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Enhancing Soil Health: Nanotechnologies for Effective Remediation and Sustainable Development

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ABSTRACT: The growing population has led to the increase in contamination to the soil, affecting the soil environment which indirectly affects importance of human health. Soil remediation is important to remove and reduce the level of contamination in the soil medium. If the contaminants present in the soil is not remediated, the possibilities of it to spread will increase due to the presence of water flow inside the soil medium, further contaminating soils that are previously clean. Hence, several nanotechnologies and nanomaterials were discovered by researchers, allowing the remediation of soil that are contaminated by different pollutants to be effectively carried out. The nanotechnologies and nanomaterials discussed in this paper involves physical, chemical and biological type of remediation. It is being known that nanoscale remediation can have higher effectiveness compared to microscale remediation. Most of the discussed nanotechnologies requires longer period of time but the effectiveness in the removal or reduction of contaminants are very high. Remediation of contaminated soils allow more land to be available for human development and exploitation. Humans are urged to reduce the chances of contamination activities or accident as contamination to the soil can adversely affect the local environment and the human health.

KEYWORDS: Contamination, soil, remediation, nanotechnologies, sustainable method

1. Introduction

Soil remediation is the implementation of the technologies that are capable in solving the problem related to soil contamination. Soil remediation is also essential in managing the probable risk that might be brought about to the human health as well as the affected environment due to exposure of contaminated soil. Cases of soil contamination can be seen present since the beginning of industrial activities and the disposal of waste without proper regulation. Contaminants that cause the soil to be contaminated can be seen to include waste such as chemical waste, illegal or improper disposal of industrial waste, and leaking cases from tanks or pipes for a considerable period of time [1].

Nanotechnology or the implication of nanotechniques on the remediation of soil can be seen to be effective in removing or removing the level of pollutants in the contaminated soil.

Due to the specification of the technology, the remediation of soil can be performed exquisitely, ensuring that more pollutants can be managed from the soil. It can already be seen that nanotechnology is no longer a very unknown techniques, as more and more industries had been utilizing the benefits of nanotechnology especially in the environmental protection activities. Advantages of applying nanotechnology in the course of soil remediation is that cost and time for remediation can be reduced compared to other technology. Nanotechnology can also promote complete degradation of certain pollutants in the soil, removing the requirement of disposing polluted soils, as incomplete degradation can lead to certain portion of soils not being cleaned. Most nanotechnology is effective and easy to be applied, allowing remediation to be carried out at the site, without needing to transfer the contaminated soil to other location, saving cost and time for the remediation [2]. This study aims to investigate the efficacy and mechanisms of advanced nanomaterials in the remediation of contaminated soils, specifically targeting heavy metal pollutants and organic contaminants. By exploring the interactions between nanomaterials and soil contaminants at the molecular level, we hypothesize that certain nanotechnologies, such as nano-adsorbents, nano-catalysts, and nano-enabled phytoremediation enhancers, can significantly improve the efficiency of contaminant removal compared to conventional remediation methods. Our review seeks to not only assess the removal efficiency but also to understand the stability, mobility, and potential environmental impact of these nanomaterials within soil matrices, thereby providing a comprehensive evaluation of their applicability and sustainability in real-world soil remediation scenarios.

1.1. Present.

Due to the ever-growing economic situation all over the world, the cases of soil contamination have been showing an increasing trend. As reported in China, the ever-growing industrialization and urbanization led to the high level of soil contamination. The survey performed indicated that 19% of the agricultural soils are already contaminated with heavy metals and metalloids with reference to the China’s soil environmental quality limits. Concentration of some heavy metal contaminants in China soil has been showing significant escalation, mainly due to the increase in usage of the contaminants for the purpose of vegetation and crops cultivation [3]. Globally, soil contamination presents diverse challenges, from heavy metal pollution in China's farmlands and lead contamination in the United States, to the long-term radioactive impact in Chernobyl, electronic waste issues in Ghana, and mercury pollution from gold mining in the Amazon [4]. These examples underscore the urgent need for innovative remediation strategies, such as nanotechnology, to address the complex issue of soil contamination that affects food safety, public health, and environmental sustainability across different regions worldwide.

