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RESEARCH ARTICLE

SUSTAINABLE WASTE MANAGEMENT APPROACHES THROUGH NANOMATERIALS AND NANOBIOREMEDIATION: A REVIEW

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Abstract

Environmental pollution resulting from the release of various pollutants into ecosystems is a growing concern worldwide. Traditional bioremediation methods have demonstrated effectiveness in detoxifying contaminated environments, yet their efficiency is often limited by the complex nature of pollutants and the dynamics of environmental matrices. In recent years, the convergence of nanotechnology and bioremediation has emerged as a promising approach to address these limitations. Researchers and scientists in various fields of environmental sciences, particularly in bioremediation, have paid close attention to nanomaterials because they possess distinctive physical and chemical features. The improvement in living standards brought about by science and technology also has an impact either directly or indirectly on the rise in toxic waste. Therefore, removing poisons from the environment with current technology does not adequately and efficiently clean it up. The use of nanomaterials for bioremediation would not only have a less negative impact on microorganisms but will increase the microbial activity of the specific waste and toxic material, lowering the overall time consumption and the overall cost. The objective of nanotechnology functional side is to improve material performance andreduce the quantity of materials needed to complete the cleanup process. Nano-bio remediation uses ex-situ or in-situ nanomaterials to treat contaminated materials. Therefore, using nanomaterials to remove environmental pollution could be an efficient, effective method that is sustainable. This review paper presents an overview of the recent advancements and future prospects of nano bioremediation, highlighting the potential of nanomaterials in enhancing the efficiency and specificity of bioremediation processes.

1. Introduction:-

Every day, enormous amounts of pollutants are released into our environment, affecting our way of life by posing a risk to pregnancy, causing cancer, weakening the immune system, damaging the nervous system, damaging the kidneys, and disrupting ecosystems by harming the forests and animal habitats. Even when various solutions were found with the aid of science and technology, this has yet turned into a constant challenge.

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The process of using living organisms, such as bacteria, fungi, plants, and others, to detoxify toxins in the environment through their metabolic processes is known as "bioremediation," and that is the word that Planet has adopted. Bioremediation is recommended over incineration or other chemical treatments since it is an environmentally benign method that produces no harmful waste or residues.

Concerning bioremediation, quickly developed further technological branches in bioremediation, and one such path led us to nanobioremediationthe use of nanotechnology.Nano bioremediation is a contemporary method for fixing the pollutants and toxins that are already present in our environment in a variety of ways. The combination of nanotechnology with bioremediation and the assistance of phytoremediation allows contaminants to be broken down into simpler compounds by enzymes that are encapsulated, making them available for fixation by plants. Nanomaterials are superior adsorbents and catalysts because they have more related adsorption sites, fewer temperature changes, customizable pore sizes, reduced inter-particle diffusion widths, and diversified surface chemistry (Zhao et al., 2019). Nanoparticles with a size range of 1 to 100 nanometres are used as carriers to transport and deliver microorganisms to contaminated sites, increasing the bioremediation process. This is the primary premise behind nano bioremediation.

Nanoparticles provide rapid, effective, and toxic-free degradation of pollutants during bioremediation processes. Based primarily on the exhibited phenomena, several nanomaterials or nanoparticles are used in bioremediation procedures. Nanomaterials exhibit a quantum effect, which results in less activation energy being required for chemical processes. Additionally, the surface plasmon resonance phenomenon is used to detect toxic materials. Thus, a variety of nanoparticles are used, including single metal nanoparticles, bimetallic nanoparticles, carbon-based nanomaterials, and many more, since they may disperse into the depths of contamination sites and are more reactive to redox-amenable contaminants (Rizwan et al., 2014). The actual factors that can influence and affect the nanomaterials and contaminants interactions are its shape, size, type of organism used, pH, and temperature (Tan et al., 2018). Nanotechnology-based bioremediation has the potential to provide practical and effective methods for eliminating a variety of toxins from various environments, including soil, water, and air. Nano bioremediation is a promising area of research that has the potential to revolutionize environmental remediation. The objective of this review is to examine nanobioremediation technologies and provide an overview of the function that nanomaterials play in the bioremediation procedure.

