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Review Article

Exploring the Potential of Nanophytoremediation for Mitigating Environmental Pollution

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Abstract

Environmental pollution is an ongoing issue resulting from human activities, leading to the continuous exposure of the environment to harmful substances. Various remediation methods, such as heat treatment, oxidation, and ion exchange, have been developed to address this problem. Among these methods, phytoremediation has emerged as an environmentally friendly approach that utilizes plants to efficiently degrade, stabilize, or accumulate both organic and inorganic pollutants. In recent years, there has been a focus on enhancing the effectiveness of phytoremediation through the application of nanotechnology, termed nanophytoremediation. This research explores the mechanisms underlying nanophytoremediation, the types of contaminants that can be targeted using this approach, the plant species commonly employed, and the factors influencing its efficiency. Additionally, the advantages of phytoremediation over traditional treatment methods are discussed, along with the limitations associated with nanophytoremediation. The paper also presents case studies that demonstrate successful implementation of nanophytoremediation. Finally, future prospects for the field of nanophytoremediation are considered, and a comprehensive discussion and conclusion are provided.

1. Introduction to Nanophytoremediation

Nanophytoremediation is a process that uses plants to clean pollution in soil, water and air. It is a green solution to environmental problems, because it is a non-invasive and cost-effective approach [1]. Nanophytoremediation is gaining popularity among the scientific and environmental community as it has proven to be an effective method for remediating contaminated sites [2]. This process involves the absorption, degradation, and removal of pollutants from the environment by plants. It has the ability to treat a wide range of pollutants such as heavy metals, pesticides and organic compounds [3]. Types of Nanophytoremediation, there are different types of Nanophytoremediation techniques, including phytoextraction, phytostabilization, phytodeganation and rhizobial filtration [4]. Each technology has its own advantages and limitations, and choosing the appropriate technology depends on the type and extent of contamination [5]. Advantages of Nanophytoremediation: Nanophytoremediation is a sustainable and environmentally friendly approach that has many benefits. It is a low-cost

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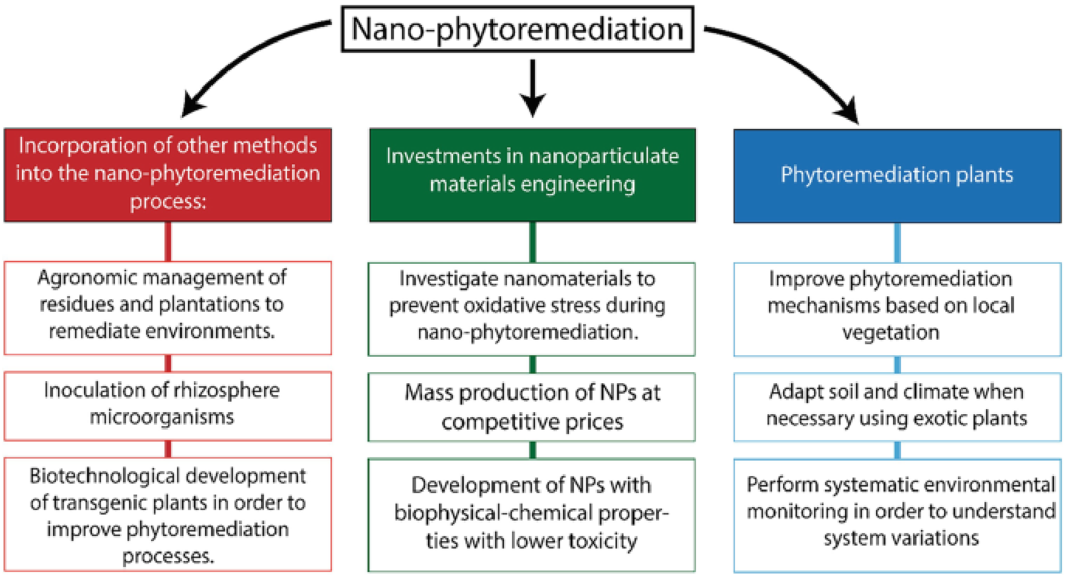
method that does not require excavation or disposal of contaminated material, making it an attractive alternative to traditional treatment methods [6]. In addition, using plants in Nanophytoremediation can improve soil quality and biodiversity, thus promoting a healthy ecosystem [7]. Selection of plants for Nanophytoremediation is a crucial step in this process.

