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Review: Efficiency of *Helianthus Annuus* L. Plant Tissues in Phytoremediation of Nano Pollutants

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Abstract:

Nanoparticles (NPs) are a high throughput, multiflexible material and have transformed nearly every part of human life in the last decade by possessing immense commercial applications all over the world. Nevertheless, these particles have found their way into the environment in many ways, causing unintended effects to the environment and risking the health of human beings and ecosystems. Conventional remediation methods often involve expensive chemical treatments that can disrupt ecosystems. In contrast, phytoremediation—the use of plants to treat polluted environments—offers an environmentally friendly and cost-effective solution. The sunflower (*Helianthus annuus* L.) stands out as an excellent candidate thanks to its rapid growth, resilience against challenging environmental conditions like high temperatures, adaptability to varying soil types, and its remarkable capacity to extract heavy metals that accumulate in its roots. This article explores nanomaterials, their environmental implications, and the innovative use of sunflower plants for their treatment. It further delves into converting the treated biomass into sustainable biofuel. Additionally, the study examines the mechanisms that improve phytoremediation efficiency, addresses the challenges encountered in the process, and discusses recent advancements designed to enhance its effectiveness.

Keywords: Environmental, Sunflowers, Nano pollutants, Phytoremediation, Pollution.

Helianthus annuus L كفاءة أنسجة نبات زهرة الشمس في المعالجة النباتية للملوثات النانوية

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الخلاصة:

تعدُّ المواد الناناوية مواد متطورة وعالية الإنتاجية أحدثت ثورةً في كل جانب من جوانب الحياة البشرية تقريبًا خلال العقود الماضية بتطبيقاتها التجارية العديدة حول العالم، ومع ذلك فقد شقت هذه الجسيمات طريقها إلى البيئة عبر مسارات مختلفة مُسببةً عواقب بيئية غير مقصودة، ومُعرِّضةً الأنظمةً البيئية المُختلفة وصحة الانسان للخطر. غالبًا ما تتضمن طرق المعالجة التقليدية مُعالجات كيميائية مُكلفة قد تُخلّ بالأنظمة البيئية. وعلى النقيض، تُقدم المعالجة النباتية - استخدام النباتات لمعالجة البيئات المُلوثة - حلاً صديقًا للبيئة وفعّالاً من حيث التكلفة. وتعدُّ نباتات زهرة الشمس مرشحا واعدا بفضل نموها السريع، وتحملها للظروف البيئية كارتفاع درجات الحرارة، وقدرتها على التكيف مع تقلبات التربة، وازالة المعادن الثقيلة المتراكمة في جذوره وتضمين المواد النانوية داخل انسجتها . تهدف هذه المقالة إلى تسليط الضوء على المواد النانوية وتأثيرها على البيئة ومعالجتها باستخدام نباتات زهرة الشمس وكيفية تحويل الكتلة الحيوية المعالجة الى وقود حيوي صديق للبيئة، ودراسة الآليات التي تعزز فعالية المعالجة النباتية، وتسليط الضوء على التحديات التي تواجهها في المعالجة النباتية والتطورات الحديثة الهادفة إلى تحسين كفاءتها.

الكلمات المفتاحية: البيئة، زهرة الشمس، ملوثات نانوية، المعالجة النباتية، التلوث.

1. Introduction:

Nanomaterial pollution has become a prevalent environmental issue, presenting serious threats to both ecosystems and human health [1]. Industrial and agricultural activities have contributed to the extensive release of nanomaterials like zinc and silver into soil and water systems [2]. These metals are highly toxic and non-biodegradable, which means they leads to long-term pollution if it remains in the environment for a long time. As these substances accumulate in the food chain, they expose humans and animals to significant health risks, including neurological damage, cancer, and organ toxicity [3].

Traditional approaches to environmental remediation, such as excavation, chemical treatments, and incineration, are undoubtedly effective but come with significant drawbacks. They are costly, consume large amounts of energy, and often result in additional ecological disruption Excavation, for instance, can strip away vital topsoil, while chemical treatments

risk introducing secondary pollutants or harmful toxins. Furthermore, the long-term sustainability of these methods is questionable, highlighting the growing demand for more eco-conscious solutions. In response to this challenge, phytoremediation has gained recognition as a viable, environmentally sustainable, and cost-efficient alternative to conventional techniques [4].