Recently, a biotechnological technique for producing desired nanoparticles using proteins from various vascular and non-vascular plants, bacteria, algae, and algae has been developed. Biomimetic nanoparticle forms are much more "clean" and "green" than their natural counterparts in terms of size and shape (Abbasi et al., 2012; Anuradha et al., 2015).

2. Environmental Biotechnology's Role in Pollution Control

Pollution is one of the most prominent environmental issues, which has an adverse effect on ecosystems and natural resources and causes a natural imbalance. Using living organisms like bacteria, fungi, or plants, bioremediation is a technique for removing or degrading toxins from a polluted environment. It is a hopefulline to pollution management as it offers a cost-effective and environmentally friendly solution to address various types of pollution. Biotechnology can be used to analyze the state of ecosystems, degrade pollutants into neutral compounds, produce biodegradable materials from renewable sources, and design environmentally friendly manufacturing and disposal techniques. In response to the crucial need for an effective environmental biotechnological process, researchers developed bioremediation which is a new strategy for restoring areas polluted by contaminants or otherwise harmed by ecosystem mismanagement.

Bioremediation strategies provide sustainable and eco-friendly solutions to manage the pollution caused around.It is an exquisite combination of biological sciences and microorganisms with man-made technologies, working together to improve the standard of the environment **(**Sakshi et al., 2018**).** Researchers have long preferred microbes for pollution treatment because they are economical and have catabolic enzymes that can destroy contaminants and pollutants. The microorganisms are chosen based on the chemical composition of the pollutants. The microorganism will be provided with all favorable conditions such as pH, temperature, and moisture. The factors that interfere with the microorganism's activity will be eliminated (McFarland et al., 1996; Prescott et al., 2002). Bioremediation is the identification or addition of specific microorganisms to degrade specific pollutants while phytoremediation removes pollutants from air and soil with the help of plants. Anaerobic digestion of organic material such as manure, food waste, municipal waste, and agricultural waste in an oxygen-free environment with the help of bacteria that produces a collective mixture of gases called methanogens and for biogas production can be used for electricity generation, as engine fuel, for cooking and much more. The mainly used methanogen is methanobacterium which helps in the production of biogas, a mixture of methane, CO2, and trace amounts of other gases **(**Enzmann, F.,et al. 2018**).**

Thus, the whole concept of bioremediation helps us in a way to fight against pollutants by maintaining the homeostasis of the planet. To fixate the existing contaminations around the world, bioremediation has always been favored as it is economical and sustainable. It can be of two types that is in-situ and ex-situ bioremediation. Bioremediation can be a natural, spontaneous process or a simulated process with the help of various principles, discussed further. Only when the microorganisms were chosen to enzymatically outbreak the contaminants and convert them to harmless substances, then the process of bioremediation is effective (Shilpi Sharma., 2012). The main aim of bioremediation is to provide them with more energy through nutrients and substances essential to increase the population and efficiency of these microorganisms to degrade toxic pollutants.

3. Nano Bioremediation Techniques and Uniqueness of Nanoparticles

Traditional bioremediation methods are limited by various factors, such as low microbial activity, limited access to the contaminant, and harsh environmental conditions. Nano bioremediation seeks to overcome these limitations by using nanoparticles to enhance bioremediation processes. Nano-bioremediation refers to the application of nanotechnology in combination with bioremediation techniques to enhance the efficiency and effectiveness of pollutant degradation or removal. It involves the use of nanoparticles, which are tiny particles typically ranging from 1 to 100 nanometers in size, to improve the capabilities of microorganisms or enzymes involved in bioremediation processes. Nano-bioremediation holds promise for addressing complex and persistent pollutants that are challenging to remediate using conventional methods alone. Nanotechnology, in its contemporary and post-modern forms, is a relatively new field of study, although it has been empirically employed by humans for thousands of years (Anuradha, 2015). The potential of nanotechnology is frequently thought to focus on nanoparticles. The primary adaptability of nanoparticles is that they have significantly different properties than their bulk counterparts.