Plants that tolerate pollutants and have a high accumulation capacity are preferred [8]. Some examples of plants commonly used in Nanophytoremediation include sunflower, willow, hops, and Indian mustard [9]. Limitations of Nanophytoremediation, while Nanophytoremediation has many advantages, it also has its limitations [10]. The process can be slow and may take several years to achieve significant results. It may also be limited by the availability of suitable plant species and their ability to survive in the polluted environment [11]. There have been many successful cases of Nanophytoremediation around the world. An example is the use of Indian mustard to remove cadmium from contaminated soil in China [12]. Another example is the use of sunflowers to clean up radioactive soil in Ukraine after the Chernobyl disaster [13].

Flow Chart: 1



Source: https://doi.org/10.1016/J.SCITOTENV.2019.05.424

Types of contaminants that can be removed using Nanophytoremediation:

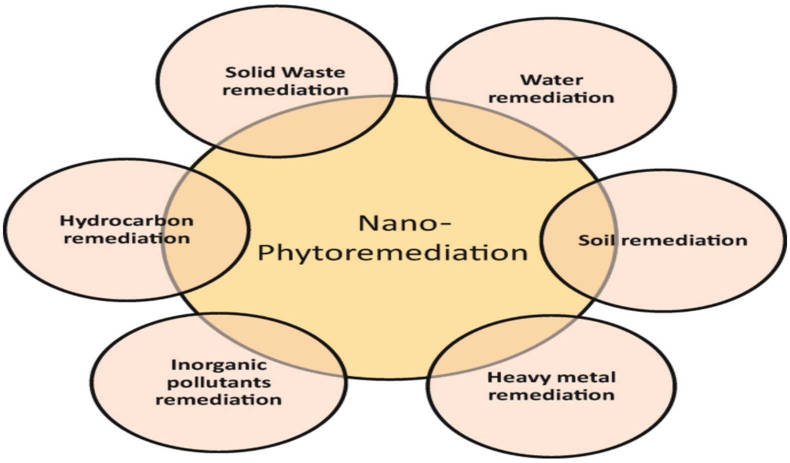
Nanophytoremediation is a promising solution to environmental pollution that has gained popularity in recent years [14]. Thanks to its many advantages and successful case studies, it has proven to be an effective and sustainable way to remediate contaminated sites [15]. Nanophytoremediation is an environmentally friendly and cost-effective way to clean contaminated soil, water and air [16]. It is a process that uses plants and associated microorganisms to remove, degrade or immobilize pollutants from the environment [17]. Different types of pollutants can be removed by plant minerals, including heavy metals, organic compounds, and radioactive materials [18]. The effectiveness of Nanophytoremediation depends on various factors such as plant species, soil conditions, pollutant concentration and climate [19]. This section will discuss the different types of pollutants that can be removed using Nanophytoremediation [20].

❖ Heavy metals such as lead, cadmium, mercury and arsenic are toxic pollutants that can accumulate in the environment and pose a threat to human health [21]. Plant standards can remove heavy metals from contaminated soil and water using plants that have the ability to absorb these metals, detoxify them, and store them in their tissues [22]. For example, Indian mustard (Brassica juncea) is a plant that can accumulate high levels of heavy metals in its tissues and can be used to remediate contaminated soil [23].

❖ Organic compounds such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides are common pollutants that can contaminate soil and water [24]. Plant standards can degrade organic compounds through various mechanisms such as phytolysis, decomposition, and phytovization [25]. For example, hybrid scale trees (Populus spp.) have been used to remediate sites contaminated with chlorinated solvents and petroleum hydrocarbons [26].