1.2. Occurrence.

Occurrence of contaminants in soil are obviously due to the constantly growing human population worldwide. As more and more human requires more food supply, agricultural activities plays a vital role in producing the sufficient amount of food supply to meet the human demand. In agricultural sectors, in order to produce higher amount of food products, usage of certain synthetic chemicals for the crops or the vegetation, leads to runoff of the unabsorbed chemicals into the soil, eventually reaching the streams, river or lake. Presence of excess nutrients in the soil are leading to a situation where the soil is being contaminated, reducing the quality of the soil affecting its ability to be used for useful events such as agricultural activities [5]. Besides the nutrients that is being provided to the agricultural land, usage of pesticides and herbicides for the purpose to ensure the growing or plantation of the crops are safe and not disturbed by pest, will also cause contamination in soil. The introduction of different types of pesticides and herbicides onto the soil will have different effect as some will eventually dissociates when reaches the soil while some will persist in the soil environment for a period of time, affecting the soil quality [6].

Livestock activities also plays an important role in the occurrence of soil contamination. Livestock such as cattle rearing in an open land produces high amount of manure that needs to be handled properly. Without proper management of the manure, leaching of nitrate ion and other contaminants into the soil will lead to soil contamination. It has been reported that livestock farming in the USA are producing more concern to the public as the large amount of manure has been showing a negative effect in environmental aspects in terms of soil and water quality at the local region [7]. Heavy metal has been widely used in many countries and inappropriate use of heavy metal also leads to soil contamination. Heavy metals such as Zinc, Copper, Arsenic, Mercury, Cadmium, Chromium, Lead are widely used in the industrial and agricultural activities. According to the article, part of the agricultural land soil in China has been contaminated with heavy metals leading to the reduction of available healthy farmland for agricultural or food production activities [8].

1.3. Environmental fate.

Contaminants present in the soil can be delivered or transported due to different factors, including pH of the soil, clay content and content of organic matter in the soil, and the properties of chemical compound in the soil. Contaminants in soil are mostly initiated from the occurrence of pollution occurring above the soil layer, either through point source or non-point source. Point source pollution can be normally found at places where there are industrial activities that releases the pollutants from their industrial building out to the external environment, forming a targeted pollution at certain point of the soil. However, non-point source pollution is the occurrence of pollution within an area, such as agricultural activities where the contaminants are being released to a wide are of land for the purpose of agricultural usage while those that are not being used by the agricultural crops will diffuse into the soil and will be transferred to the nearby water source [9].

1.5. Major Challenges.

In the field of remediation for contaminated soils, there are several challenges encountered in ensuring that the remediation practice can be totally successful. First of all, the geological conditions of the contaminated land might be a challenge for the remediation to take place. When the contaminated soils are located at a location that is very hard and challenging to approach, remediation work will not be easy to be executed. Geochemical conditions might also be part of the concern as when the land is contaminated with highly acidic or highly alkaline contaminants, human might not be able to approach the contaminated site to study and carry out remediation work. Implementation of nanotechnology, nanomaterials or nanocomposites requires high cost and when the contamination is in a large scale, cost to allow total remediation of the contaminated soil will increase the cost even higher. This will be a problem for the remediation work as when there is not enough funding by the local authorities, the remediation might be halted after the existing funds have been used up. To tackle the geological and geochemical challenges of soil remediation, nanotechnology offers innovative solutions. Enhanced nano-adsorbents like modified nanoclays and carbon nanotubes possess high surface area-to-volume ratios, improving pollutant adsorption in complex soil matrices. Nanoparticle-based remediation, such as zero-valent iron (nZVI), facilitates in-situ treatment by degrading contaminants via redox reactions, particularly effective in low-permeability soils [10]. Nano-enhanced phytoremediation utilizes nanoparticles like titanium dioxide (TiO2) to boost plant growth and enhance pollutant uptake and degradation. Smart nanosensors enable real-time monitoring of soil conditions and contaminant levels, optimizing remediation strategies. Biodegradable nanomaterials stabilize contaminated soils without secondary pollution, immobilizing contaminants while breaking down into harmless substances [11]. These approaches, blending nanotechnology with traditional methods, promise more efficient, sustainable, and cost-effective soil remediation, addressing the complex challenges posed by contaminated sites worldwide.

