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Article

Mechanobiological mechanisms in the remediation of soil lead pollution using two-dimensional carbon materials and Morchella: A molecular-level study

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Abstract: Graphene-based 2D carbon composites and Morchella mushrooms are used in the paper to study the mechanobiological mechanisms of soil lead remediation. Soil is contaminated with lead, which threatens ecosystems and human health, making it even more important to find remedies. To fully comprehend these processes, present-day materials, and organic compounds are needed to improve soil nutrition and eradicate lead. To deal with the challenge of finding effective means of lead removal; limitations associated with traditional soil pollution remediation methods; and merging biology and material sciences. Multifunctional graphene wettability-patterned nanocoated membranes (MGW-PNM) is a novel technique developed to overcome these challenges. Such processes result in membranes with different wettability patterns that take advantage of the properties of graphene. This facilitates better interaction between the membrane itself and the surrounding soil as well as lead contaminants by modifying its hydrophobicity or hydrophilicity characteristics. For effective removal of lead, extensive simulation studies were done using MGW-PNM. In line with this, it can be inferred that MGW-PNM also remediates highly capable soils at high-efficiency levels. This was established when comparing modern techniques to past ones where considerable improvements were made on how much lead is extracted from them. The study suggests new ways of addressing environmental contamination resulting from microbial activities in soils by combining advanced materials with biological substances such as Morchella spp. For this purpose, it investigates various molecular interactions occurring among carbonaceous species called Morchella microbes and environmental pollutants like those including Pb.

Keywords: mechanobiological; lead pollution; two-dimensional; carbon materials; Morchella; molecular-level; multifunctional; graphenic; wettability; nanocoated; membranes

1. Introduction

Among all the problems that concern people's lives now, there can be singled out contaminated soil which is especially dangerous for industrialized urban areas [1]. Much attention has been paid to the question concerning cleaning up landfills or soils [2]; PNM allows for polluted land reclamation including groundwater sources where heavy metals or hydrocarbons are found [3]. The contaminated area can also be ex-situ remediated, either by moving it off-site or to a different place [4]. Conversely, in situ remediation involves treating soil or groundwater pollution without excavating the subsurface [5]. One of the biggest obstacles for developing nations when it comes to environmental sustainability is the high expense of remediation, which involves removing and replacing polluted soil [6].

The use of nanotechnology has been on the rise across several industries in the last few years. Because of the wide range of applications, they have made possible, PNM possesses several important and interesting features [7]. The production of NPs requires the integration of many academic disciplines, including engineering and molecular-level manufacturing [8]. The broad definition of nanotechnology is a set of practices centered on the construction, study, and potential use of particles with sizes ranging from one to one hundred nanometers [9]. The chemical, electrical, biological, and biotechnology industries are just a few of the many that are making use of nanotechnology [10]. Nanotechnology has been the subject of several efforts to treat pollution, and remediate polluted soil, among other environmental protection initiatives, even though many companies manufacture and utilize nanoparticles in different forms [11]. Technologies have been used for polluted areas that utilize nano treatment. There have been very few field-scale uses of the studies done to assess nano remediation methods, and the majority have been bench-scale [12].

Nano remediation has several benefits for soil and groundwater remediation, including shorter cleanup times and lower costs [13]. It also eliminates the need to transfer polluted soil or pump groundwater, and it completely degrades some contaminants [14]. PNM is used in nano remediation methods to convert and detoxify pollutants [15]. Catalysis and chemical reduction are the primary processes by which NPs remediate [16]. The PNMs enable adsorption, another removal process, due to their high surface-area-to-mass ratios and diverse distribution of active sites, which enhances their adsorption capabilities [17]. Unlike microparticles, PNM can disperse across a wider area and enter even the most microscopic subterranean cavities, all while remaining suspended in groundwater for an extended period [18].

The main objective of this paper is as follows:

To Investigate Mechanobiological Mechanisms:

The goal is to learn more about the mechanobiological mechanisms at work in lead remediation from soil utilizing two-dimensional carbon composites based on graphene and Morchella mushrooms, paying special attention to the interactions between the materials and the soil environment.

To Evaluate the Efficacy of MGW-PNM:

To better remove lead from polluted soils, this study aims to evaluate MGW-PNM. All of this involves running extensive simulations to see how MGW-PNM stacks up against more traditional forms of remediation.

To Integrate Biological and Material Science Approaches:

To show how innovative material science approaches, in conjunction with biological agents like Morchella mushrooms, may improve soil lead remediation methods and open the door to new possibilities.

The remainder of this paper is structured as follows: In section 2, the related work of soil remediation is studied. In section 3, the proposed methodology of MGW-PNM is explained. In section 4, the efficiency of MGW-PNM is discussed and analyzed, and finally, in section 5, the paper is concluded with future work.

2. Related work

A major environmental problem is the buildup of heavy metals in soil as a result of human activities including metal mining and smelting, farming, industrial processes, and vehicle emissions, among others. Heavy metal soil contamination must be addressed to stop the biomagnification of heavy metals in the food chain and the subsequent damage they cause to biota. At present, several approaches have been used to purify heavy metals from soil, including physical, chemical, and biological remediations. Chemical immobilization stands out as a potential soil remediation method due to its straightforward operation, rapid results, and rapid onset of action.

Machine Learning Technique (MLT):

Another reliable indication for soil contamination mapping is the reflectance spectra of observed plants. To decipher spectral data and forecast soil contamination levels, machine learning calibration models are used. This is accomplished using methods such as random forest, neural networks, and partial least squares regression. This analysis lays out the steps that make up each of these methods. The membrane capacities are lower in MLT, investigation and talk about present difficulties and potential future study possibilities by Jia et al. [19].

Artificial Intelligence (AI):

Restoring damaged ecosystems, improving human health, and maintaining soil quality all depend on accurate soil contamination mapping and assessment. Artificial intelligence has been successful in our technologically advanced era. Soil contamination mapping and measuring using various AI models is discussed in this chapter along with case studies and pertinent information about their pros and cons by Aniagor et al. [20].

Convolutional Neural Networks (CNNs):

Yue et al. [21] developed prediction models for mine soil remediation success indicators using CNNs and compared and evaluated the outcomes for fundamental soil physical and chemical characteristics index. While the data demonstrated that the CNN model's projected values were in agreement with the real soil conditions, overfitting did happen throughout the fitting procedure. Due to their more scientific fitting procedures and more intricate structure, CNN models can avoid fitting into local extremes and the soil nutrients and soil pH values are not enough in this network.