❖ Radioactive materials: Radioactive materials such as uranium, cesium, and strontium can contaminate soil and water through nuclear accidents or nuclear waste disposal [27]. Nanophytoremediation can remove radioactive materials through a process called phytosequestration, which involves absorbing and storing these materials in plant tissue [28]. For example, sunflowers (Helianthus annuus) were used to remove radioactive cesium from contaminated soil in Fukushima, Japan after the 2011 nuclear disaster [29].

Flow Chart: 2



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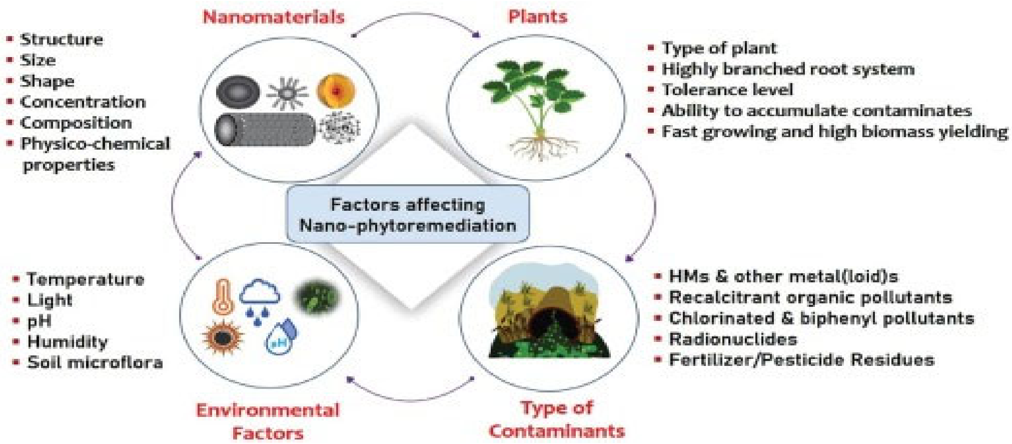
Nanophytoremediation is a versatile and sustainable method for cleaning up polluted environments [30]. Different types of pollutants can be removed through Nanophytoremediation, and the choice of plant species depends on the nature and concentration of the pollutants [31]. Nanophytoremediation has the potential to provide green solutions to pollution problems and contribute to a healthier and cleaner environment [32].

Plants used in Nanophytoremediation:

Nanophytoremediation is a green solution to pollution that uses plants to remove or neutralize pollutants from the environment [33]. Plants have a unique ability to absorb and break down pollutants through natural metabolic processes [34]. This process is not only environmentally friendly, but also cost-effective compared to traditional methods of treating pollution [35]. Nanophytoremediation is gaining popularity around the world as a sustainable solution to pollution, and its use is expanding into various fields, including agriculture, mining and industrial waste management [36]. In Nanophytoremediation, plants can be classified based on their ability to remove specific pollutants from the environment [37]. Here are some plants used in Nanophytoremediation:

- Sunflowers are known for their ability to remove heavy metals from contaminated soil [38]. Sunflower roots can absorb and store heavy metals such as lead, arsenic and cadmium [39]. After harvesting plants, heavy metals can be extracted from plant biomass and safely disposed of [40].
- Willow is commonly used to absorb organic pollutants such as petroleum and other hydrocarbons [41]. Willow tree roots contain microbes that break down these pollutants into harmless compounds [42]. This process is known as phytolysis [44].
- Indian mustard is used to remove heavy metals such as lead, cadmium and zinc from contaminated soil [45]. The plant absorbs heavy metals through its roots and stores them in the leaves and stems [46]. Contaminated plant parts can then be harvested and disposed of safely [47].
- Ferns are known for their ability to absorb arsenic and remove it from contaminated soil [48]. Ferns can accumulate large amounts of arsenic in their fronds, which can then be safely removed and disposed of [49].
- Water hyacinth is used to remove contaminants such as heavy metals, organic compounds and nutrients from contaminated water [50]. The plant absorbs pollutants through its roots and stores them in its leaves and stem [51]. Contaminated plant parts can then be harvested and disposed of safely [52].