Phytoremediation stands out as an innovative and eco-friendly approach to mitigating the impact of environmental pollutants. By harnessing the natural abilities of plants, particularly hyperaccumulators, and fine-tuning environmental conditions, this method offers an effective solution for pollution control across various sites, aiding in ecosystem recovery [5]. Its reliance on plants as self-sustaining agents minimizes the need for expensive infrastructure and energy-heavy remediation efforts. The adaptability of phytoremediation to address diverse contaminants—ranging from heavy metals and organic compounds to emerging pollutants—highlights its potential across a broad spectrum of environmental challenges. Aligned with the principles of ecological balance and conservation, this strategy reduces dependence on chemical interventions while lowering the likelihood of unintended adverse effects. Moreover, phytoremediation supports ecological health by fostering biodiversity and bolstering ecosystem resilience [6].

Sunflower (*Helianthus annuus* L.) has emerged as one of the most effective plant species for phytoremediation, largely due to its rapid growth, substantial biomass production, and remarkable ability to absorb diverse heavy metals [7]. Originally native to North America, this annual species thrives across various environments, ranging from farmlands to industrial areas polluted by metals. Its distinct advantages over other phytoremediation plants include superior biomass yield and highly efficient metal uptake, positioning it as a prime choice for large-scale remediation efforts [8]. Whether addressing contaminated soils or polluted water bodies, sunflowers excel in extracting pollutants. Their extensive root system enhances the absorption of contaminants, making them equally suited for both land-based and aquatic remediation projects. Sunflowers stand out as an appealing option due to their low cultivation costs and ease of handling, making them accessible for various applications [9]. While their potential for pollutant treatment shows promise, there are significant challenges that need resolution to fully capitalize on their effectiveness. These challenges primarily involve concerns such as metal toxicity, environmental fluctuations, and the disposal or management of metal-rich biomass post-phytoremediation. This review seeks to offer a detailed exploration of nanotechnology, emphasizing its ecological impact and the mechanisms

driving its role in phytoremediation. Particular attention will be given to sunflower's capability in removing nano-pollutants and the feasibility of repurposing treated biomass for biofuel production. Additionally, it will delve into the existing obstacles and suggest future research directions aimed at optimizing the use of sunflowers for pollutant remediation efforts.

2. Pollution

Adding pollutants to the natural environment causes harmful changes. Pollution can come from a variety of sources: chemicals or energy, such as noise, heat, and light. However, when these levels exceed normal levels, they are classified as pollution. Environmental pollution is one of the worst emerging problems in our world today, negatively impacting humanity and other living organisms, "Environmental pollution is defined as pollution of the physical and biological components of the Earth's atmospheric system to the extent that normal environmental processes are negatively affected" [10].

In recent decades, factories and means of transportation have developed whose waste destroys the environment and overuses pesticides, which are toxic substances and fuel materials [11]. As well as a significant increase in heavy metals, which are a group of common metallic chemicals such as cadmium (Cd), mercury (Hg), lead (Pb), arsenic (As), zinc (Zn), copper (Cu), nickel (Ni) and chromium (Cr) that originate either from natural or industrial sources including wastewater released from the oil and gas industries [12], as well as the use of phosphate fertilizers in agriculture sanitation, pesticide use, and fossil fuel burning which pose a significant threat to human health [13]. The widespread use of NPs in various products and applications further escalates environmental contamination, released into the air, water, and soil, these nanoscale particles present a grave threat; their minuscule size allows them to float in the atmosphere, spread via water systems into soil, and eventually enter the food chain through plant absorption. This accumulation in plants leads to transmission into humans, ultimately causing harmful impacts; therefore, it is necessary to find therapeutic methods to rid the environment of heavy metals or reduce their quantities [14]. Biological techniques to address the problem of pollution are one of the most used and safe methods for the environment, known collectively as biological remediation, and include the use of living organisms (plant, microorganisms, genetically modified organisms with the ability to reduce pollution levels through metabolic biological processes to reduce or prevent pollution [15].