In nano bioremediation, nanoparticles are designed to target specific contaminants and enhance biodegradation or immobilization of the contaminants. It enhances the effectiveness of bioremediation processes by improving the accessibility of microorganisms to contaminants. For example, nanoparticles can be used to increase the porosity of the soil, allowing for better transport of nutrients and oxygen to the microorganisms involved in biodegradation. The treatment of contaminated groundwater with harmful heavy metals, organic contaminants, and petroleum hydrocarbons is one of the most promising uses for nano bioremediation. Treatment of contaminated soils is another use for nano bioremediation(Arjun et al., 2022).

3.1. Nano Biofilters

Contaminated water comprises of hazardous substances, such as pollutants or pathogens, making them unsafe for human use or consumption. Contaminants are introduced into the water from various sources such as industries, households and agricultural practices. Ranging from chemical contaminants such as pesticides, fertilizers, herbicides, chemicals from the agricultural grounds, heavy metals such as mercury, and lead, improper disposal of pharmaceutical wastes, pathogens such as viruses and bacteria through animal wastes, sewage from nuclear power plants, radioactive materials etc., can be disposed into the water bodies, affecting a great deal and making the water bodies uninhabitable and unusable. In the presence of all these contaminants, the consumption of such water can lead to severe consequences. The plan of action to overcome such problems is wastewater treatment. Filtering, microfiltration, ultrafiltration, crystallization, sedimentation, gravity separation, flotation, precipitation, coagulation, oxidation, solvent extraction, evaporation, distillation, reverse osmosis, ion exchange, electrodialysis, electrolysis, adsorption, setting out, centrifugal and membrane separation, fluidization, neutralization and remineralization, reduction and oxidation, are some of the ways to treat wastewater (Ali, 2012). Nanomaterials are the perfect solutions for water treatment providing their high performance, modular, highly efficient, multifunctional properties (Konda Reddy et al., 2017). These nanomaterials in combination with biological entities such as microorganisms or enzymes combine the advantages of both nanotechnology and biotechnology. The contaminated fluid is passed through nano biofilters that contain nanoscale materials such as carbon nanotubes, graphene, or metal oxide nanoparticles. These materials provide a high surface area - volume ratio and can adsorb or react with the pollutants, while the biological component selectively degrades or metabolizes the pollutants, resulting in their removal from the system.

Nano biosorbents, one of the nano biofilter technologies, have a large surface area and are effective at removing organic and heavy metal pollutants from water (Mahamadi, 2019). Maghemite nanoparticles which is a nanobiosorbent can be useful to physically or chemically adsorb organic molecules using the techniques such as organic vapor condensation, polymer coating, surfactant adsorption, and direct salination to coat the surface (Afkhami et al., 2010). Carbon nanotubes have an enormous capacity for absorbing various contaminants, including heavy metals and dyes (TayyebehMadrakian et al., 2011). Manganese oxide-coated carbon nanotubes can be useful for removing lead ions from aqueous solution. The porosity and surface functionalization of carbon nanotubes has a significant impact on their ability to absorb substances (Badawi et al., 2021). Graphene and its derivatives are an alternative to carbonaceous sorbent nanomaterials (Lee et al., 2021). Graphene oxide nanosheets synthesized from graphite were used as biosorbents for the removal of $Cd2+$ and $Co2+$ from aqueous medium. The abundance of surface functional groups on the graphene oxide nanosheets and the solution's pH and ionic strength are all important factors in the sorption of heavy metal ions (Badawi et al., 2021).

In recent years, the application of zero-valent metal nanomaterials had shown a promising role in the treatment of industrial wastewater (Abdelbasir and Shalan, 2019).The creation and use of nano biofilters still face difficulties, like those faced by any newly developed technology, such as issues with their long-term stability, scalability, and potential toxicity. To enhance their functionality and guarantee, their safety and efficacy for practical applications, more studies are required.

3.2. Nano Bioreactors

An instrument used to carry out biological reactions on a very small scale, often in the nanoliter or even picoliter range, is referred to as a nano bioreactor, and sometimes known as a nanoreactor. It resembles a tiny bioreactor, which is a device used to cultivate and maintain vast populations of microorganisms or cells for use in industry or research.