Flow Chart 3:



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Nanophytoremediation is a promising and sustainable solution to remediate pollution [53]. By using plants to remove pollutants from the environment, we can reduce reliance on traditional, expensive and often harmful remediation methods [54]. The use of plants in Nanophytoremediation is expanding, and more research is being conducted to identify new plant species with unique abilities to remove pollutants from the environment [55].

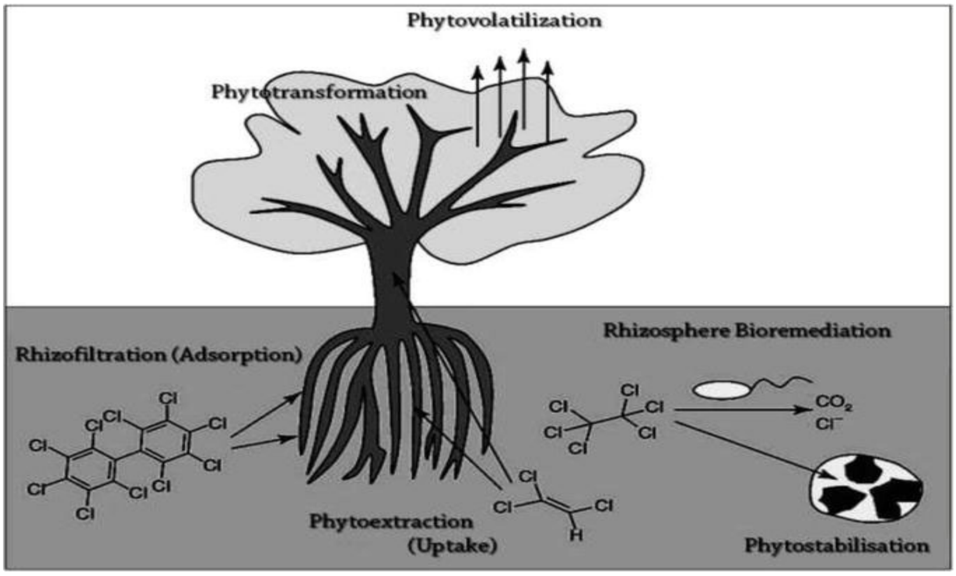
Nanophytoremediation mechanism:

Nanophytoremediation has emerged as a promising green solution to combat pollution [56]. It is an environmentally friendly and cost-effective technology that uses plants to remove, degrade or immobilize pollutants from soil, water and air [57]. The mechanism of Nanophytoremediation involves uptake of pollutants by plant roots, translocation to above parts, and transformation or degradation by plant-associated microbes [58]. The efficiency of Nanophytoremediation depends on various factors such as plant species, type of pollutants, concentration and environmental conditions [59]. Different types of Nanophytoremediation technologies have been developed to target specific contaminants and environmental conditions [60, 61]. Here are some insights into the mechanism of Nanophytoremediation:

- ***Phytoextraction:*** This technique involves the absorption and accumulation of pollutants in the above parts of plants, which are harvested and then disposed of [62]. It is effective for removing minerals and minerals such as arsenic, cadmium, lead, and mercury [63]. For example, Indian mustard (Brassica juncea) has been used to extract lead and zinc from contaminated soil [64].
- ***Phytostabilization:*** This technique involves freezing pollutants in the soil by plant roots and associated microbes [65]. It is effective for stabilizing minerals and minerals such as arsenic, chromium and lead [66]. For example, hybrid Poplar (Populus spp.) have been used to stabilize arsenic in mine tailings [67].
- ***Rhizobial degradation:*** This technique involves the degradation of pollutants in soil by plant-associated microbes stimulated by root exudates [68]. It is effective in decomposing organic pollutants such as polycyclic aromatic hydrocarbons (PAHS) and petroleum hydrocarbons [69]. For example, Switchgrass (panicum virgatum) has been used to reduce PAHs in contaminated soil [70].
- ***Phytovolatization:*** This technique involves the absorption and release of pollutants into the air by plant leaves [71]. It is effective for removing volatile organic compounds (VOCs) such as benzene, toluene and xylene [72]. For example, hybrid Poplar (Populus spp.) have been used to remove trichlorethylene (TCE) from contaminated groundwater [73].