3.Nanotechnology

Nanotechnology is the science, engineering, and technology of materials at a nanoscale ranging from 1 to 100 nm [16], which is the study and application of extremely small objects and is used in all other fields of science, such as chemistry, biology, physics, materials science, and engineering. Nanomaterials manifest in the environment through several pathways, including (i) intentionally crafted man-made nanomaterials, which afford precise control over size and properties. There are two types of methods to synthesize nanoparticles: The top-down process involves taking raw materials in bulk and reducing their dimensions using various techniques, such as grinding and lithography. The bottom-up method is a chemical and biological approach in which atoms or chemical compounds, along with a reducing agent (such as leaf extract), are used for cost-effective nanoparticle synthesis, allowing for the rapid formation of nanoparticles [17] (**Fig.1**). (ii) unintentional nanomaterials generated by industrial processes like combustion in heat engines, and natural phenomena such as fires, and (iii) naturally occurring nanomaterials. Recent years have witnessed an upsurge in nanoparticle production [18], exemplified in their use as antibacterial agents, where they mitigate bacterial proliferation and enhance the efficacy of antibacterial treatments. In drug delivery systems, nanoparticles offer physiochemical properties that selectively target cancer cells while minimizing side effects, albeit higher concentrations may induce toxicity [19]. Nanoparticles also serve as protective shields in food preservation, feature in sunscreens to shield against ultraviolet radiation, contribute to diagnostic procedures [20], and aid in pathogen elimination. Furthermore, their applications extend to the purification of water sources, removal of heavy metals from water, and augmentation of fertilizers for agricultural purposes. The electronics industry also harnesses the potential of nanoparticles [21]. Nanoparticles are integral to our daily lives, thanks to their unique physical, chemical, and biological properties. Their behavior and characteristics shift based on factors such as size, shape, acidity, and concentration. While these transformations can lead to environmental harm through specific reactions, nanoparticles also offer significant benefits. They contribute to enhanced plant growth, support advancements in renewable energy, and are essential in pharmaceutical treatments. Their influence spans multiple fields, bringing both advantages and challenges. To ensure the well-being of living organisms, it is crucial to adopt environmentally responsible practices that maintain a balanced ecosystem.

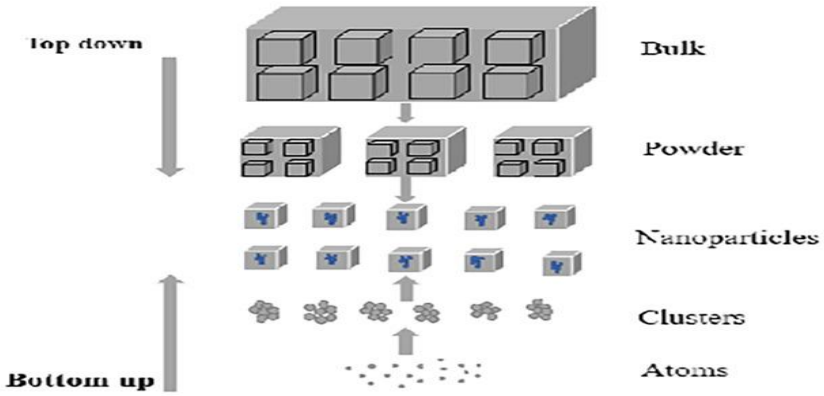


Figure 1: Top-down and bottom-up approach to the synthesis of nanoparticles [17]

4. Impact of Nanoparticles on Environmental

In today's world, numerous human activities contribute to the release of nanoparticles into the environment, leading to contamination in essential elements such as soil, air, and water. Among the key sources of these emissions is the disposal of unwanted nanomaterial waste, which often involves burning, releasing nanoparticles in the form of ashes. Construction sites, as well as gas, petroleum, and water pipelines, also contribute to environmental emissions. Cement industries release small particles into the environment during their processes, and even different fields like agriculture, roadside traffic, and the polymer industry experience toxic emissions of nanoparticles. Workers are particularly susceptible to this nanoparticle exposure, which may increase the risk of health problems such as skin issues, damage to the respiratory system, and harm to certain cells in the body. Nanoparticles' behavior changes depending on their size, shape, and other factors, leading to changes in their chemical and physical properties. Nano fertilizers are responsible for soil toxicity, climate changes, soil deficiency, and other issues [22] . Zinc nanoparticles can induce cellular toxicity in plants, leading to growth retardation, reduced photosynthesis, and altered gene expression in all affected plants. Higher nanoparticle concentrations are primarily responsible for the reduction in photosynthesis. AgNP can also inhibit plant growth [23]. Nanoparticles represent a double-edged sword, offering immense potential while demanding caution to mitigate their negative impact. Often described as "invisible pollution," nanoparticle contamination is among the most critical environmental issues to address [24]. Due to their extremely small size, these particles pose significant risks by infiltrating plant and animal cells and even penetrating human skin, potentially causing severe adverse effects. The widespread use of nanoparticles