3.3. Nano phytoremediation

Phytoremediation is a technique where plants and its physiological processes are used to treat soil, water and other resources from pollutants. Phytoremediation provides a greener option to remediation techniques by utilizing plants' innate capacities to absorb and break down pollutants. Nano Phytoremediation is the use of nanomaterials to increase the efficiency and effectiveness of phytoremediation procedures. Nanoparticles can alter the physicochemical composition of soil or water, facilitating the uptake of contaminants by plants (Fig1). Nanoparticles can serve as carriers for the precisely timed release of particular compounds, including nutrients or enzymes that aid in the breakdown or immobilization of contaminants and pollutants. Furthermore, by enhancing procedures like photocatalysis or redox reactions, nanoparticles can be used as catalysts to break down contaminants (Aken et al., 2010).

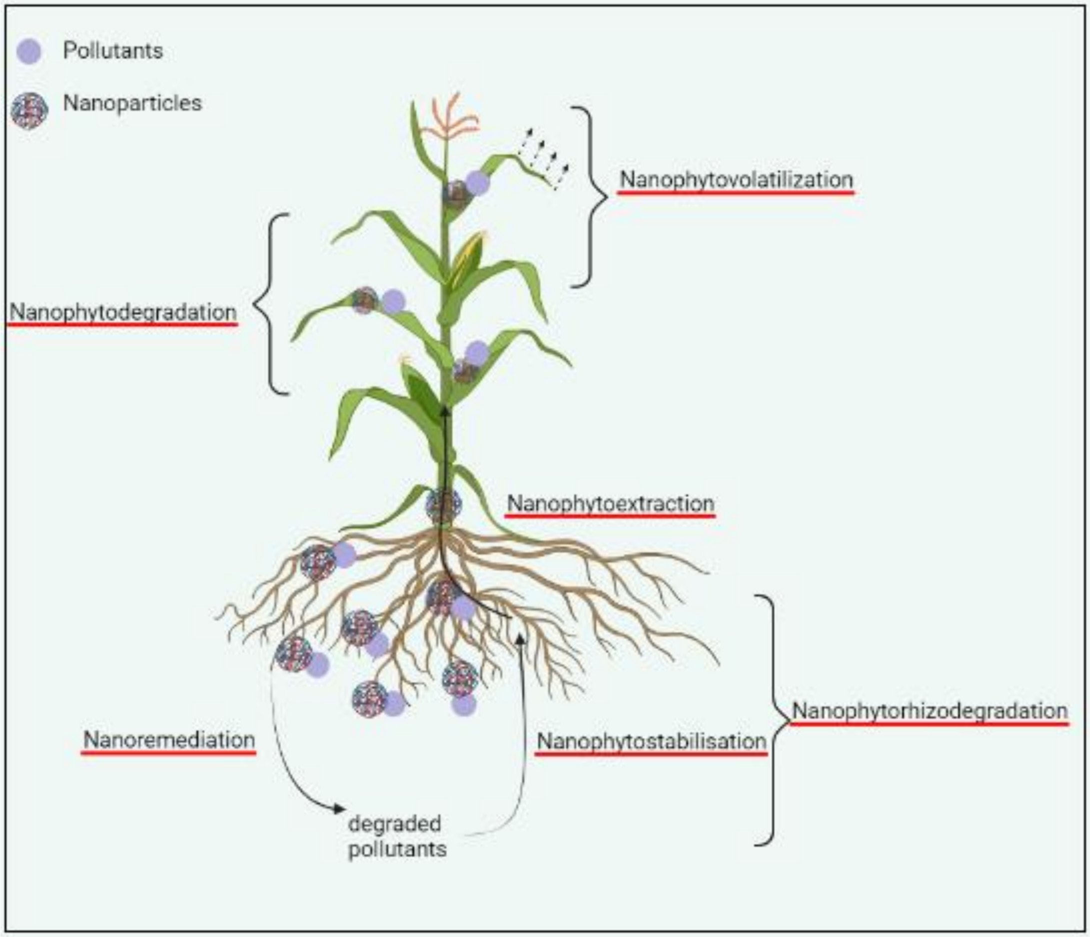

Fig1:- Integration of Nanomaterials and Plants for Environmental Cleanup (Figure created with the drawing application Biorender, Canada).

