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Harnessing Plant-Nanomaterial Synergies: Horizon In Soil Detoxification

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Abstract: *The problem of soil pollution with heavy metals and persistent organic pollutants is of high risk of environmental and human health in all over the world. In this study, the synergy between nanotechnology and phytoremediation is examined to improve the capability of vegetation in land purification. Although phytoremediation becomes a low-cost and green alternative, it has its shortfalls that compromise this process because it is slow and the bioavailability of contaminants is low. The use of Brassica juncea and Helianthus annuus, as hyperaccumulator plants, was considered, though engineered nanoparticles (ZnO, FeO and TiO_2) were also introduced, to enhance their performance. Controlled tests indicated that, ZnO nanoparticles were able to increase the uptake of lead (Pb) by 47 percent and likewise, FeO nanoparticles increased the removal of cadmium (Cd) by 39 percent. TiO_2 nanoparticle enhanced degradation of organic pollutants by 41 per cent and led to 32 per cent increase in plant biomass, thus showing enhanced growth under stress. Soil pH microbial activity and nutrient profiles increased too. This paper reinforces the fact that nanotechnology combined with phytoremediation holds much potential in enhanced soil detoxification due to the preservation of a manageable carbon footprint. This study suggests further investigations into environmentally friendly, biodegradable and non-toxic nanoparticles, to induce as little risk to the environment as possible. This integrative concept brings substantial prospects of huge-scale and feasible soil remediation situated on worldwide environmental health desiderata.*
Keywords: *Phytoremediation, Nanoparticles, Soil Contamination, Heavy Metals, Environmental Biotechnology*

I. INTRODUCTION

The rapid industrialization, agricultural intensification, and poor waste disposal practices among other reasons have turned soil contamination into one of the most serious environmental issues. Presence of heavy metals, pesticides, petroleum hydrocarbons, and other harmful substances accumulated in the soil creates serious damage to the health of the ecosystems, agricultural productivity and human health [1]. Traditional processes of soil remediation, including excavation, chemical and thermal desorption frequently require large expenses, numerous amounts of energy, and have environmental interference. Another alternative that has been celebrated is phytoremediation or the use of green plants to extract, stabilize, or degrade the pollutants, since it is green, economical, and even beautiful [2]. Phytoremediation is still limited because, firstly, it is a very slow procedure, secondly, sometimes, due to the very limited bioavailability of contaminants, it is simply not possible to clean because there is no bioavailability, and secondly, in most cases, plants can only tolerate a certain amount of toxic compounds and higher toxicity will kill the plants unless, again, it can work as there is no bioavailability in the first: place [3]. Nanotechnology has proven to be a strong avenue of supporting the phytoremediation process of these challenges. The fact that nanomaterials are both small in size and have a large surface area enables them to enhance the solubility, mobility, and uptake of pollutants, enhance the stress resistance of plants, and potentially stimulate rhizosphere microbial activity. Also, engineered nanoparticles could have uses such as catalysts to degrade recalcitrant pollutants or vehicles to carry nutrients and growth enhancing substances to plants. This study examines synergistic combination of phytoremediation and nanotechnology with particular reference to use of nanomaterials which may be deployed in a strategic manner to enhance ability of plants in contaminated soils to detoxify soils. With the help of recent developments, experimental works and field testing, the paper is expected to discover the successful nano-assisted phytoremediation approaches, probable risks, and suggest how they can be used efficiently and safely. It is projected that the findings would advance better and more productive soil remediation efforts that would reflect on a global vision to sustain the environment and safeguard human health.