Deep Learning Algorithm (DLA):

Arsenic in the topsoil poses a risk to both humans and ecosystems. However, chemical analysis and on-site sampling remain the mainstays of conventional identification procedures; both approaches are laborious, expensive, less efficient, and time-consuming. Wu et al. [22] provide a technique for predicting the content of topsoil using deep learning in conjunction with visible near-infrared spectra. High levels of resilience and generalizability were shown by the optimal fully connected neural network model. Human populations that may be impacted were identified and the relative content at global and regional sizes was assessed using the model.

Support Vector Machines (SVM):

Soil quality refers to the soil's ability to support life as know it that is, to grow plants and animals, to keep or improve the quality of water and air, and to facilitate human health and housing. Many models exist for evaluating soil quality, each using a unique combination of criteria and data, but the adaptability is lower. Therefore, while evaluating soil quality, it is crucial to use a suitable soil categorization model. The purpose of Liu et al. [23] is to evaluate soil quality in metropolitan areas by introducing a novel, all-encompassing classification model based on support vector machines.

Cloud Cluster Analysis (CCA):

The use of CCA to see how soil pollutants spread and how their locations varied. To determine the primary causes of air pollution in the region, researchers used multivariate statistical methods, such as principal component analysis. The primary objective is to group things into clusters where they are similar to one another and distinct from objects in other clusters. Clustering may help find intriguing distributions and patterns in the data, which can lead to understanding its structure better by Pandey et al. [24].

Data Mining (DM):

Microbial-assisted phytoremediation technology about inorganic contaminants, hyperaccumulators, and stabilizers should get more focus to achieve technological transition and enhance soil remediation capability. Investigation into environmentally friendly and economically viable methods of decreasing organic contaminants in soil remediation should be undertaken. Qi et al. [25] provide useful data on the future of technological growth and reveal potential areas for SPRT-related developments and achievements.

Table 1. Summary of Research Methods.

S. No	Methods	Advantages	Limitations
1	Machine Learning Techniques (MLT)	Effective in predicting soil contamination levels using spectral data. Can handle complex, non-linear relationships.	Requires large datasets for accurate calibration. May suffer from overfitting if not properly tuned and lower membrane capacity.
2	Artificial Intelligence (AI)	Automates soil contamination mapping and assessment. Can analyze large datasets quickly.	Model accuracy depends on the quality and quantity of training data. May require significant computational resources.
3	Convolutional Neural Networks (CNNs)	Effective for complex pattern recognition in soil data. Can capture intricate spatial relationships.	Prone to overfitting, especially with small datasets. Low soil nutrients and less pH value
4	Deep Learning Algorithms (DLA)	Highly resilient and generalizable for predicting contaminants like arsenic. Can model intricate relationships in large datasets.	High complexity, leading to long training times. May not perform well with limited or noisy data.
5	Support Vector Machines (SVM)	Provides robust classification for soil quality assessment. Works well with smaller, well-labeled datasets.	Performance heavily depends on the choice of kernel and parameters. Can be less effective with large, complex datasets, lower adaptability.
6	Cloud Cluster Analysis (CCA)	Effective in visualizing pollutant distribution patterns. Helps identify underlying causes of pollution.	May require expert interpretation of clusters. May not handle high-dimensional data efficiently.
7	Data Mining (DM)	Useful for discovering patterns in large, complex datasets. Facilitates the identification of potential areas for remediation.	Can produce misleading results if data quality is poor. Requires significant preprocessing and data cleaning.

In summary, soil contamination mapping and remediation make use of several sophisticated methods and models, which are summarized in the text. In **Table 1**, spectral data is analyzed using machine learning approaches such as neural networks, random forest, and partial least squares regression to estimate degrees of soil contamination. Soil quality evaluation and remediation prediction using artificial intelligence models, such as DLAs and CNNs, are covered. Soil quality evaluation using SVM is the main focus, while DM and CCA are used to comprehend the distribution of contamination and improve remedial capacities. All things considered, these methods constitute huge leaps forward in environmental cleanup and monitoring.

3. Proposed method

Organic pollutants, such as petroleum hydrocarbons, herbicides, and solvents, may be degraded and trace element species can be transformed to make them less available using bioremediation, an in situ biological therapy that employs soil microbes for remediation. Both aerobic and anaerobic methods may be used to carry out these biological therapies. How the pollutants may be destroyed and under what circumstances each treatment procedure works are two key differences. To encourage aerobic microorganisms, aerobic biological therapy makes use of ambient oxygen, which is sometimes drawn up from the ground. In contrast, reducing chemicals are often used to enhance anaerobic biological therapy, which does not need oxygen.

Contribution 1: To Investigate Mechanobiological Mechanisms.

2D carbon materials with Morchella fungus for soil remediation, and membrane distillation for desalination. The first strategy improves soil health by adsorbing and immobilizing lead from lead-contaminated soil using a combination of graphene oxide and fungus. The second one is devoted to desalination, which is the process of effectively removing salt from salty water by using temperature gradients and a patterned membrane in a membrane distillation system.

One potential method for cleaning up lead-contaminated soil is to use two-dimensional carbon materials like graphene oxide in conjunction with Morchella, a kind of mushroom. These carbon materials bind to soil components when added to soil, causing lead ions to be adsorbed and immobilized on their surfaces. The process successfully decreases the soil's ability to retain lead. Mechanobiological mechanisms in soil lead pollution remediation involve using plants (phytoremediation) and microbes (bioremediation) to stabilize or remove lead. Plants uptake lead through roots, aided by root exudates, while microbes can transform lead into less toxic forms through bioleaching or biosorption. The mechanical properties of soil also influence lead mobility and availability for biological remediation. By interacting with the immobilized lead, the Morchella fungus promotes bioaccumulation of the metal within its hyphae, further enhancing this process. Soil detoxification is enhanced when the fungus reduces the toxicity of lead through its metabolic processes. Soil health is restored, lead levels are reduced, and a balanced ecosystem is supported by this synergistic approach that combines carbon materials with fungi. This makes the soil safer for plant growth. Soil organisms will have a safer habitat and agricultural conditions will be improved as a result of a remedied soil environment with substantially lower lead content as shown in **Figure 1**.