2. Remediation Technologies

For the remediation of the contaminated soil, researchers have discovered several methods to treat and remove contaminants or pollutants from the soil medium. These techniques involve technologies that is able to remediate the contaminants in different ways, which are physical method, chemical method and biological method. Several types of remediation technology have been shown with the advantages and disadvantages being described.

2.1. Physical remediation.

Physical remediation is a method where contaminants are being treated in their physical states such as liquid, gas and solid. In this remediation method, the contaminants will be transferred from one location to another, which in this case is transferring the contaminants or the pollutants from the soil medium to another location for further treatment.

2.1.1. Thermal Desorption

The physical remediation method for contaminated soil is through thermal desorption. It is being proven to be the most successful method in which this technology is effective in remediating hydrocarbon contaminated soil. The simple method to describe the process in thermal desorption is that the contaminated soils are being exposed to high temperature until the boiling point of the contaminants is achieved, allowing the contaminants to be volatized. Then the contaminants presence in the form of volatile or semi-volatile phases are transferred to the following chamber for off-gas treatment where the vaporized contaminants will either be removed using thermal oxidizer or condensed into liquid form using the vapor recovery unit (VRU) [12]. Adsorption or incineration method can also be applied to treat the vaporized contaminants as the off-gas treatment is to ensure that secondary pollution by the contaminants can be avoided [13]. This thermal desorption technology is added with the nano zerovalent iron (nZVI) for remediation of soil contaminated with the chemical polychlorinated biphenyl (PCB) [14].

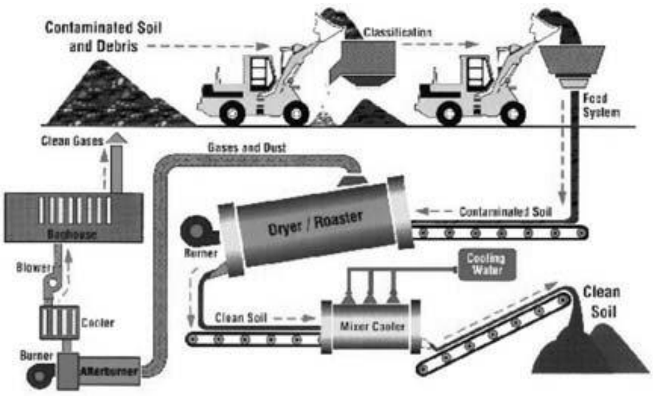

Figure 1. Thermal desorption process for contaminated soil [15].

Figure 1 shows the process of the remediation for the contaminated soil using application of thermal desorption method. The contaminated soil is being transferred from one point to another and involves many stages and requires high amount of energy to operate in remediating the contaminated soil [15]. The advantage of using thermal desorption is that it is very useful in treating different types of contaminants presence in the soil. The treatment process is very short and not time consuming as all process can work in short time frame and having high efficiency in soil remediation in which removal efficiency can reach up to 80% in just 30 minutes. Apart from that this method is quite safe to operate, reduces the chances of secondary pollution and are able to obtain the treated soil and removed contaminants separately. Disadvantage observed in this method is that, it might not be very cost effective as heating up the contaminated soil requires high and constant heat where the heating process will be costly, increasing the operating cost. Acidic or harmful gases such as sulphur dioxide, nitrogen oxides, chlorides or some aromatic organic compounds will be generated, mixing together with the volatile contaminants. To encounter the presence of these acidic or harmful gases, wet scrubber and devices that allows emergency cooling are required to be involved in the process, thus complicates the overall process and system, which requires more techniques in handling the process and requires workers to be knowledgeable in operating these added systems [13].