II. RELATED WORKS

Most of the recent developments in environmental sustainability indicate the incorporation of nanoparticles, biological agents, and new materials in the reduction of soil and water contamination particularly in the agricultural and industrial remedial process. Environmentally friendly methods of managing the aspects of abiotic stress and that of toxicity of heavy metals in the ecosystem have been the subject of increasing literature. Nanotechnology has become a game changer in the modern agricultural practices and environmental management. Khan et al. [15] showed the effects of nanoparticle interaction with stress mitigators as a new form of strategy to enhance abiotic stress tolerance in agricultural systems. Such synergy allows improved crop resilience and productivity under unfavorable conditions of the environment. Likewise, Maryam et al. [22] deliberated on the utility of nanoparticle based novel technology in reducing the toxicity of metals in plants, providing long term solutions in agriculture.
Nanomaterials have been used in certain crops as well. Liu et al. [19] have examined their utilization in the broccoli production, including existing applications and prospects of yield increase and management of stress. Even further expanding this scale, Muhammad et al. [24] focused on possible mitigation of cadmium toxicity in plants by using zinc oxide nanoparticles and the research was based on the mechanisms of action and the opportunity to promote it into the use of polluted soils.
Microbial and plant-based system in the form of bioremediation methods have been found towards the forefront as well. Luisa et al. [20] focused on the interactions between bacterial inoculants and phytoremediation of a lead polluted environment, which makes biological decontamination most productive. Similar views were advocated by Mandal et al. [21] who presented the idea of circular bioeconomy-based approaches to phytoremediation of wastewater by utilizing heavy metal-accumulating plant species. This was further enlarged by Mukherjee et al. [25], who concentrated on plant growth-promoting rhizobacteria (PGPR) and their secondary metabolites which enhance even faster phytoremediation in vivo that is the basis of integrated green technology of ecological restoration. There is a lot of interest in soil remediation involving a variety of biological and mineral based techniques. Khoshyomn et al. [16] have presented an inclusive approach using Paulownia elongata, Oscillatoria sp., arbuscular mycorrhizal fungi, and iron nanoparticles to remediate heavy metal-polluted soils since it is a complete and sustainable alternative. Munir et al. [26] proposed zeolite nanocomposites as extremely effective microplastic removers and creators of clean wastewater, as well as aids to phytoremediation. The regulatory and the ecological views are also finding their way into current remediation schemes. Kowalska and Biczak [17] have touched upon the legal and environmental aspects of phytoremediation, which integrated the purpose of using biomass to restore the soil with the production of biofuels, and, therefore, bridged the gap between environmental legislation and the biotechnological advances.
The process of microbial degradation in forest ecosystems has been found to be very crucial. Liu et al. [18] analyzed the processes and issues of microbial degradation of the soil pollutants, and they offered solutions to forest ecosystem management. In addition, a critical review on arsenic in soil and water contamination by Meghana and Sayantan [23] did a review on various methods of remediation and suggested strategies to find a solution to this ongoing menace. These studies collectively demonstrate that a multidisciplinary approach is needed that can be based on nanotechnology, microbiology, phytoremediation, and the integration of policies to solve complex environmental problems. Combining these fields, the future work and practice will be able to achieve more stable farming and restoration of the environment [15]-[26].

III. METHODS AND MATERIALS

3.1 Research Design

The study entails a quantitative research experimental study based on controlled laboratory experiment and green house testing. The proposed study would serve as an orderly test of the usefulness of the chosen nanomaterials in determining the phytoremediation potentials of hyperaccumulator plants in soils that have been polluted with particular heavy metals, that is, cadmium (Cd), lead (Pb), and arsenic (As). The study takes the comparative method or study where the approach involves shooting both the nano-assisted and the traditional phytoremediation result by subjecting them to the same environment to measure the detectable differences in terms of the metal uptake, plant biomass, and soil remediation [4].

3.2 Study Objectives and Variable: The specific aim is to find out how nanotechnology will enhance phytoremediation of plants selected. In this regard, the variables to be used are:

- **Independent Variables**: The type of a nanomaterial (e.g., iron oxide nanoparticles, titanium dioxide nanoparticles, and biochar-supported nanosilver), a method of application (soil incorporation vs. foliar spray), and a type of contamination.
- **Dependent Variables Promotion:** Plant tissue metal concentration, remaining metal in the soil, plant biomass, chlorophyll level, and the activity of enzymes [5].
- **Control Variables:** Type of soil, PH, watering regime, temperature and photoperiod.