Nanophytoremediation is a promising green pollution control technology that involves the absorption, transformation and removal of pollutants by plants and their associated microbes [74]. Different types of Nanophytoremediation technologies have been developed to target specific contaminants and environmental conditions [75]. The efficiency of Nanophytoremediation depends on various factors such as plant species, type of pollutants, concentration and environmental conditions [76]. Therefore, Nanophytoremediation can be tailored to specific pollution problems and can provide a sustainable and cost-effective solution for environmental remediation [77].

Flow Chart 4:



Source: https://www.intechopen.com/chapters/73169

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Factors affecting the efficiency of Nanophytoremediation: Nanophytoremediation is a promising, environmentally friendly technology that uses plants to remove pollutants from soil, water and air [78]. However, the efficiency of Nanophytoremediation depends mainly on several factors that affect the ability of plants to absorb pollutants and remove toxins [79]. Understanding these factors is crucial to improving Nanophytoremediation and enhancing its effectiveness in cleaning up contaminated sites [80]. From plant selection to environmental conditions, the following factors play an important role in the efficiency of plant treatment:

• ***Plant species:*** Choosing the appropriate plant species is essential for the success of Nanophytoremediation [81]. Some plants are better suited to removing some pollutants than others, depending on their ability to tolerate and accumulate toxins [82]. For example, Indian mustard (Brassica juncea) is a heavy metal scavenger, while sunflower (Helianthus annuus) is effective in removing organic pollutants such as petroleum hydrocarbons [83].
• ***Soil properties:*** Soil properties such as pH, texture, and organic matter content can greatly affect the efficiency of Nanophytoremediation [84]. Plants thrive in specific soil conditions, and the presence of pollutants can change these conditions, making it difficult for plants to grow and absorb pollutants [85]. For example, low pH can reduce the availability of essential nutrients, limit plant growth and reduce their ability to detoxify pollutants [86].
• ***Concentration of pollutants:*** The concentration and type of pollutants present in soil or water can affect the efficiency of Nanophytoremediation [87]. High concentrations of pollutants can be toxic to plants, reducing their growth and ability to absorb pollutants [88]. Furthermore, some pollutants are more toxic than others, making it difficult for plants to detoxify them [89].
• ***Environmental conditions:*** Environmental conditions such as temperature, humidity, and light can also affect the efficiency of Nanophytoremediation [90]. Plants require optimal growing conditions to thrive and remove pollutants effectively [91]. For example, plants may need supplemental water in arid regions to maintain their growth and absorb pollutants [92].
• ***Duration of Nanophytoremediation:*** The time required for Nanophytoremediation depends on the type and concentration of pollutants, as well as the plant species used [93]. Nanophytoremediation is a slow process that requires patience and long-term monitoring to achieve the desired results [94]. However, it is a cost-effective and sustainable technology that can provide long-term benefits [95].

The efficiency of Nanophytoremediation is affected by various factors that must be considered when planning and implementing Nanophytoremediation projects [96]. Selection of appropriate plant species, soil management, pollutant concentration, environmental conditions, and duration of Nanophytoremediation are all critical factors that can affect the success of this green solution to pollution [97].

Advantages of phytotherapy over traditional treatment methods: Nanophytoremediation is a green and sustainable solution to clean up polluted environments [98]. Compared to traditional remediation methods, Nanophytoremediation has many advantages that make it a preferred choice for many environmental remediation projects, in this section, we will discuss the advantages of Nanophytoremediation over traditional treatment methods [99].