2.1.2. Electrokinetic.

Electrokinetic remediation method is a technology involves the usage of electrodes to absorb the contaminants that has either positive charge or negative charge in the soil. It is known that electrokinetic technology has the ability to remove heavy metals such as lead, cadmium, mercury and zinc, radioactive substances such as uranium, caesium and strontium, anions such as nitrates and sulphates, and hydrocarbons. For this electrokinetic remediation to function effectively, soil condition is required to be wet as the contaminants requires solvent for transport in the soil medium. When electrodes are inserted into the soil medium, the electric current will create an electrical field, making one electrode to act as a positively charged electrode and another to act as a negatively charged electrode. Contaminants in the soil that present in different charges will move to the respectively electrode and accumulate onto the electrode. Removal of electrode from the soil medium allows the contaminants that is attached on the electrode to be removed together [16].

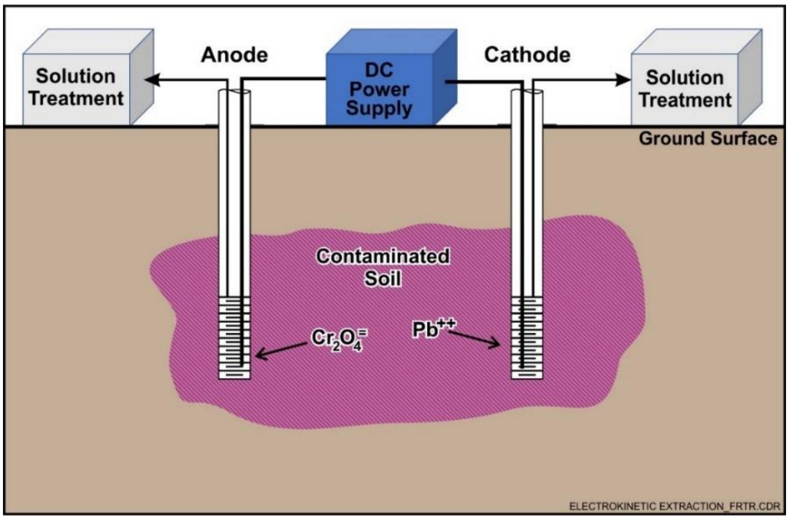

Figure 2. Electrokinetic process for in situ contaminated soil remediation [17].

Figure 2 shows the installation of the electrodes into the soil medium for the electrokinetic process to occur. When the electricity is applied, one end of the electrode will turn to anode and the other will turn to cathode, placed in between the contaminated soil. Advantage of using electrokinetic method to remediate contaminate soil is its capability to remove many types of contaminants from the soil by just applying electric current and this method can also be applied in clay medium [17]. This remediation method can be performed at the site, making the remediation cost to be lower. However, the disadvantage of this remediation method is very time consuming as this process applies the same concept as electrolysis. Apart from that, metal objects that were already present in the site might interrupt the performance of this electrokinetic remediation as current flow might be disturbed. Another disadvantage is that targeted contaminants might not be able to be effectively removed when its' concentration is very low compared to other ions that are not part of the targeted contaminants that are required to be removed. This happens when electric field attracts the higher concentration ions in the soil medium rather than only the targeted ions, resulting in low concentration of the targeted contaminants being removed [18].

2.1.3. Nanoscale zero-valent iron particles.

Another nanotechnology that can be used to remediate contaminated soil is by injecting the nanoscale zero-valent iron particles (NIP) into the contaminated area. When the NIP is injected into the soil medium, the contaminants compound will transfer towards the iron and get adsorbed onto the iron surface. Halogenation occurs in the form of reduction on the surface of the iron and the reduced products will be desorbed. These desorbed products will then be transferred to the bulk solution [19].