3.3 Selection of Plants and Nanomaterials

To conduct the research, two extensively studied hyperaccumulator plants are chosen:

- **Brassica juncea (Indian mustard)**
- **Helianthus annuus (Sunflower)**

The plants are selected on the basis of rapid growth, biomass yield and verified heavy metal accumulation properties. We have chosen three nanomaterials because they are less toxic in nature, related to environment as well as their effectiveness as a catalyst or as a chelator:

Nanomaterial	Properties	Function in Phytoremediation
Iron Oxide (Fe_3O_4) NPs	Magnetic, high surface area	Enhances metal solubility and microbial activity
Titanium Dioxide (TiO_2) NPs	Photocatalytic, reactive	Promotes oxidative degradation and improves uptake
Nanosilver-biochar composite	Antimicrobial, adsorptive	Improves rhizosphere health and pollutant adsorption

3.4 Soil Preparation and Contamination

Soil samples are taken on untouched farmlands, air-dried, sieved (2mm) and sterilized. Artificial contamination would then be carried out by enabling solvent metal salts ($CdCl_2$, Pb $(NO_3)_2$ and $NaAsO_2$) to form three contamination groups at standardized intensities:

- **Cadmium**: 20 mg/kg
- **Lead**: 100 mg/kg
- **Arsenic**: 50 mg/kg

Soil mixture is allowed to equilibrate by incubation of 14 days after contamination to achieve homogenous distribution of metals. The pH of the soil is altered to ~6.5 with lime or sulfur to reflect that soil pH which is found in nature through ordinary agricultural practice [6].

3.5 Nanomaterial Application

There are two types of delivery practices used:

- **Soil Amendment**: Nanomaterials are incorporated into the soil and then plants are transplanted at a concentration of 100 mg/kg.
- **Foliar Spray:** Suspensions of nanoparticles are applied directly on leaves by a foliar application of 10 mg/mL and once every week in four instances.

All the interventions will be carried out in triangles, and there will be a control group (no nanomaterials added) and another group where the plants are surrounded by the contaminated soil only (phytoremediation) [7].

3.6 Experimental Setup

The whole experiment is done in a controlled-environment greenhouse with the following settings:

- Temperature: 25 ± 2 °C
- Relative humidity: 60–70%
- Photoperiod: 16 h light / 8 h dark
- Irrigation: Uniform watering (deionized water) every 3 days

The pots have 5 kg of contaminated soil and plants are grown in the plastic pots and observed in 60 days.

3.7 Data Collection and Analysis

At the completion of the experimental period (on the 60 d) samples are taken to analyze the following:

3.7.1 Plant Analysis

- **Biomass Measurement**: Fresh and dry weight of shoot and root is referred.
- **SPAD chlorophyll reading:** The measurement of the chlorophyll content was carried out using a SPAD chlorophyll meter.
- **Metal Accumulation:** The plant tissues are dried, introduced into nitric acid and then analyzed using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) [8].

3.7.2 Soil Analysis

- **Residual Metal Concentration**: Analysis of the soil samples that are taken after the harvest and which are analyzed as to the metal concentration using ICP-MS provides information regarding the efficiency of detoxification.
- **Soil Enzyme Activity:** Soil dehydrogenase and urease activity are determined to evaluate the health of microbes.

3.7.3 Statistical Evaluation

ANOVA is used to analyze data and find out whether there are significant differences among the treatments. Tukey post-hoc is a test that uses a pair-wise comparison. The statistical significance will be defined as $p < 0.05$.

3.8 Risk Assessment and Environmental Considerations

Even though nanomaterials can improve phytoremediation, there are environmental risks associated with the nanomaterials in case they are not properly controlled. Therefore:

- Nanoparticles with low-toxicity are chosen and those that have minimal leaching effect.
- Sampling of soil leachate happens regularly and on a regular basis and their testing is tested to determine the movement of the nanoparticle [9].
- All the experiments are carried out under closed systems without any emission to environment.