• ***Cost-effective:*** Nanophytoremediation is a cost-effective solution to clean up polluted environments [100]. Unlike traditional methods, which require heavy machinery and equipment, Nanophytoremediation uses plants to remove pollutants from soil and water [101]. This makes it a more affordable option for many environmental projects [102].
• ***Sustainable:*** Nanophytoremediation is a sustainable solution that does not require the use of harsh chemicals or other pollutants [103]. Instead, it uses natural processes to remove pollutants from the environment [104]. This makes it a more environmentally friendly option than traditional treatment methods [105].
• ***Versatile:*** Nanophytoremediation can be used to clean up a wide range of contaminants, including heavy metals, organic compounds and pesticides [106]. Different types of plants can be used to target specific contaminants, making it a versatile solution for environmental remediation projects [107].
• ***Long-term benefits:*** Nanophytoremediation provides long-term benefits to the environment [108]. Once plants are cleared of pollutants, they continue to provide other ecosystem services, such as improving soil quality, providing habitat for wildlife, and reducing erosion [109].
• ***Community engagement:*** Nanophytoremediation can also involve the community in environmental restoration efforts [110]. Planting and maintaining plants can involve local residents, schools and community organizations, creating a sense of ownership and participation in the restoration process [111].

Overall, Nanophytoremediation is a promising solution for cleaning up polluted environments [112]. It provides a cost-effective, sustainable, versatile and long-term solution that provides benefits beyond simply removing contaminants [113]. With increasing awareness of the importance of environmental sustainability, Nanophytoremediation is likely to become a preferred solution for ecological restoration projects [114].

Nanophytoremediation restrictions:
Nanophytoremediation is a promising eco-friendly technology that uses plants to clean environmental pollution [115]. It is considered a low-cost and sustainable approach compared to other traditional methods of removing pollutants [116]. However, like any other technology, Nanophytoremediation also has its limitations and cannot be considered a silver bullet solution for all types of pollutants [117]. There are many factors that can affect the effectiveness of Nanophytoremediation, such as plant species, type of contaminants, soil conditions, and climate [118]. In this section, we will discuss the limitations of

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Nanophytoremediation from different perspectives and highlight some of the challenges that need to be addressed to make this technology more effective [119].

• ***Slow process:*** Nanophytoremediation is a slow process, and it may take several years to achieve the desired level of treatment [120]. This is because plants need time to grow and establish themselves before they begin removing pollutants from the soil [121]. Furthermore, the rate of pollutant removal depends on the growth rate of plants, which can vary depending on species and environmental conditions [121]. Therefore, Nanophytoremediation may not be suitable for sites that require rapid remediation [122].

• ***Limited plant species:*** Another limitation of Nanophytoremediation is the limited number of plant species that are effective in removing specific contaminants [123]. For example, some plants are better at removing heavy metals, while others are better at removing organic pollutants [124]. Therefore, selecting the appropriate plant species is crucial to the success of Nanophytoremediation [125]. In some cases, genetic engineering techniques are used to enhance the ability of plants to remove pollutants [126].

• ***Soil conditions:*** The effectiveness of Nanophytoremediation also depends on soil conditions [127]. Plants require specific soil conditions to grow and thrive, and if the soil is polluted or lacks essential nutrients, it can limit plant growth [128]. Therefore, soil preparation is critical to ensure that plants have the necessary conditions to grow and remove contaminants effectively [128].

• ***Climate:*** Climate is another factor that can affect the effectiveness of Nanophytoremediation [129]. Different plant species have different temperature and humidity requirements, and if the climate is not suitable, it may limit the growth of plants [130]. Furthermore, extreme weather events such as floods and droughts can have a negative impact on Nanophytoremediation [131]

Nanophytoremediation is a promising technology with many benefits, but it also has its limitations and the effectiveness of Nanophytoremediation depends on several factors, such as plant species, type of contaminants, soil conditions, and climate [132]. Therefore, it is necessary to carefully consider these factors before implementing Nanophytoremediation as a treatment method [133].