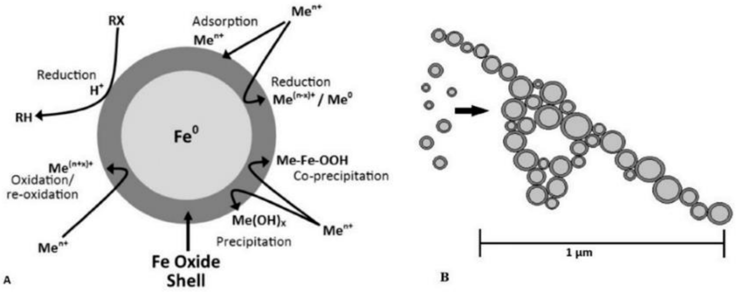

Figure 3. Nanoscale zero-valent iron particles in soil remediation [2].

Figure 3 shows the mechanism of the iron particles to adsorb the contaminants in the soil. This nanotechnology is more efficient towards soil that is contaminated with metal contaminants due to its attractive forces between nanoscale zero-valent iron particles and the metal contaminants present in the soil medium [2]. Advantage of using this nanoscale zero-valent iron particles is that it has high reactivity for the decontamination process to occur as it exists in very small size, allowing this material to be used for in-situ remediation. However, this technology also has some disadvantages which are its aggregation speed and the settling characteristics of the nanoscale materials when it is being used for contamination remediation purpose. Aggregation occurs when the iron particles move closer to each other and starts forming chains due to the effect of dominant magnetic attractive forces. These attractive forces will increase the overall size of the materials to become microsize iron particles [20]. This will affect the efficiency of the decontamination process due to reduce in total surface area of reaction. When aggregation occurs, settling effect will occur due to increase in overall weight of the iron particles, affecting the effectiveness in remediating the portion of contaminated soil [19].

2.2. Chemical remediation.

Chemical remediation technologies involve the treatment or removal of contaminants or pollutants from the soil medium through addition of chemical compound. Addition of chemical compound into the soil medium allow the level of toxicity of the contaminants or the pollutants to be altered by the characteristics of the chemical compound present in the soil medium. This allows the toxicity of the contaminants to be reduced so the contaminants will not cause adverse impact to the local environment.

2.2.1. Immobilization.

Immobilization is a technology that reduces the concentration of the existing dissolved pollutants or contaminants in the soil by increasing sorption effect or promotes precipitation so as to reduce the solubility of the pollutants in reducing the chances of pollutant transport in the soil medium [21]. Implication of nanomaterials in the treatment process to remediate the polluted soil is another method that can be carried out. Nanomaterials additives including carbon type nanomaterials, metal oxides nanomaterials and nanocomposites have been known to be used extensively in immobilization of inorganic and organic pollutants present in the soil medium [22]. However, selection of the nanomaterials that will be employed in remediation of contaminated soils greatly depends on the properties of the contaminants as well as the condition of the soil medium. Carbon type nanomaterials allows the organic contaminants to be absorbed by the Van der Waals forces and also the interactions that will happen between the π and π bond. One of the carbon nanomaterials that are providing high efficiency in the adsorption effect of the contaminants in soil is the carbon nanotubes due to its high adsorption ability [9]. Application of these nanomaterials can then remove the contaminants from the soil medium. Usage of nanomaterials for chemical immobilization to remediate contaminated soil will promote the growth of some vegetation planted in the soil. This is because nutrients and pesticides that are being exposed into the soil are being immobilized by the carbon nanotubes technology, where it can enrich the vegetation when these nutrients are being transported to the roots and leaves of the planted vegetation. The disadvantage of nanomaterials being used for soil remediation is the potential harmful effects onto the terrestrial organisms living in that area and also the soil ecosystem. Some of the carbon nanomaterials were observed to be having high concentration present in the plant cell due to translocation and uptake process by the plants. Intake of these toxicated plants or vegetations will lead to toxication in human body, adversely affecting human health. Besides that, nanomaterials being present in very small size will leads to an increase of soil porosity, therefore increase interactions between organic matters and soil particles [9].