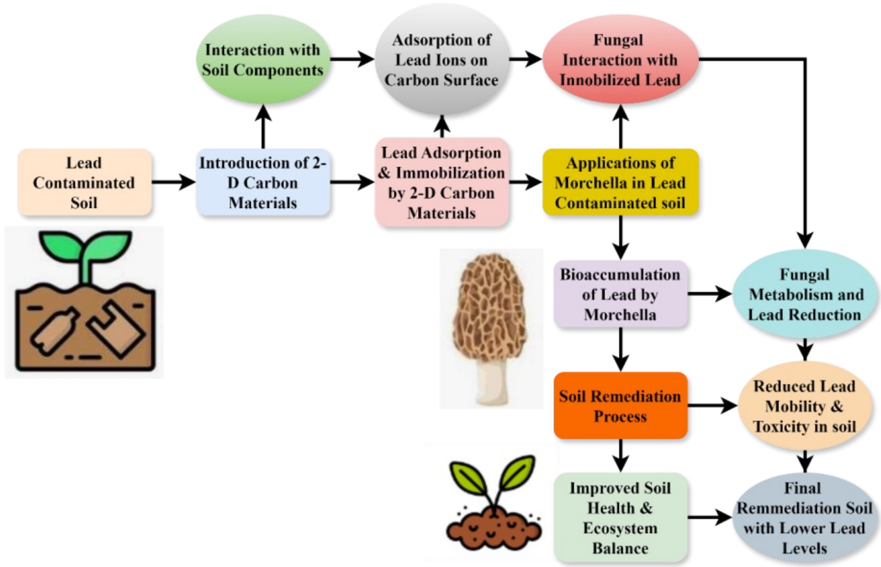

Figure 1. Two-dimensional carbon compounds in soil remediation.

$$K_{n,w} = 4 \times Q_{m,s} + R_k \left(\frac{\partial e_1}{b} \times s\right) \times w\ ep - 4\left(\frac{p_b, s}{g} \times w\right) \quad (1)$$

The corresponding Equation (1) defines $K_{n,w}$ where the overall productivity of lead sequestration, which features materials determined by $4 \times Q_{m,s}$ and R_k (wetness s and barrier monolayer connections $\frac{\partial e_1}{b}$), as well as biological variables $\frac{p_b, s}{g}$ and $w\ ep$ (associated with w Morchella activity). The equation tends to encapsulate the connections with the biological and technological balance removal lead optimization technique integration.

$$Z \sin c\forall + C \cos w\partial(w - p) = 4\big(GH(j - k)\big) \times W_R \left(\frac{v_f, p}{3}\right) - 2n \quad (2)$$

In this corresponding Equation (2), the constants were determined through the graphic membrane $Z \sin c\forall$ and $C \cos w\partial(w - p)$ considered to be determined, the factorial environment aspect is dealt with $2n$ and performance remedy aspects, by $4\,\big(GH(j - k)\big)$ and $W_R \left(\frac{v_f, p}{3}\right)$. The lead elimination efficacy is determined by improved soli pollution where the interactions with the model description with the mechanism's conjunction.

$$e(s, p) - vfg(er) = q(s, -p) \times E\big(ew(k - 1)\big) + X\big(w, (n + 2)\big) \quad (3)$$

Equation (3) denotes the pollutants and soil with the energetic state values by $e(s, p)$, it is otherwise shown by the fungi activity with the energy aspects by $(after)$. The variables such as $E\big(ew(k - 1)\big)$ and $q(s, -p)$ define the surroundings and material contacts based on the capture remediation process, where $X\big(w, (n + 2)\big)$ is determined by the lead removal optimized required with the energy input values. The efficiency of purification in the soil is determined by the variable and ecological materials demonstrated by the equation.

$$f(m, n - k) = Q_{d-fp} - j(w - kp), \qquad for\ (m, b) > E_f - 1 \quad (4)$$

The wettability pattern impacts and the screen graphene performance is the respective Equation (4) as $j(w - kp)$ and Q_{d-fp}. The pollutant lead values are distorted material based on the connection reflected using $f(m, n - k)$. The conditional ambient and physical necessary values are removed $E_f - 1$ from the optimal lead requirements and the indications (m, b). The equation provides the optimization of atmospheric and material accurate engineering based on the restoration soil with high-efficiency delivery.

Figure 2 shows a patterned membrane distillation device that was developed for desalination. The procedure starts with a feed stream tank that mimics saltwater with a NaCl solution of 35 g/L. The membrane distillation method relies on a temperature gradient, which is created by heating the solution to 70 °C using a temperature controller. The membrane distillation cell, with its uniquely patterned membrane, is then used to filter the hot salt water. A membrane may separate salt from water by letting vapor through but preventing salt and other contaminants from passing through. A separate temperature controller keeps the other side of the membrane at a more moderate 20 °C. This chilly side collects permeated water by condensing water vapor. The purity of the permeate water is determined by measuring its conductivity; this metric shows how well the desalination process worked. Using temperature gradients and membrane technology, the setup attempts to effectively manufacture fresh water from salty sources.

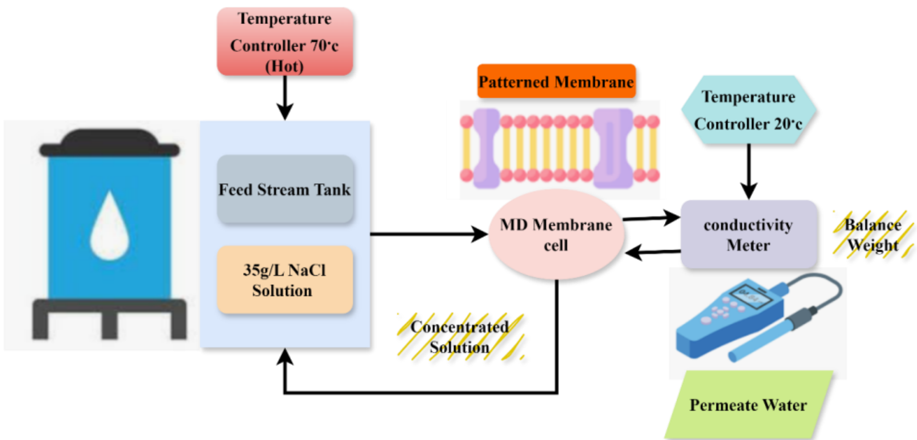

Figure 2. Desalination using a patterned membrane.

$$C_v = W_{q-1} + \left(\frac{b}{(n-k)}, r^{s-1}\right) \tan pn - kvl - 1 \times \times g(zv, df) \tag{5}$$

The environmental factors C_v, where the capability sequestration leads the membrane $\frac{b}{(n-k)}$ with the graphene values with the quality structures r^{s-1}. The values W_{q-1} aspects determined to impact the environmental aspects $p\left(n - kv^{l-1}\right)$ and structural $g(zv, df)$ where parameters define the impacts tan. The parameters defined with the altering the efficacy removal lead membrane optimized with the altering achievement determined in Equation (5).

