of contaminated soil or aquatic environments, students gain a deeper understanding of spatial dynamics and microbe-pollutant interactions (Martínez-García et al., 2020). Because direct access to polluted sites or live microbes is often unsafe or impractical, AR serves as a safe simulation tool, replicating hazardous scenarios without real-world risk (Bacca et al., 2014).





Educational Use Cases

- AR Oil Spill Lab Simulation: Using Meta Quest or mobile devices, students deploy virtual microbes on oil slicks and observe degradation across different conditions.
- Interactive Soil Remediation Map: HoloLens-based AR allows learners to explore layered soil models showing contaminant spread and microbial colonization (Gadd, 2010).
- Real-Time Sensor + AR Dashboard: Environmental sensors track pollutant levels; AR overlays show microbial responses, linking data to biological function (Martínez-García et al., 2020).
- 3D Microbial Explorer App: Students scan QR codes to activate detailed models of bacteria, highlighting cell structures and biodegradation roles (Beck et al., 2022).

These applications are supported by accessible tools and platforms including Unity 3D, AR Foundation, ARKit/ARCore, and 3D modeling software like Blender and Sketchfab. Hardware such as Microsoft HoloLens and Meta Quest 3 supports immersive, real-time experiences that are increasingly affordable and scalable.

Curriculum Integration

AR can be introduced into environmental science, biotechnology, or microbiology courses across high school, university, or vocational education. Effective pedagogical strategies include:

- Inquiry-Based Learning: Encourages students to test variables within virtual bioremediation environments.
- Game-Based Learning: Adds motivation through missions or problem-solving challenges.
- Flipped Classrooms: Students explore AR modules before class and apply concepts during discussion.

The benefits of AR in this context are summarized below:

Benefit	Description
Immersion	Realistic, interactive simulations of remediation environments
Retention	Multisensory learning improves understanding and memory
Accessibility	Portable and scalable across digital devices
Customization	Simulations can be tailored to local pollutants, ecosystems, or microbes
Collaboration	Supports team learning and shared AR environments

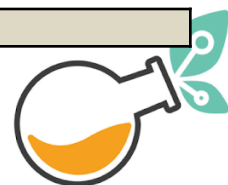
Future developments may include AI-driven AR tutoring systems, sensor-integrated visualizations, and cloud-based AR learning platforms, further enhancing accessibility and adaptability across disciplines and locations.

Conclusion

Augmented Reality represents a powerful educational tool to enhance learning in microbial bioremediation. By converting invisible biological processes into visible, interactive, and manipulable experiences, AR helps learners grasp complex environmental interactions that are often inaccessible through traditional methods. It enables safe simulation of real-world scenarios, improves engagement through interactive learning, and supports knowledge retention through spatial and visual reasoning.

As the field of immersive technology evolves, AR is poised to become integral to environmental education and outreach, particularly in promoting sustainable practices, interdisciplinary learning, and scientific curiosity. Whether in a classroom, lab, or public setting, AR can foster a generation of learners more equipped to understand and tackle pollution through biological and ecological solutions.

Phase	Description
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Explore	- Investigate how microbes clean up environmental pollution through bioremediation and how this is applied in real-world scenarios.
	- Content Development: Create educational content linking biology, environmental science, and technology related to microbial cleanup.
	- Needs Analysis: Identify learners' understanding of pollution, microorganisms, and ecological restoration to shape effective instruction.
Execute	- Curriculum Implementation: Present interactive lessons on pollution types, microbial action, and bioremediation mechanisms using AR tools.
	- Interactive Exercises: Use AR apps (e.g., Curiscope Virtuali-Tee, Merge Cube) to simulate polluted environments and microbial activity.
	- Feedback Collection: Record student observations and feedback on virtual cleanups and microbial behavior simulations to refine learning experiences.
Enhance	- AR Integration: Apply AR to visualize polluted ecosystems, microbial colonies, and their pollution breakdown processes.
	- Interactive Learning: Let students test virtual microbial efficiency by introducing contaminants and measuring cleanup results.
	Gamified Content:
	- Points and Badges: Earn rewards for identifying pollution types, simulating effective cleanups, or optimizing microbial action.
	- Leaderboards: Rank performance in timed challenges on cleaning up virtual polluted sites.
- Quests and Levels: Unlock stages of increasing complexity, from identifying pollutants to managing entire remediation ecosystems.	
- Rewards for Exploration: Hide microbial species or cleanup clues within AR environments to encourage deeper inquiry.	
- Collaborative Gamified Tasks: Teams work together to tackle large-scale AR-based environmental disasters using microbial strategies.	
	AR-Based Assessments:
	- Assess understanding by having students' complete pollution cleanup missions using AR and report results with before-and-after analyses.





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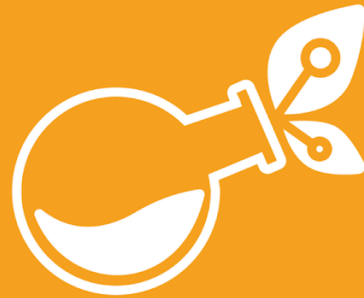
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