4. Nanomaterials in Nano Bioremediation Process

Nanomaterials are used to expand the effectiveness and adeptness of bioremediation by increasing the surface area for microbial activity, improving the transport and bioavailability of pollutants, and providing additional functionalities, such as catalytic activity and selectivity. Solid waste remediation, groundwater and wastewater remediation, hydrocarbon remediation, uranium remediation, and heavy metal pollution remediation are all areas in which nanomaterials are used in bioremediation. The examples of nanomaterials used for the bioremediation process are as follows.

4.1. Metal Nanoparticles

The metal nanoparticles are synthesized by combining metal salts to reversed micelles and using potent reducing agents like $NaBH_4$, N_2H_4, and H_2 gas. This method is used to synthesize a variety of metals (Grumezescu, 2016).

Reductive dechlorination is biocatalyzed by single metal nanoparticles. In a bioreductive test incorporating Pd (II), palladium Pd (0) nanoparticles can be deposited on the cell wall and inside of the cytoplasm of Shewanellaoneidensis and can be charged with H radicals by adding a number of substrates as electron donors, including hydrogen, acetate, and formate. When these charged Pd (0)-deposited S. oneidensis cells come into contact with the chlorinated compounds, the H radical on the Pd (0) can catalyse a reaction with pentachlorophenol that eliminates the chlorine molecule from the chlorinated compounds (Windt et al., 2005).

Bacteria have been used to create metal nanoparticles for a long time due to their quick multiplication rate and capacity to produce smaller nanoparticles. Bacterial strains such as *Pseudomonas aeruginosa*, *P.denitrificans*, *P. fluorescens*, *P. veronii*,Rhodopseudomonas capsulate, Shewanella algae, Bacillus species, *Escherichia coli* so on and so forth are used for the production of nanoparticles (Menon et al., 2017). The gold nanoparticles obtained from the above-mentioned species are mainly applied as sensors to detect pollutants in air, water and soil. Zinc sulfide nanoparticles are produced from cocci and bacillus that help to reduce organic dyes from the environment. Other important nanoparticles are silver nanoparticles derived from bacteria such as Aeromonas species, *E. coli*, Bordetella species, etc., whose application is to remove heavy metals, in air purification, wastewater treatment, and also degradation of photocatalytic organic pollutants (Singh et al.,2015). Fungi-Mediated silver nanoparticles are also synthesized. Due to their tolerance for heavy metals and ability to absorb and bioaccumulate metals, fungi are frequently utilised as reducing and stabilising agents.In addition, fungus may readily be grown on an industrial scale to manufacture nanoparticles with precise size and morphology (Guilger-Casagrande & Lima, 2019).

4.2. Carbon Nanomaterials

Numerous environmental applications can be found and addressed with the help of new technologies. In addition to sorbents, high-flux membranes, depth filters, antibacterial compounds, environmental sensors, and renewable energy technologies, carbon-based nanomaterials like carbon nanotubes and nanocrystals also make these things happen quickly. In the industrial setting, solvents like benzene and toluene are frequently utilized for downstream processing, equipment cleaning, and organic synthesis. Due to landfill leaching, inappropriate waste disposal methods, accidental spills, and leaks in underground storage tanks and pipes, they are frequently discovered in groundwater and can lead to serious ill effects on the human race (Shim et al., 2002). Studies show that carbon nanotubes tend to have a high affinity with organic chemicals, thus they can help in the efficient removal of benzene and toluene from water and be used in wastewater treatment (Bina B. Amin, et al., 2012). Carbon-based nanomaterials can also be efficient in the removal of copper from contaminated sites when immobilized by calcium alginate (Li et al., 2010) and, also be applied to remove nickel ions and cationic dye from solution. Additionally, 1, 2-dichlorobenzene, trihalomethanes, microcystins, fluoride, lead, nickel, and arsenate have been demonstrated to be among the contaminants to carbon nanotubes most effectively removed. They are tiny, have a huge specific surface area, and have hollow, layered structures, which account for this (Gong et al., 2009).