Case studies of successful implementation of botany: Nanophytoremediation has gained attention as a green solution to pollution. It is a process that uses plants to remove pollutants from soil, air and water [134]. There are many case studies showcasing the successful implementation of Nanophytoremediation [135]. These case studies provide insights from different perspectives, including environmentalists, scientists, and policy makers [136]. It highlights the effectiveness of Nanophytoremediation in cleaning up contaminated sites and reducing the environmental impact of pollution [137]. Here are some examples of successful implementation of Nanophytoremediation:

• In 1999, New York City implemented Nanophytoremediation to clean up a petroleum-contaminated site [138]. The city planted sunflowers, which were able to absorb petroleum from the soil. The sunflowers were then harvested and disposed of safely, effectively removing contaminants from the site [139].

• In China, Nanophytoremediation has been used to clean soil contaminated with heavy metals [140]. Researchers have found that some plants, such as Indian mustard and sunflower, are able to absorb and store heavy metals in their tissues [141]. These plants can then be harvested and disposed of safely, removing contaminants from the soil [142].

• In 2014, a study was conducted in Australia to test the effectiveness of Nanophytoremediation in cleaning up contaminated groundwater [143]. The researchers planted trees and shrubs around the contaminated site, which were able to absorb and break down the pollutants [144]. The study found that Nanophytoremediation was effective in reducing contaminant levels in groundwater [145].

• In the United States, Nanophytoremediation has been used to clean up sites contaminated with hazardous waste [146]. The Environmental Protection Agency (EPA) has identified several plants that are effective at removing pollutants from soil, including poplars and willows [147].

Overall, these case studies demonstrate the effectiveness of plant remediation in cleaning up contaminated sites and reducing the environmental impact of pollution [148]. They provide valuable insights into the potential of Nanophytoremediation as a green solution to pollution [149].

Future prospects for botany: As plant standards continue to gain momentum as a green solution to pollution, its future prospects look promising [150]. Thanks to its cost-effectiveness, low maintenance, and environmentally friendly nature, it is an attractive alternative to traditional treatment methods [151]. The future of Nanophytoremediation lies in its ability to solve complex environmental problems [152]. One of their biggest advantages is that they can be customized to treat specific contaminants and can be used in a variety of settings, from industrial sites to residential areas [153]. Some future prospects of Nanophytoremediation are as follows:

• Advances in genetic engineering could lead to the development of plants that can remove a wide range of pollutants and can do so more efficiently [154]. For example, scientists are exploring the use of genetically modified plants that can break down toxic chemicals such as TNT, a common ingredient in explosives [155].

• Using Nanophytoremediation in combination with other green technologies can enhance its effectiveness [156]. For example, scientists are exploring the use of Nanophytoremediation in conjunction with nanotechnology to create hybrid systems that can remove pollutants more efficiently [157].

• The development of Nanophytoremediation techniques that can be used in a wider range of environmental conditions can increase their applicability [158]. For example, researchers are exploring the use of Nanophytoremediation in arid regions where water is scarce [159].

- The use of Nanophytoremediation in urban areas can help improve the quality of life for residents [160]. For example, using plants to remove pollutants from the air can help reduce the incidence of respiratory diseases [161].
- The use of Nanophytoremediation can have economic benefits [162]. For example, using plants to remove pollutants can help reduce the cost of traditional treatment methods, which can be expensive and time-consuming [163].

The future outlook for Nanophytoremediation is promising [164]. With advances in genetic engineering, the use of Nanophytoremediation in combination with other green technologies, and its potential applicability in a wide range of environmental conditions, Nanophytoremediation is poised to become a major player in the fight against pollution [165].

2. Discussion and Conclusion

Successful application of Nanophytoremediation requires careful selection of plant species to remove heavy metals, break down organic compounds, and clean contaminated soil [166]. In recent years, researchers have conducted extensive studies to adapt some plant species to grow in soil contaminated with heavy metals such as lead, nickel, zinc and copper, and organic pollutants such as TNT and trichloroethylene (TCE).