$$\sqrt{B_p^2 + C_w^3} > H_{k,p}\left(h(v - qp) + h\big(-\partial t - (wr)\big)\right) \tag{6}$$

The forces involved with lead treatment $H_{k,p}$ are related to the overall durability $h(v - qp)$ and rigidity of the materials made from graphene (B_p^2) and C_w^3 in the specified equation. Due to this disparity h, it seems that the material's resilience matters for lead removal $-\partial t - (wr)$, as it needs to be able to withstand biological and environmental stresses while still performing admirably in soil repair in Equation (6).

$$n_{k-q} = R_w \left(\frac{\forall d_{f+1}}{b}\right) \times \left(\frac{B_v}{\sqrt{B_l^2 - c_{f-1}^4}}\right) + F_{d(n-1)} \times \tan p\ (v-1) \quad (7)$$

In this context, the net rehabilitation efficiency is represented by the equation n_{k-q}, whilst the material's capacity to retain functionality under stress and the effect of environmental factors $F_{d(n-1)}$, such as lead shipment, are addressed by R_w and $\frac{\forall d_{f+1}}{b}$. To achieve high remediation efficiency $\frac{B_v}{\sqrt{B_l^2 - c_{f-1}^4}}$, it is essential to optimize the physical characteristics of the monolayer membranes tan and the ambient circumstances $p\ (v-1)$. Equation (7) demonstrates how these optimizations might boost the overall effectiveness of lead removal.

In summary, both technologies provide new ways to fix important environmental problems, such as polluted soil and dirty water, and they could have big positive effects on the environment and people's health. By delivering cleaner soil and more easily available fresh water, MGW-PNM offers an effective and long-term answer to critical environmental problems.

Contribution 2: To Evaluate the Efficacy of MGW-PNM.

Hydrocarbons found in petroleum include a wide variety of chemicals. Unfortunately, little is known about the amount, characteristics, degradation mechanism, and toxicological impact of chemical substances that make up minuscule fractions on the health of humans and other animals. Therefore, to provide long-term remediation solutions, further research into the toxicological effects, degradation processes, and all of the chemicals found in petroleum hydrocarbons is required.

The MGW-PNM method was faster and easier to regulate, and it allowed for on-site soil treatment, which eliminated transportation expenses. A uniform rate of bioremediation throughout the pile necessitated thoroughly mixing the soil. The amounts of Total Petroleum Hydrocarbons (TPH) were effectively lowered to acceptable levels using the improved bio pile treatment. Backfilling the remediated soil into the original excavations was the process. The large amounts of contamination and the affected regions have been addressed via waste disposal and cleanup efforts. Parts of the property still have contamination levels below the Stockholm Convention's minimum threshold for Persistent organic pollutants (POP) designation of 50 parts per million. Regardless, high levels of soil pollution may restrict land usage. Soil laccase activity, Poly Chlorinated Biphenyl (PCB) elimination, actinobacteria, and firmicutes active metabolism were all positively correlated. In **Figure 3**, the Morchella might be used as an adaptable, inexpensive organic substrate to activate processes that would lead to the oxidation of highly contaminated. Furthermore, using it as a filler in bio heaps is a great way to recycle organic waste from growing edible mushrooms for industrial purposes.

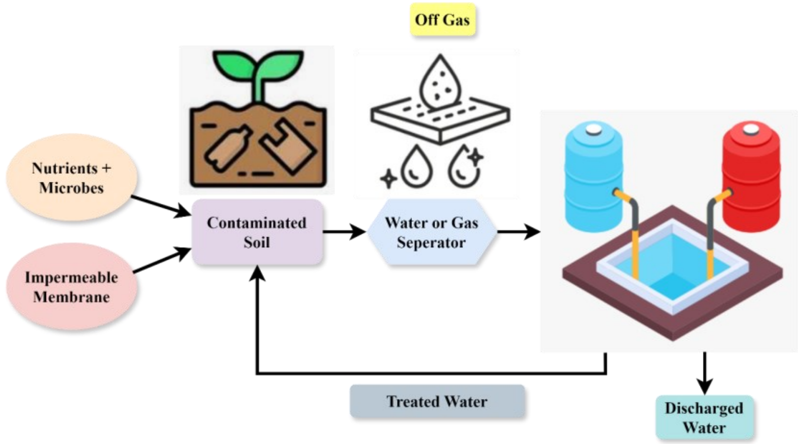

Figure 3. Assembly of bio cells and pipes for cleanup.

$$v(a, nb) = R_s\left(\frac{g_{h,r}(u-1)}{v} \times 2n(k-1)\right) \times \big(B\tan w(q-1) - C\cos p(n-k)\big) \quad (8)$$

The environmental variables ($g_{h,r}(u-1)$) and v) and material properties (a, nb) impact the variable repair capacity, which is captured by the equation $2n(k-1)$. The removal efficiency optimization $B\ tanw$ deals with the combined adjustments $q-1$ with the elements based on the environmental membrane $C\ cosp$ circumstances through the physical properties. The equation dealt with the techniques based on the adaptive remediations

$$G(y, z) \times F(w, qp) + Pz(w - jk) = BD_f + CV_{m-1} + \big(k - (mnR^2)\big) \quad (9)$$

Here, the surrounding environment $F(w, qp)$, and contamination variables $Pz(w - jk)$ are incorporated into the equation $G(y, z)$, while the material's structure mnR^2 and reaction to lead absorption are represented by BD_f and k, respectively. A little effort is dealt with by the environment based on the lead removal process with the remediation with the parameters of Equation (9). Hence the material aspects are optimized through the property materials.

$$\partial v + \forall_{d-1} = \frac{v}{\sqrt{c^2 - 1}} + H(y, xp), for\ z^2 + a^2 > 1 \quad (10)$$

The lower half of the equation, which includes $H(y, xp)$, shows how the substrate reacts to these modifications $\frac{v}{\sqrt{c^2-1}}$, while the shows the restoration capacity $z^2 + a^2$ and the environmental change (∂v) and $\forall_{d-1}$ are represented. The removal leads to optimum values of the accomplishment based on the conditional characteristics which run on the guarantee requirements with the environmental conditions

$$C_f(n-1) + s_{f(yp-2)} = ds\big(w - m(k+1) \times R_s(f \times rt)\big) \quad (11)$$

Here, the lead absorption property of the material is represented by the equation $C_f(n-1)$, and changes depending on particular contamination circumstances are reflected by $s_{f(yp-2)}$. Environment-related factors affect the scaling factor, which is represented by $f \times rt$. The remediation effectiveness $w - m(k+1)$ of the process is captured by R_s, and other operational elements are reflected by ds. The circumstances of environmental dealings through the material performance with the balance emphasized with the success with the successful lead removal.