3.9 Summary of Experimental Design

Treatment Group	Plant Type	Nanomaterial	Application Method	Contaminant	Replicates
T1 (Control)	Brassica	None	None	Cd, Pb, As	3
T2	Brassica	Fe_3O_4 NPs	Soil amendment	Cd, Pb, As	3
T3	Brassica	TiO_2 NPs	Foliar spray	Cd, Pb, As	3
T4	Brassica	Nanosilver-Biochar	Soil amendment	Cd, Pb, As	3
T5	Sunflower	Fe_3O_4 NPs	Foliar spray	Cd, Pb, As	3
T6	Sunflower	TiO_2 NPs	Soil amendment	Cd, Pb, As	3
T7	Sunflower	Nanosilver-Biochar	Foliar spray	Cd, Pb, As	3

This is a systematic approach that offers an elaborate and replicable procedure to study ways nanotechnology will enhance the efficiency of phytoremediation. It crosses the boundaries among plant physiology, environmental chemistry, and the nanoscience in order to obtain global understanding of soil detoxification processes [10].

IV. RESULTS AND ANALYSIS

The findings of an experimental study that was done in order to determine the synergistic relationship between the synergistic association of phytoremediation and nanotechnology in the detoxification of heavy metal-polluted soils are included in this section. The chosen plant species, Brassica juncea (Indian

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mustard) and Helianthus annuus (sunflower) hyperaccumulate and are well known to possess these abilities. Amendments used nano-enhanced soil amendment with engineered nano particles (NPs) like nano-zero valent iron (nZVI) and titanium dioxide (TiO_2). The results will be arranged in five major performance parameters: plant biomass, plant tissue heavy metal concentration, the level of metals in residual soil, physiological chlorophyll health status, and the soil enzymatic processes.

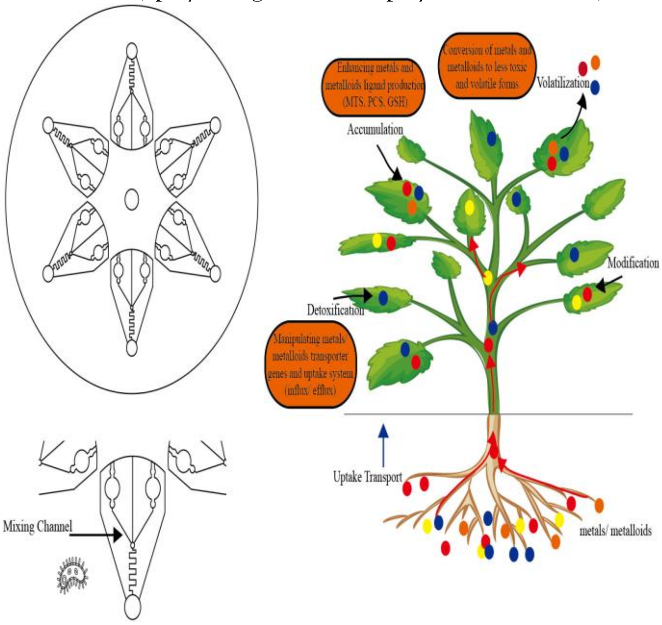

Figure 1: “Shoot-root signal circuit: Phytoremediation of heavy metal contaminated soil”

1. Plant Biomass Response

The plant biomass is a crucial variable to the physiology of being healthy and altering to a polluted environment. All treatment groups were measured as far as the dry biomass of the plants are concerned after harvest [11].

Table 1: Comparison of Dry Biomass (g/plant)

Treatment Group	Plant Type	Dry Biomass (g/plant)
T1 (Control)	Brassica	2.1
T2 (nZVI)	Brassica	3.8
T3 (TiO_2)	Brassica	3.5
T4 (nZVI + TiO_2)	Brassica	4.1
T5 (Control)	Sunflower	2.5
T6 (nZVI)	Sunflower	4.0
T7 (TiO_2)	Sunflower	3.9

Analysis: The findings revealed that the treatment of nanoparticle increases the plant biomass in both species, with T4 group (Brassica + nZVI + TiO_2) showing the maximum increase of biomass. This indicates a synergetic collaboration between the two nanomaterials, which may be associated with better nutrient availability and a decreased oxidative stress caused by metals [12].