Most Nanophytoremediation research focused on cleaning up sites contaminated with one type of pollutant [167]. For example, the Indian mustard plant Brassica Juncea was used to extract lead from contaminated soil, and poplar trees were used to withdraw and digest organic pollutants and some heavy metals and In a study conducted by researchers from the University of Washington; It has been shown that the organic solvent trichlorethylene (TCE) (a cleaner used to remove oils and grease from metals and causes damage to the nervous system and damage to the kidneys and liver) can be treated by Trichocarpa Deltoides hybrid poplar trees [168]. In other studies, this plant species was used to remove heavy metals and nitrates from soil and groundwater, respectively [169]. In Sweden, poplar and willow trees have been used as biofilters to remove cadmium from sewage sludge (sludge resulting from the biological treatment of wastewater), in order to produce biomass that is later converted into energy [170].

The peace lily (Sphathiphyllum) plant has also been used as an air cleaner, removing formaldehyde, benzene (two carcinogenic pollutants found in gas and oil), and trichlorethylene from polluted air [171]. Researchers at Savannah University are working on developing a plant treatment technology capable of dealing with sites contaminated with different types of waste [172]. It is expected that poplar trees will constitute an ideal treatment for such sites due to their rapid growth, deep roots, abundance of microorganisms associated with their roots, and most importantly, their ability to adapt [173].

Other important applications in this field include [174]. Using poplar trees through enzymes found in their roots to change the chemical composition of PCBs, which are a group of permanent pollutants that vary in their properties and toxicity, and are receiving increasing global attention due to their danger, as they cause cancer and damage to the nervous system in living organisms [175]. Although these compounds have not been produced for more than 30 years, they are still present in the environment due to their ability to resist decomposition and disintegration, and have led to the contamination of several sites of soil and water in large parts of the United States of America, such as the Hudson River [176]. US EPA reports show more than 300 sites contaminated with PCBs are at the top of the Site Cleanup Support Fund list [177].

Currently, a joint team from the Chinese Academy of Sciences and the University of Iowa is studying the ability of poplar trees to modify the chemical composition of PCBs and transform them into compounds that are less harmful to humans and the environment [178]. In other studies, clover plants and juniper trees were used to remove petroleum and hydrocarbon materials from the soil and groundwater [179]. Successful experiments were also conducted on parrot feather plants and algae to get rid of ammunition and explosive waste [180]. The International Atomic Energy Agency conducted an assessment of the health and radiation status of the area surrounding the Chernobyl reactor in Ukraine, and the results indicated that emissions of radioactive materials and heavy metals, including iodine, cesium, strontium, and plutonium, are still concentrated in soil, water, plants, and animals, despite the passage of years [181].

Chernobyl reactor explosion accident (1986). Some wild plants such as cranberries and mushrooms showed high levels of cesium, and the Canadian Nuclear Association noted a marked increase in thyroid cases in areas surrounding the nuclear accident [182]. These radioactive materials enter the food chain through grazing sheep and cows that feed on plants grown in contaminated soil, after which the toxins are concentrated in meat and dairy products consumed by humans. Recently, a company developed genetically modified strains of sunflower plants capable of removing 95% of radioactive pollutants in less than 24 hours [183]. Sunflowers were grown in a water pond contaminated with radiation near Chernobyl [184]. Within 12 days, the concentration of cesium in its roots was 8,000 times greater than in pond water, while strontium concentrations were 2,000 times greater than in pond water.

The same company planted industrial hemp to remove radioactive contaminants from the soil near Chernobyl [185]. One of the recent applications of using plants in environmental cleanup is research that examined the ability of the water hyacinth plant (Eich hornia Crassipes) to remove phosphorous pesticides [186]. It is expected that this plant will constitute an effective, economic and environmental alternative for removing and demolishing pesticide waste and disposing of agricultural industrial waste in general [187, 188].

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