Sites or soils polluted with petroleum hydrocarbons need a comprehensive strategy for management that prioritizes recovery, rehabilitation, and remediation. Restoring environmental quality is the primary goal of recovery techniques, which include minimizing contaminants in aquatic and air environments. The rehabilitation process revolves around green remediation techniques, which aim to reduce land pollutants and turn waste into useful resources. This helps with both social development and environmental health. To ensure the effective removal of toxins and promote economic growth, long-term environmental sustainability requires sustainable remediation solutions. These approaches not only deal with pollution right away, but they also encourage reusing polluted land, which helps convert trash into treasure and has positive social and economic effects. Overall, the goal of the integrated strategy for managing areas polluted by petroleum hydrocarbons is to strike a compromise between developing sustainably and restoring the environment. With this all-encompassing plan, it is confident that the cleanup process will not only the pollution; it also helps the people and economy that are directly affected, leading to a brighter, longer-lasting future as shown in **Figure 4**.

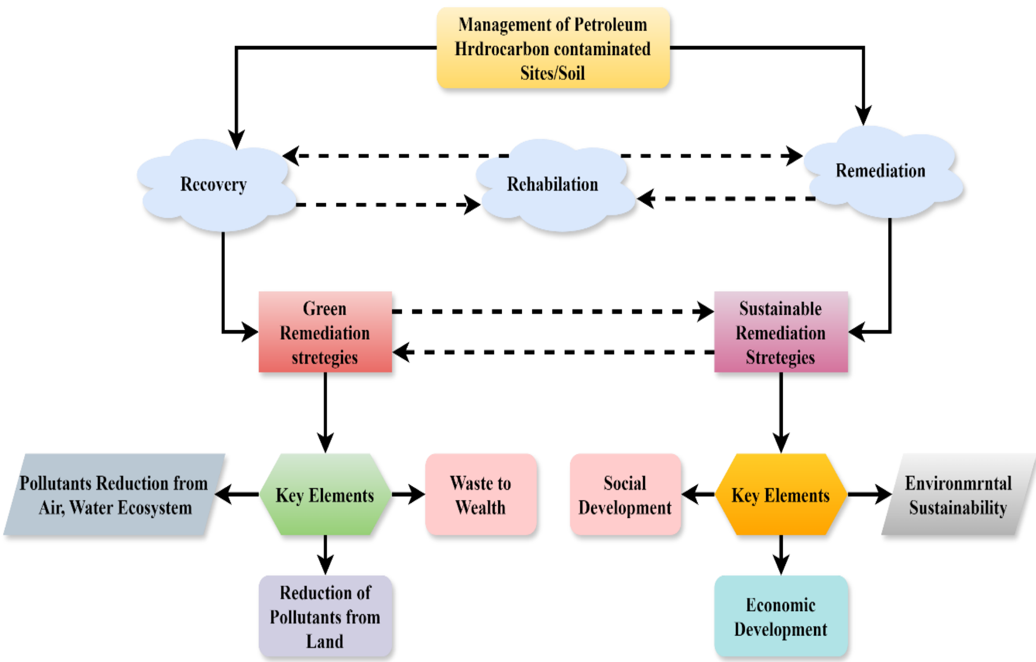

Figure 4. Contamination of soil with petroleum hydrocarbons and its remediation.

$$B_7 = \sqrt{g(y,z)} \times J(v,b) + \left(\frac{r_f * h^{2p}}{b}\right) - \tan \partial v(p + qr) \quad (12)$$

The total efficacy of the rehabilitation system is represented by equation B_7, which is affected by $J(v,b)$, which encompasses $g(y,z)$ the combined effects $p + qr$ of material attributes $\frac{r_f \times h^{2p}}{b}$ and ambient circumstances $\tan \partial v$. The system fluctuations are compensated with the variable considerations with the term aspects with the material behaviors. The equation has the purpose of the parameters dealing with the leads with the parameters required with the removal efficiency and effective optimization.

$$v_{b-1} = \partial_{qw}(m+n) \times Wq\big(v, p(w-jq)\big)\sin\partial \times ez + Jp \quad (13)$$

In this case, the revised cleanup efficacy ez is represented by the equation v_{b-1}, where $\partial_{qw}(m+n)$ denotes the combined effect $q\big(v, p(w-jq)\big)$ on the substance sin and cleaning variables Jp. Equation (13) deals with effective remoteness where the lead is set to be improved by surrounding materials considering the requirements with the significance. The changes over the important aspects are improved by the environmental changes and operational aspects.

$$r_u = \forall d + \beta Pk(u-1) - H(u+gp), for\ (a,s) \equiv E_b, u < 0 \quad (14)$$

The restoration efficiency, denoted by the equation r_u, is affected by the starting point remediation capacity, denoted by $\forall d$, and the modifications depending on the material and environmental characteristics, denoted by $\beta Pk(u-1)$. Additional operational impacts are taken into consideration by the term $H(u+gp)$, where the circumstances (a,s) denotes special operational E_b, u limitations. Equation (14) defines the components of the integrated system optimized aspects with the removal of the efficiency.

$$\sqrt{Z_x^d + W_e^r} < K_{q,p}\left(h(\forall) - h\big(\equiv \partial(v-pk)\big)\right) \quad (15)$$

The combined structural and environmental variables impacting cleanup capability are represented by the inequality $\sqrt{Z_x^d + W_e^r}$. The effectiveness threshold, which is $K_{q,p}$. Here, $h(\forall)$ is a scaling factor and $\partial(v-pk)$ functions include the influence of dynamic variables. The boundary effectiveness is dealt with by the system treatment functions with lead removal optimization with the surrounding conditions and material management.

In summary, remediation and rehabilitation solutions are all part of a holistic strategy for managing areas polluted by petroleum hydrocarbons. Pollutant reduction, environmental health restoration, and sustainable development are the main goals of these approaches. A few important components include promoting economic and social growth, reducing pollutants, and turning waste into usable resources. Effective pollution control, environmental sustainability, and community well-being are all supported by this integrated strategy.