4.3. Single-Enzyme Nanoparticles

Oxidation causes enzymes to lose their activity, which reduces their stability and shortens their lifespan, making them less effective. Attaching the enzymes to magnetic iron nanoparticles is a successful method of enhancing the constancy, durability, and reusability of the enzymes. Applying a magnetic field makes it simple for enzyme separation from reactants or products if they are coupled to magnetic iron nanoparticles. Trypsin and peroxides, two distinct catabolic enzymes, have been employed to uniformly create magnetic nanoparticles (MNPs) with a core and a shell. According to the study, MNP-enzyme conjugates are more stable, efficient, and practical, and enzyme lifetime and activity significantly increase from a few hours to weeks. The study shows that MNPs shield the enzymes, preventing their oxidation. The enzymes live longer as a result of this. MNPs with high magnetism enable the effective magnetic separation of nanoparticle-enzyme conjugates, increasing the productivity of enzymes **(**Seenuvasan et al., 2018).

5. Nanobioremediation in the management of wastes

Due to growing industrialization and population development, waste management has become an increasingly important issue on a global scale. Traditional waste management techniques frequently fail to address the complex nature of toxins, posing risks to human health and the environment. However, a cutting-edge technique known as nano bioremediation has come to light as a potential remedy to efficiently handle and mitigate different forms of waste.

Bioremediation may be advanced far beyond its existing boundaries by the advancements in nanotechnology and the usage of nanomaterials. The utilization of nanomaterials and advancements in nanotechnology made it possible to use bioremediation much more effectively.

These methods frequently offer more opportunities for addressing pollutants in wastewater and groundwater. By reducing process intermediates, lowering associated costs, and mitigating their negative environmental effects, these techniques typically provide a wider range of options for managing contaminants in groundwater and wastewater, heavy metal- and hydrocarbon-contaminated sediments, and organic or inorganic compounds in soil (Bina and Pourzamaniet al., 2012; Vázquez-Núñez et al., 2020).

By supplying a bigger surface area for microbial action, nanoparticles can greatly boost the breakdown efficiency of contaminants (Fig2). As a result, toxins including heavy metals, chemical compounds, and even new pollutants can biodegrade more quickly and effectively.