in numerous products and applications has led to substantial environmental pollution. Once released into the air, water, and soil, nanoparticles present serious concerns due to their ability to disperse through these mediums and accumulate within plants. These contaminated plants eventually enter the human food chain, leading to harmful and sometimes long-term consequences [25] [26]. Nanoparticles can directly interact with plants through their foliar parts, affecting growth, development, biochemical processes, and physiological functions [27]. For example, copper nanoparticles (CuNPs), widely used as bactericides and fungicides in agriculture, are highly toxic to aquatic ecosystems [28]. The effects of nanoparticle pollution are far-reaching, disrupting environmental balance, destabilizing ecosystems, and contributing to a range of human health disorders. Prolonged exposure to nanoparticles elevates the risk of severe cardiovascular and respiratory diseases and can also result in premature death [29]. Inhaling air laden with nanoparticles triggers pulmonary inflammation and worsens respiratory conditions in humans [30]. As the production of nanoparticles continues to surge across various sectors, it exerts an undeniable influence on both the environment and living organisms, impacting health and well-being (Fig. 2).

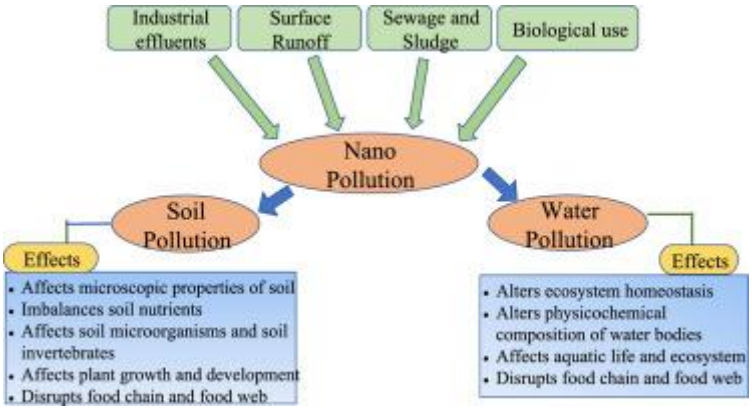


Figure 2: Impact of nanoparticles on environmental [24]

5. Phytoremediation

The origin of the word phytoremediation from the prefix "Phyto" means plant and remediation means treatment or reversal of damage, Phytoremediation is the practical application of plants to clean up or sequester (fix) contaminants in a growing medium (soil, water, or sediment) through natural biological processes and/or plants, which is one of the important means ensure in cleaning the environmental pollutants and usually plant species with the ability to attract those pollutants and convert them into forms less harmful to the environment or useful in its growth, and depends on the plant type and its ability on the

absorption of pollutants [31], scientists have tended to use methods that can treat these pollutants by less harmful means through bioremediation techniques, in particular plant treatment to clean sites contaminated with plants, this treatment is often a better option than traditional methods of soil cleaning, such as digging the soil or treating it with chemicals, as it is less expensive and more aesthetically pleasing than those methods, but it is important to use plants that are usually found naturally that can break down a specific contaminant from a specific source, such as lead from a nearby plant, for example when using a plant to absorb contaminated water, it will be necessary to choose a plant with a comprehensive root system, including willow, Indian mustard, poplar and sunflower, and phytotherapy can be used to clean pollutants such as metals, pesticides, solvents, explosives, multiple aromatic hydrocarbons, and sediments from the environment [32].