2.3. Biological remediation.

Apart from physical and chemical remediation method for soil contamination, biological remediation is also effective in treating contaminated soil. Implementation of biological remediation is the use of microorganisms or certain plants species targeting to reduce or remove the toxic contaminants from the soil medium. This type of remediation method is a greener method to remediate contaminated soil as the process occurs naturally and rarely produces secondary waste or products that are hazardous or toxic to the environment [23].

2.3.1. Phytotechnologies.

Phytotechnologies being another effective method to remediate contaminated soils is being known to be using vegetation to remediate the contaminants present in the soil [24]. Phytoremediation is the use of green plants or crops to remediate contaminants present in soil. Plant or crops is very effective in the removal of toxic metals from contaminated soil as well as volatile organic contaminants. This is a technology that allows remediation process to be carried out in-situ without the need of transferring the contaminated soil to other location for further remediation process [25]. Advantage of using phytotechnology in soil remediation is its low capital costs as cultivation of crops and vegetation requires less external energy and water to allow the remediation process to occur. Other than that, the community living in the nearby area are more likely to accept the implementation of phytotechnological method in soil remediation as it promotes and improve ecosystem of the environment, benefiting public health and social welfare when the vegetation is being planted. Creating open space with green vegetation allows community to have stress relief effect. Plantation of crops can also improve the air quality in the surrounding area, with greater effect when phytotechnologies are implemented in urban areas. Disadvantage of this technology is that when vegetation cultivated at the contaminated soil is for the food intake purposes, the food supply might not be safe for human consumption. This is because contaminants presence in the soil might differs in many types and kinds, leads to the result that contaminants that are harmful to human might be uptaken by the plant [26]. Phytotechnology requires longer time for the remediation of contaminants in soil and the results might not be very uniform due to the soil characteristics [25]. Phytoremediation typically takes months to years due to plant growth cycles and gradual contaminant uptake. To optimize this process, selecting hyperaccumulator plants, enhancing plant-microbe interactions, and employing genetic engineering can expedite contaminant removal. Soil amendments like organic matter and coupling phytoremediation with other techniques such as soil washing can further accelerate the remediation process. These strategies ensure faster and more efficient soil cleanup without compromising effectiveness, making phytoremediation a sustainable solution for environmental restoration [27].

2.3.2. Phytoextraction.

Implementation of phytoextraction technology is the use of plantation or vegetation as the remediation tools in managing the contaminants in the soil. Plants or vegetation is being planted on the soil that is contaminated with certain types of metal contaminants. The contaminants that are primarily being removed or absorbed by plants are metal contaminants. When the plants mature and are ready for harvesting, removal of plants or vegetation from the contaminated soil will at the same time remove the absorbed metal contaminants from the soil. Plants are capable of absorb high amount of certain metal such as copper, cobalt, iron, manganese, nickel and zinc, which is the minerals essential for the plant growth. This remediation technique has been discovered when plants are able to accumulate incredibly high amounts of metal from the soil, making plants being the effective method in remediation of contaminated soil [28]. Advantage of phytoextraction is the ability of the plants in removing many different types of metal contaminants from the soil as shown in the figure above. The metals are uptaken by the plant and stored inside the body of the plants. This method is also cost effective as not much energy and water is required for the remediation process to take place. When the plant or vegetation is harvested from the contaminated soil, these products are incinerated or composted to obtain the metals present inside the plant, as to recycle the metal for other purposes [25]. Disadvantage of this method is that the process takes up longer period as metal intake by plant roots is a slow process. Other than that, some of the metal uptake effectiveness, such as cadmium and lead is not known, resulting in remediation of soil contaminated with these two metal to be less effective [28]. When the plants are incinerated for the purpose of obtaining its metal, the ash produced will be the waste that will need to be disposed in hazardous waste landfill, increasing the volume of waste to the landfill as well as leading to secondary pollution [25].