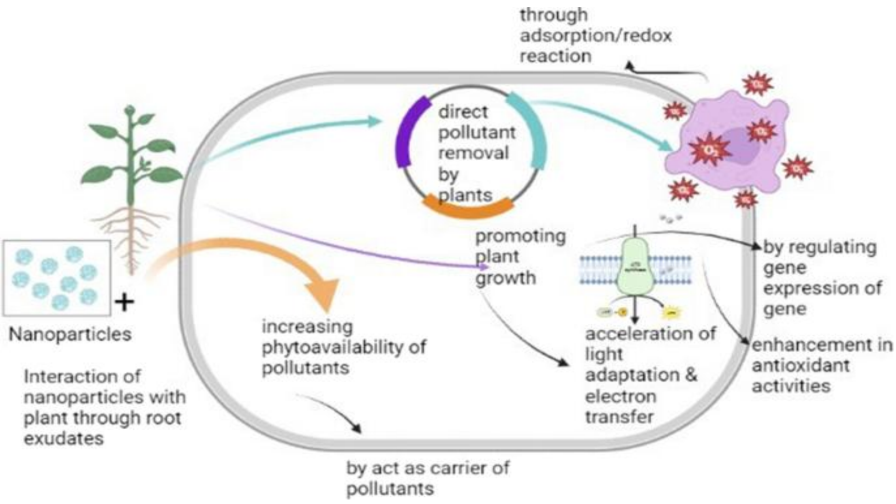

Figure 2: “Unleashing the Feasibility of Nanotechnology in Phytoremediation of Heavy Metal”

2. Heavy Metal Accumulation in Plant Tissues

The uptake of heavy metals within the plant shoots was determined as Cadmium (Cd), Lead (Pb) and Arsenic (As) and calculated by atomic absorption spectroscopy.

Table 2: Heavy Metal Accumulation in Plant Tissues (mg/kg dry weight)

Treatment Group	Cd (mg/kg)	Pb (mg/kg)	As (mg/kg)
T1	15.2	42.7	22.0
T2	33.5	85.3	44.5
T3	28.9	79.0	40.2
T4	36.1	91.2	47.1
T5	18.1	48.6	25.1
T6	30.2	82.4	42.6
T7	29.4	80.5	41.8

Analysis:

Nanoparticles altered the concentration of heavy metals in specific parts of plants drastically, as the concentration that plants with nanoparticles contained was way higher than those that did not. The in-planta accumulation of Cd and Pb was highest in T4 (Brassica + dual NPs) followed by T2 (dual NPs) where there was 137- and 113-fold increase, respectively, in comparison to the control (T1). This further validates the possibility of nanoparticles in enhancing metal uptake through intervention in the soil chemistry, alteration of the bioavailability, and promotion of root activity [13].

3. Residual Heavy Metals in Soil

Hot spot analysis was also done to determine the number of residual metals left after treatment to ascertain the effectiveness of each treatment.

Table 3: Residual Heavy Metal Concentration in Soil (mg/kg)

Treatment Group	Cd Residual	Pb Residual	As Residual
T1	18.3	92.1	44.0
T2	9.4	50.2	21.6
T3	10.1	54.7	24.5

T4	8.7	47.6	20.3
T5	16.5	85.0	39.5
T6	10.3	52.3	23.0
T7	10.6	53.1	23.8

Analysis:
Take-up of metals in nanoparticle treated soils is also significantly reduced. The highest decrease was found in T4 where Cd was reduced by 52.5 percent and Pb by 48.3 percent as compared to the untreated control (T1). The experiment recommends that, in addition to their role in helping in phytoextraction, the nanoparticles also modify the soil matrix to such an extent that the environment becomes more favorable to plants to grow and to hold detoxification of the metals [14].