Contribution 3: To Integrate Biological and Material Science Approaches

A fresh strategy for cleaning up soil that has been polluted with lead by using a mix of cutting-edge materials and biological agents. The procedure starts with soil preparation and pre-treatment, then incorporates Morchella fungus and MGW-PNM to immobilize and convert lead. This approach's efficacy is evaluated using mechanobiological processes and simulation research. Soil permeability and particle size are important factors in the vaporization of hydrocarbons, and their efficiency is dependent on them. Free ions have a crucial role in the restorative process of ionic conduction, which is triggered by electric fields that cause rapid heating.

A methodical procedure including materials and biological agents is used to remediate soil that has been polluted with lead. This approach efficiently lowers the levels of lead. Making sure the soil is ready for further treatment is the first step in the process, which is called pre-treatment and soil preparation. After that, biological agents like the Morchella fungus are brought in, along with materials like MGW-PNM. While Morchella is essential for lead absorption and transformation, MGW-PNM interacts with soil lead to help immobilize it. By using mechanobiological processes in these interactions, may learn how efficient the remediation in PNM is. This integrated approach's efficiency and flexibility are further evaluated using simulation research. A post-treatment examination is carried out to assess the total efficacy of the procedure after the soil has been remedied and the lead levels have been drastically decreased. The result in **Figure 5**, is an optimization feedback loop that allows the MGW-PNM and Morchella methods to be fine-tuned indefinitely. In the end, this method guarantees a long-term solution for lead contamination remediation that is both successful and sustainable.

Figure 5. Multifunctional graphenic wettability-patterned nanocoated membranes.

$$B_v = E_b \times (y,z) + \partial_{a-bp} \times (rw \times Wq), C_{f-1} = G(y,z) \quad (16)$$

The starting point for effectiveness B_v and modifications depending on material attributes and environmental circumstances E_b are combined in the equation (y,z) to indicate the total efficacy ∂_{a-bp} of the remediation procedure. The capacity of the materials C_{f-1} constructed from graphene concerning $G(y,z)$ ecological factors is captured by the expression $rw * Wq$. The integrated variables are determined by the values with the removal of copper by efficiency and enhanced maximization of analysis of membrane capacity.

$$\frac{B_n}{\sqrt{d^r + e^2}} = v_{f(n-1)} + er_{(n+1)} - \left(h(k-p) + \frac{R}{fr} m_{n-1}\right) \tag{17}$$

This equation, which takes into consideration the effect of material qualities and environmental variables, indicates the modified cleaning capability $\frac{R}{fr} m_{n-1}$. The initial efficiency ($v_{f(n-1)}$) together with other factors ($\frac{B_n}{\sqrt{d^r+e^2}}$) and improvements for operating circumstances ($h(k-p)$). The environmental aspects are dealt with by the characteristics balance needed to emphasize the equation on the successful lead removal to deal with the analysis of soil nutrition.

$$E, \left(f\left(p(m-n)\right)\right) = \frac{C_v(k-JK)}{v} + \sqrt[2]{B_v(m-nk)} \tag{18}$$

Here, the improved remediation efficacy, affected by $\frac{C_v(k-JK)}{v}$, the substance's storage limit, and operation modifications p, is represented by the equation $\sqrt[2]{B_v(m-nk)}$. The material performance of the setting is captured by the term $p(m-n)$, while other performance variables E and their interactions are reflected by f. The need to minimize adverse ecological effects while optimizing material qualities for lead removal with effectiveness is shown by this equation for the analysis of efficiency.

$$E'(T-up) = H(u-kp) + \sqrt[3]{g^2 + v_2\,(nk - (pvm^{2-k}))} \tag{19}$$

The repair process's efficacy is represented by the calculation $E'(T-up)$, which is affected by $H(u-kp)$, which accounts for material and operational circumstances $\sqrt[3]{g^2}$. Additional effects from material feature v_2 and external factors are reflected in the phrase $nk - (pvm^{2-k}$. To maximize lead removal efficacy, this equation indicates the way material performance interacts with external factors based on the analysis of adaptability.

$$F_{d(n-1)} = E_{r-1} + \left(k(e-wq) + s^{p(w-1)}\right) \tag{20}$$

The remediation effectiveness at a certain stage, as indicated by the beginning efficiency E_{r-1}, is represented by the equation $F_{d(n-1)}$. Additional operational modifications are taken into consideration by the term $s^{p(w-1)}$ and material-specific and environmental factors are adjusted for by the term $k(e-wq)$. The importance of adjusting the material and surrounding circumstances in enhancing the overall efficacy of lead eradication is shown by this Equation (20) defines the analysis of soil PH.

In summary, Constant enhancement is guaranteed via post-treatment analysis and an optimization feedback loop. Reduced lead levels in polluted soils, improved environmental health, and sustainable land use may all be achieved via this integrated approach. Importantly, every aspect of the remediation process affects the decision-making process and improves the success of the remediation. Consequently, there is a pressing need for innovative, cost-effective methods of recovering polluted soils that are both environmentally benign and capable of reducing PHs.

4. Result and discussion

A novel approach to remediating lead-contaminated soil is investigated in this research using Morchella mushrooms and Multifunctional Graphenic Wettability-patterned Nanocoated Membranes (MGW-PNM). With a focus on increasing soil health, the project aims to enhance lead sequestration efficiency, flexibility, and overall efficacy by using innovative materials and biological agents.

Dataset Description: State Superfund and Brownfield Cleanup are two of the remedial programs run by the DEC, and they are rehabilitating regions that are known as Environmental Remediation Sites. There are records of locations that have been remedied or are under the agency's management in this database. Due to overfitting and other problems, the findings will be subpar since the dataset is quite small. To learn quickly, a small dataset is useful. To avoid squandering thirty minutes or more of training the model and costly computing, a tiny dataset aids learning [26].

4.1. Analysis of membranes' capacity

The MGW-PNM is the subject of the study's capacity analysis, which aims to remediate lead-contaminated soil. These membranes improve the effectiveness of lead sequestration by their interaction with soil and lead pollutants, which is enhanced by their distinctive wettability patterns are explained in Equation (16). To assess the membranes' performance, the research conducted extensive simulation studies. The results showed that MGW-PNM is very adaptable and efficiently removes lead. It seems that these membranes can interact with the polluted soil more efficiently since MGW-PNM exhibits considerable gains in lead cleanup when compared to traditional methods. The analysis highlights the possibility of combining state-of-the-art material properties with biological agents, such as Morchella mushrooms, to develop a strong and innovative method for soil lead remediation. This method would combine interactions at the molecular level with state-of-the-art material properties to improve environmental outcomes. In the proposed method of MGW-PNM, the membrane capacity is increased by 98.12% as shown in **Figure 6**.