2.3.3. Nanobioremediation.

Nano-enhanced bioremediation has been showing good effects in the path of remediating contaminated soil. This type of nano-bioremediation technology is the integration of both nano-sized materials with the microorganisms to act as a biodegradation approach in the field of remediation work [29]. Application of both nanotechnology and bioremediation in providing remediation for contaminated soils occurs in nanoscale process. When the nanoparticles are added into the soil, adsorption followed by degradation or modification process occurs to the contaminants in the soil. The nanoparticles are able to act as a catalyst in reducing the activation energy that is needed to dissociate the contaminants [30]. Studies identified that nanoparticles or nanomaterials being used in the remediation of environmental contamination such as soil contamination is effective due to its ability to reach to zones that are contaminated where these zones are normally unreachable by microparticles. Besides, nanoparticles or nanomaterials have higher reactivity for redox reaction to occur when reacted with contaminants [31]. Disadvantage of nanobioremediation is that the usage of nanoparticles or nanomaterials can penetrate through the leaves and roots of the plant or vegetation, altering the morphogenic capabilities of the plant species, which can possibly lead to adverse health effects to the plant health. Toxicity of nanoparticles being applied to the soil for contamination remediation might mostly due to the production of reactive oxygen species (ROS) that can interrupt the electron mobility inside the mitochondria and chloroplasts of the plant cells, which might affects the growth of the plants or vegetation, indirectly affects human health [32]. Research into nanobioremediation's health effects on plants has led to safety measures ensuring its overall safety. Studies examine nanoparticle uptake, translocation, and impacts on plant growth and function. Safety measures include developing biocompatible nanoparticles and optimizing size and concentration to enhance uptake efficiency while minimizing harm. Rigorous monitoring and risk assessments track nanoparticles in the environment and assess their impact on ecosystems [33]. These efforts ensure nanobioremediation remains a safe and effective environmental cleanup method, mitigating potential adverse effects on plant species and surrounding ecosystems [34].

2. Challenges for Future Research

The main challenge that will be encountered when applying nanotechnology for contaminated soil remediation is the negative effect of the nanoparticles on the microbes in the soil. This is because some of the nanoparticles that are being used for remediation for the soil is toxic to the microorganisms and hinder the activities of enzyme in the soil. Even though researchers have been performed to lower the level of toxicity of nanomaterials onto the soil organisms, different results were obtained from different studies, which requires extensive experiment to be performed in order to effectively lower down the toxicity of nanomaterials against soil organisms [9].

There is also cases being reported that usage of nanoparticles in remediation of contaminated soil will lead to an increase in the dispersion of the polycyclic aromatic hydrocarbon (PAH) in the soil. This shows that some of the nanoparticles or nanotechnologies that are implemented into the soil remediation work still requires further research and studies. There is also some challenges that involves the human and environmental risk-benefit balance, which is the proper use of the nanotechnologies for the remediation of contaminated soil. Different type of nanotechnologies might involve the problem that benefits of environment will be beyond the benefits of human as it might lead to adverse impact on human health. Thus, further research and studies are required to analyze the effectiveness in soil remediation as well as ensuring benefits of human are secured [35].

To the community, the future for the remediation of contaminated soil allows more land to be available as less land is available for construction and development as well as agricultural use. When better nanotechnology can be used in soil remediation, contaminants present in the soil will bring little to no harm to the people that are present on top of the previously contaminated soil. This is to ensure that with the increase in human population, contaminated soil will not be a problem to stop human from exploring more habitable land [36].

3. Conclusion

Soil contamination has been greatly affecting the soil environment which can indirectly affects the benefits of human including human health. When nanotechnology or nanomaterials have been effectively researched and applied into the field of remediation for soil contamination, it is trusted that contaminants can be effectively managed. Apart from physical, chemical, or biological remediation technologies, scientists and researchers are urged to discover and identify more and different ways to effectively remove the contamination in the soil. Nanotechnology will surely be the future in soil remediation as the nano size allows process to occur to the very small detail part, ensuring that remediation can happen effectively.

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Competing Interest

All authors have no competing interest to declare.

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