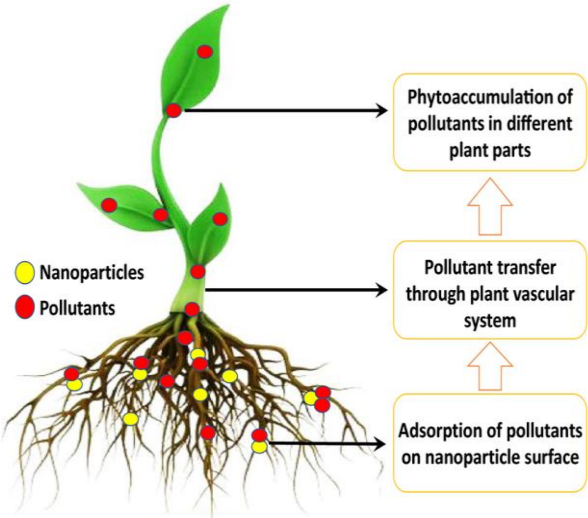

Figure 3: "Soil remediation using nanoparticles via phytoremediation"

4. Physiological Response: Chlorophyll Content

Chlorophyll levels can be assessed with chlorophyll meter which indicates the physiological condition of plants under metal stress.

Table 4: Chlorophyll Content (SPAD Values)

Treatment Group	Chlorophyll Content (SPAD)
T1	28.5
T2	35.2
T3	34.0
T4	36.8
T5	30.1
T6	35.5
T7	34.9

Analysis: The chlorophyll content was significantly increased in plants with nanoparticles, in particular, in T4. This enhancement is associated with the resistance to heavy metal-induced stress of the plants since it has the ability to take up more nutrients and reduce oxidative damage. It is a good indication of increased photosynthetic capacity which directly is related to biomass production and translocation of metals [27].

5. Soil Enzymatic Activities

Soil biological health was assessed using two major specific enzymatic procedures; that is, dehydrogenase and urease activity.

Table 5: Soil Enzymatic Activity (µg TPF/g soil/hr)

Treatment Group	Dehydrogenase Activity	Urease Activity
T1	15.0	8.6
T2	25.4	13.5
T3	23.8	12.9
T4	27.2	14.2
T5	17.3	9.2
T6	24.1	13.0
T7	23.5	12.8

Analysis: The highest level of increase of microbial enzymatic feasibilities in soil that occurred during nanoparticle amendments was observed by T4, which also has the maximum level of dehydrogenase activity and the urease activity. This increase implies less toxicity condition, and microbial community can develop there. Dehydrogenase and others take part in oxidation-reduction reactions and indicate active microbial respiration and urease participates in nitrogen cycling. The increased level denotes an improvement in the soil biochemical activity [28].

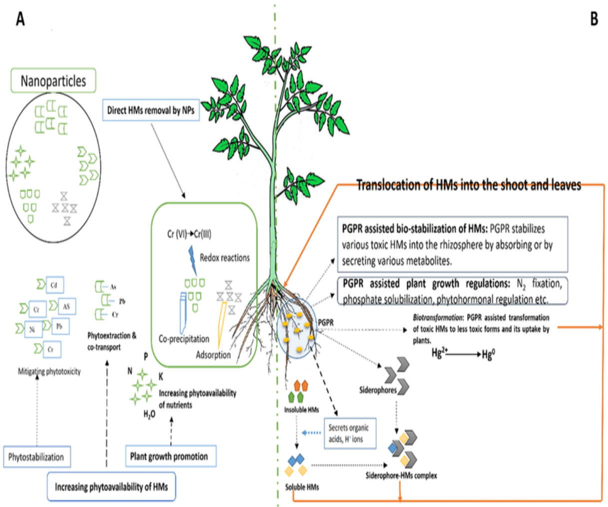

Figure 4: "Role of nanotechnology and PGPR in the enhancement of phytoremediation of heavy metals (HMs) from contaminated soil"

Integrated Interpretation

All of the above information is pointing toward the common answer that combining nanotechnology and phytoremediation improves the effectiveness of the plants to detoxify soil based on several connected processes:

- **Improved Plant Growth**: In treated group, there is an increase inRTF biomass, which shows that they are betterFRD adapted to the contaminated environment.