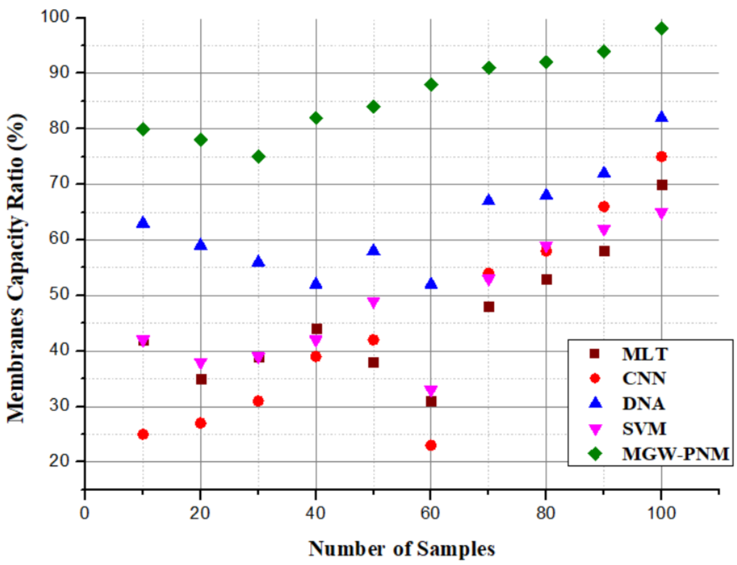

Figure 6. The graph of membrane capacity.

4.2. Analysis of soil nutrition

In **Figure 7**, an examination of soil nutrition highlights the need for improved soil fertility for efficient lead removal. The bioremediation method relies on helpful bacteria, such as Morchella mushrooms, but in lead-contaminated soil, nutrient depletion might prevent their development. The research delves into how biological agents may be integrated with graphene-based two-dimensional carbon composites to enhance soil nutrition and enable more efficient lead removal. In addition to helping with lead sequestration, the MGW-PNM assists soil health restoration by encouraging the preservation of vital nutrients are explained in Equation (17). The membranes facilitate the development and metabolic activities of Morchella by establishing an atmosphere favorable to microbial activity, which improves the remediation process as a whole. The study emphasizes the two-pronged advantage of this novel method: first, it rids the soil of harmful lead; second, it restores the soil's nutritional value, guaranteeing the soil's health and the ecosystem's longevity. The ratio of 97.66% of soil nutrition is gained in this MGW-PNM.

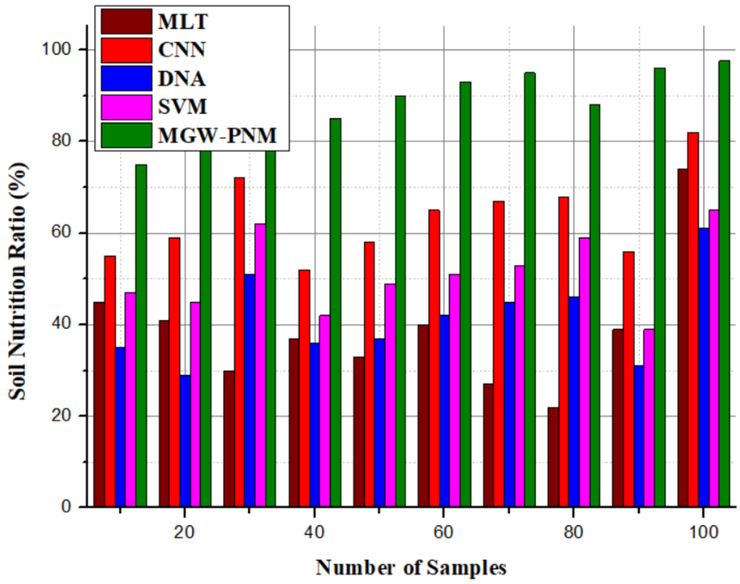

Figure 7. The graphical representation of soil nutrition.

4.3. Analysis of efficiency

In **Figure 8**, the MGW-PNM approach with more traditional forms of remediation, can gauge its efficacy. The graphical results show that MGW-PNM's superior design optimizes the interaction between the membranes and soil pollutants, leading to far higher lead removal rates. Improved and accelerated cleanup procedures are possible because of the membranes' unique wettability patterns, which increase their ability to trap and sequester lead particles are explained in Equation (8). By decomposing and stabilizing lead chemicals in the soil, the incorporation of Morchella mushrooms as biological agents further enhances efficiency. In addition to increasing the total yield in lead removal, the combination strategy speeds up the detoxification process. This efficiency study highlights the possibility of MGW-PNM as a better option than conventional approaches, providing a quicker, more flexible, and longer-lasting remedy for lead contamination in soil. The efficiency ratio is achieved by 97.23% in the proposed method of MGW-PNM.

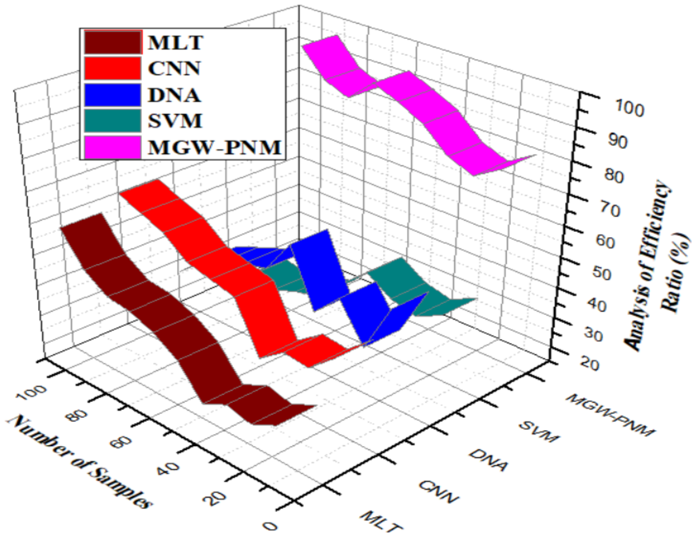

Figure 8. The graphical representation of efficiency.

4.4. Analysis of adaptability

Various soil lead contamination situations may be addressed by the MGW-PNM, as shown in **Figure 9**. The capacity of the membranes to perform well in a variety of environmental circumstances and pollution levels is about their adaptability. A very versatile remediation tool, MGW-PNM may be adjusted to target soil types, moisture levels, and lead concentrations, which are explained in Equation (19). The membranes can adapt their interaction with different soil matrices to provide optimum lead sequestration in different situations, according to their varied wettability patterns. The addition of Morchella mushrooms improves the system's overall performance by increasing its flexibility. These biological agents may grow in diverse soil conditions. Because of its versatility, the MGW-PNM approach shows promise as a solution to a wide range of environmental soil remediation problems, from moderately polluted agricultural land to severely polluted industrial sites. The adaptability ratio is gained by 98.62% in the proposed method of MGW-PNM.