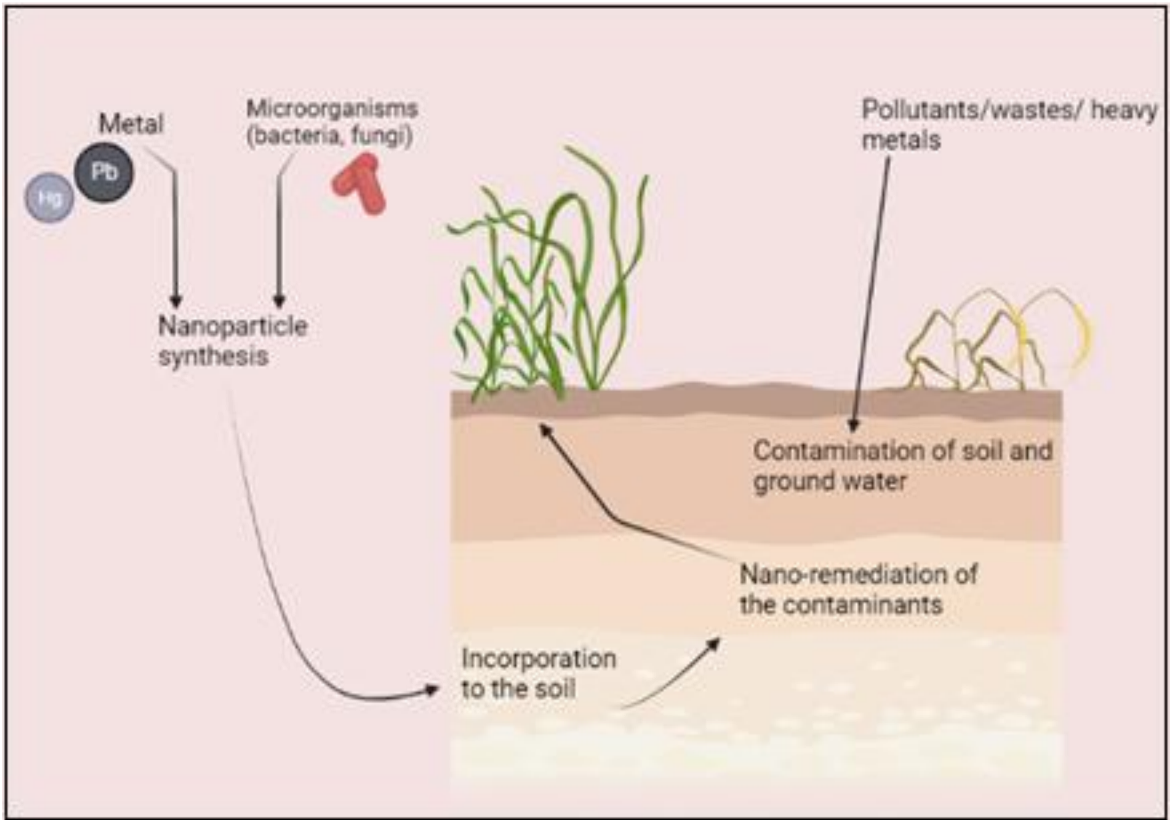

Fig2:- Nanobioremediation for Waste Management(Figure createdwith the drawing application Biorender, Canada).

Numerous ions, heavy metals, petroleum hydrocarbons, pesticides, radioactive substances, as well as new pollutants including pharmaceutics and personal care items, can contaminate water supplies (Jadhav et al.,2015). Due to their qualities, which include the ability to absorb large amounts of contaminants and the selectivity of some pollutants various nanoparticle-based methods have been used in the cleanup of water in recent years. For example, a variety of metal oxide (titanium dioxide, zinc oxide, and iron oxide) nanoparticles is used in water filtration methods (Aragaw et al., 2021) whereas due to their strong adsorption capacity and stability iron nanoparticles have been used to neutralizecolors in wastewater from the textile, paint, and paper industries. Methyl orange and methylene blue, two of the most frequently used industrial dyes and ones that have the most negative effects on human health and the environment, have recently been shown to be extremely successful in being adsorbed by these NPs. Heavy elements like chromium (VI), in addition to dyes, contribute significantly to water contamination (Nasar &Mashkoor, 2019; Yang et al., 2013).

Nanomaterials have lately become popular for soil remediation because of their high reactivity, high surface-to-volume ratio, surface functionalization, and capacity to change physical characteristics like size, shape, porosity, and chemical composition. These qualities work together to trap impurities efficiently and selectively. By intercalating nanoparticles in the soil by in situ application, it is possible to clean broad regions more quickly and affordably. Nanoscale zero-valent iron, carbon nanotubes, and magnetic and metal nanoparticles have dominated soil pollution nano treatment (Alazaiza et al., 2022; Mukhopadhyay et al., 2021). Pb2+, Cu2+, Ni2+, and ZN2+ can be removed using carbonaceous nanomaterials, however, heavy metal immobilization is influenced by pH, the amount of organic matter present, and the presence of silt and clay particles. Carbonaceous nanoparticles can also remove contaminants from soil, such as hexachlorocyclohexane, DDT, crude oil, and total petroleum hydrocarbons, while also boosting the microbial population and plant development (Shan et al., 2015). Application methods for carbonaceous nanoparticles include their integration into aqueous dispersion, separation columns, and membrane filtration.

6. Conclusion:-

Nano bioremediation represents a remarkable advancement in pollution management, leveraging the potential of nanotechnology to enhance the efficiency, selectivity, and environmental sustainability of bioremediation processes. Its ability to remediate a wide range of pollutants in diverse environmental settings makes it a promising solution for tackling pollution challenges.

The integration of nanotechnology with bioremediation processes offers innovative strategies for the efficient and sustainable restoration of contaminated sites. Continued research and development, coupled with responsible implementation, will overlay the way for the successful application of nanobioremediation techniques, contributing to a cleaner and healthier environment. However, further research, regulatory frameworks, and risk assessment are necessary to fully understand the potential of this innovative approach. With continued advancements and integration with other sustainable practices, nanobioremediation has the potential to revolutionize pollution management, leading to cleaner and healthier environments for future generations.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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