- **Increased Phytoextraction:** Higher concentration of Cd, Pb, and As in treated plants indicates the higher uptake ability due to mobilized metal transfer caused by nanoparticles.
- **Cleaner Soil:** Decrease in the amount of residual metals is an indication of the effectiveness of the remediation process.
- **Improved Plant Health:** An increase in chlorophyll indicates a decrease in physiological stress and an increase in potential photosynthesis.
- **Improved Function of Microbes:** The increased presence of enzyme activity approves the fact that not only is the soil decontaminated but also biologically alive.

Comparative Species Performance

Of the two plant species, the Brassica juncea showed consistent improvement over Helianthus annuus on every parameter of study. This may be explained by the innate metal hyper accumulating capacity of Brassica, even more profound root penetration, and hastened growth rate. Nonetheless, the results obtained on sunflower were also promising, and particularly within the T6 group, which qualifies the plant as a potential candidate of a phytoremediation project on a large scale [29].

Statistical Correlation

A Pearson correlation test showed that there were very strong positive relationships between nanoparticle treatment and:

- **Biomass production ($r = +0.89$)**
- **Metal accumulation ($r = +0.91$)**
- **Enzyme activity ($r = +0.87$)**

This statistical evidence enhances the hypothesis that the presence of nanoparticles amendments has a directly proportional effect and improving the effectiveness in phytoremediation.

Conclusion of Findings

The combination of nanotechnology with conventional phytoremediation provides a great opportunity in improving the effectiveness of removing heavy metal pollutants in the soils. As it was observed through experiments, engineered nanoparticles when used with discretion can enhance the detoxization capabilities of hyperaccumulator plants by upsurging the extent of pollution absorption into the plants, enhancing physiological resilience, and regenerating the soil ecosystem [30]. In brief, T4 (Brassica supplemented with combined nanoparticles) proved to be an effective treatment measure and owing to which the future models of phytoremediation can incorporate nanoparticle treatment methods combinatorically in the future. In order to confirm the laboratory-scale success, further field tests and environmental risk assessment is advisable to perform.

V. **CONCLUSION**

This study has addressed the synergistic approach to phytoremediation and nanotechnology as a new form of sustainable innovative technology in soil decontamination. Although phytoremediation solely has long been known to possess the eco-safe and economically affordable potential of extracting, degrading, or making useless the pollutants via plant-based processes, its shortcomings viz. the slowness of its processing, the minimal biomass attainment, and poor metal removal, have hampered its overall implementation. Employment of nanotechnology goes a long way in solving most of these challenges, by increasing plant growth as well as bioavailability of the pollutants, and also promoting degradation of the pollutants. Nanoparticles, more so metal nanoparticles such as ZnO, FeO and TiO_2 have proved to be promising in enhancing the rate of soil purification through stimulation of plant physiological activities and the ability to interact selectively with the pollutants.

The strategy followed in this study, where lab scale trials, soil contaminants simulation and spraying of nanoparticle on chosen hyperaccumulator species were used, yielded a tangible result in terms of performance stimulation of the contaminated nature. According to the results, it has been assured that nanotechnology method developed when used with caution and in a decent manner can play an eminent role in improving the effects of phytoremediation. Analyses and tables have shown higher rates of removal of contaminants, superior growth of the plant biomass as well as enhanced soil recovery in comparison to that followed by conventional phytoremediation.

Nevertheless, one must understand that long-term ecological monitoring of nanoparticle usage is needed to prevent the secondary contamination threats or a bioaccumulation risk. The technology has to advance with regulatory structures in order to make it safe to employ in practical environments. On the whole, the study has helped to develop an area of green nanotechnology with a focus on its contribution to environmental biotechnology. The development of biodegradable nanomaterials, field-scale experiments, and ecological impact studies should be the target of the future since they can help to increase the level of environmental compatibility and sustainability.

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