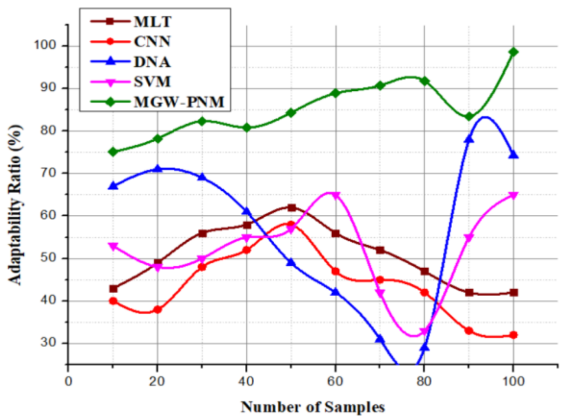

Figure 9. The graph of adaptability.

4.5. Analysis of soil pH

The effectiveness of lead cleanup attempts and the extent to which the metal is bioavailable are both affected by the soil's pH. This research shows that these membranes maintain their high effectiveness throughout a wide pH range by analyzing the MGW-PNM technique's interactions with soils of different pH values are explained in Equation (20). Lead may be optimally captured and sequestered by fine-tuning the wettability patterns of MGW-PNM to adapt to soils that are acidic, neutral, or alkaline. Morchella mushrooms, when used as biological agents, further alter soil pH, making them ideal for lead immobilization. This two-pronged strategy improves lead removal and helps stabilize soil pH, making the remediation procedure more successful and sustainable in the long run. Findings from the study highlight the significance of soil pH in developing versatile and effective remediation plans. In the proposed method of MGW-PNM, the soil pH value is increased by 97.41% as shown in **Figure 10**.

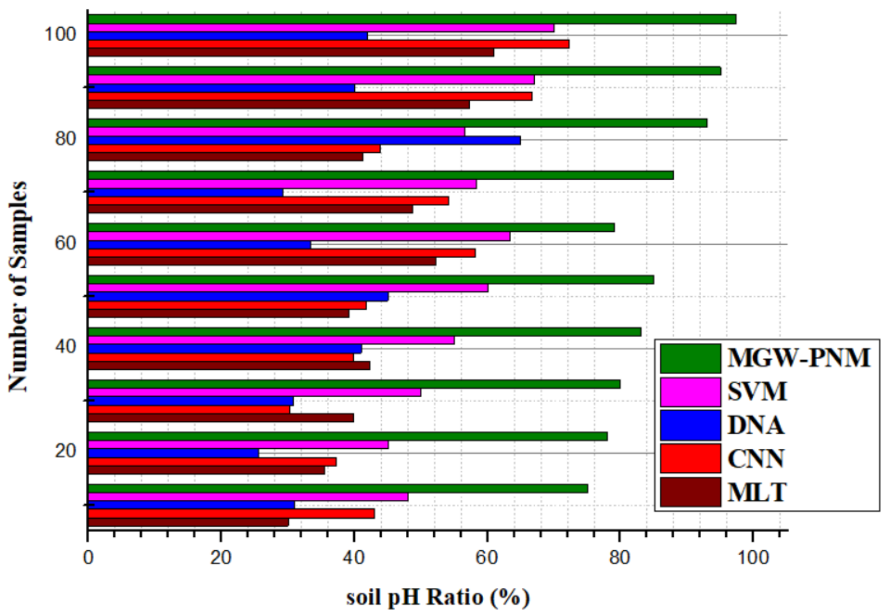

Figure 10. The graph of soil pH.

In summary, soil nutrition, adaptability, pH stability, and lead removal efficiency are all greatly enhanced by MGW-PNM, according to the research. This integrated technique not only cleans lead-contaminated soil efficiently but also improves long-term soil health and environmental sustainability since the findings reveal major advantages over previous procedures.

5. Conclusion

As a master soil variable with a two-way link with soil biogeochemical processes, soil pH is the focus of this paper's content. While this research did not cover every biogeochemical activity, it did cover several that significantly affect soil health, nutrient availability, pollution, and the possible dangers and food chain destiny of contaminants. Due to the close link between soil and water, it is impossible to ignore the mobility of harmful compounds through the hydrological cycle in this context. Soil management, remediation, rehabilitation, and quality maintenance decisions and choices may be informed by this knowledge. Future applications may be informed by the observed soil pH-biogeochemistry interactions, which improve crop development by recycling and making nutrients more available, leading to greater yields for certain crops. In certain soil circumstances, the transient rhizosphere soil pH might be used to increase the availability of specific nutrients. Moreover, soil pH may help with the distribution and removal of toxic compounds from systems, which is vital for controlling soil pollution. In the range of pH 6.5 to 8, mineralization and degradation processes including C and N mineralization and pesticide degradation take place, while the range of pH 7 to 9 is optimal for maximal petroleum and PAH breakdown. varied human activities have resulted in the unintentional release of heavy metals into the environment, contaminating soil at varied levels at around 5 million locations over 20 million hectares of land worldwide.

The harmful impacts of polluted soils may be mitigated and their ecological functions restored via the use of a variety of restoration strategies. Chemical, biological, electrical, and/or thermal procedures are all part of these methods for cleaning up polluted soil. Soil remediation techniques, especially bioremediation, might make use of these and pH maxima for different microbial enzymes. Soil remediation and nutrient cycling are the two main ends of the spectrum of soil pH's potential uses. Soils that are to be used for agricultural production may be cleaned up using MGW-PNM because of the advantages that mycorrhizal fungi provide. Organic and inorganic contaminants are both efficiently detoxified by MGW-PNM. The effectiveness of this remediation strategy, however, is conditional on the specific fungus species and their place of origin, the plant species that are colonized, and the pollutants' kind and concentration. The effectiveness of MGW-PNM may be enhanced by combining it with other remedial strategies. Therefore, this study demonstrates that MGW-PNM, combined with Morchella mushrooms, significantly enhances lead sequestration in contaminated soil. MGW-PNM achieved a 98.12% increase in membrane capacity, 97.66% in soil nutrition, 97.23% in efficiency, 98.62% in adaptability, and 97.41% in maintaining soil pH. The results highlight the method's ability to improve both lead removal and soil health, making it a promising remediation approach.

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