Phytoremediation is a green strategy that uses highly accumulated plants to stabilize pollutants in the soil, decompose them in water or transfer them to the environment [33], and this technique is highly efficient, cheap and adaptable to the environment, and there are many technologies used in phytoprocessing (Fig. 3): including the following:

- **Phytostabilization**

In phytostabilization, plants are used to reduce metal mobility and bioavailability in soils by a process of stabilization [35]. It is vital to mention that this process does not lead to a decreased concentration of metals in the contaminated places; it only renders metals immobile and reduce metal movement off sites making it less harmful. This is because the metals are restricted to the vadose zone of the plants there by means of this process, it is inhibited to be mobile [36].

- **Phytovolatilization**

Plants take in and break down the pollutants of heavy metals in the soil and release them as less harmful vapors through transpiration. During this process, heavy metals are taken up into volatile organic compounds but released as the biomolecules [37]. The phytoremediation process is only applicable to very few elements of the metals, which can come in the gaseous state in the environment. Such as Hg [38].

- **Phytoextraction**

This takes the form of phytoremediation where plants are used to hyper-accumulate metal. This is a solar-based technology that greatly relies on the ability of plant roots to absorb the metals, translocate them to parts above the ground so that it can accumulate there. The effect of the process is the reduction of metal concentration in soil and increasing the metal contaminants concentration that are above the grounds of plants, although this technology will ensure that the metals in the soils are eliminated, it is not suitable at high level of metal contamination because plants cannot withhold metal contaminants in the soils over long periods of time. Plants capable of accumulating high concentration of metal contamination into their shoot tissues with little to no visible toxicity consequence are generally referred to as hyperaccumulators [39].

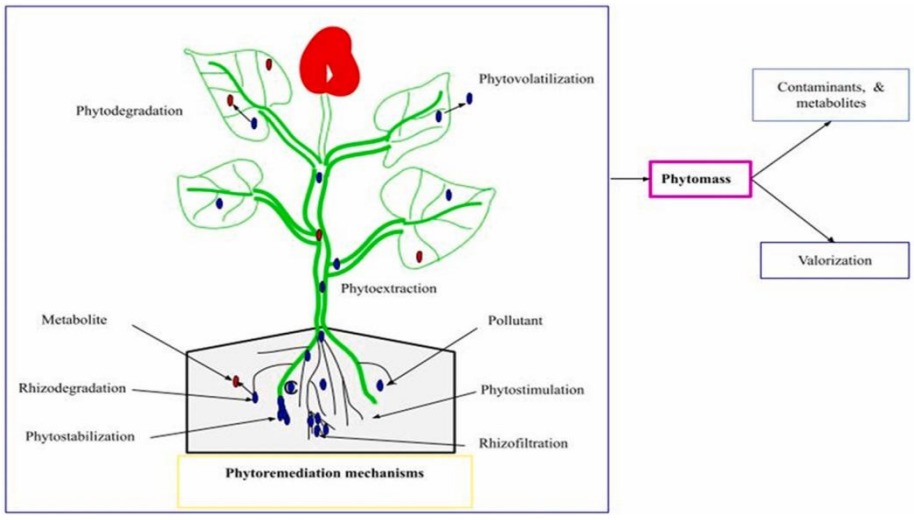


Figure 3: Phytoprocessing Technologies [34]

Advantages of plant processing [40, 41]

- Maintain the natural balance of the ecosystem using organisms that already exist.
- The possibility of companies specialized in mining from the plant recovering and reusing heavy metals.
- Ease of procedure and low cost.
- Prevents corrosion and leaching of metals by fixing metals, which reduces the risk of contaminant spread.

Disadvantages of plant treatment [42, 43]

- Determined by the land area and rooting depth the roots take up.

- Heavy metals in large proportions are difficult to process.
- Processed vegetative growth requires a long time and the need to increase biomass.\
- The leakage of pollutants into groundwater cannot be prevented entirely without removing contaminated groundwater, which is an essential aspect of the pollution problem.

6. Factors Effecting on Phytoremediation

Plant types, root region, environmental conditions, root composition and elemental species, as well as the soil physio-chemical and biological properties, all have an effect on HM buildup and distribution in plants. The remediation process can also be improved by applying agricultural practices (such as pH correction, the use of chelators, and fertilizers). Other factors to consider include soil pH, organic matter, and phosphorus content. In addition, the uptake of HMs by plants depends on various aspects, as described below [1].

7. Sunflower plants as a phytoremediation for Nano pollutants

The sunflower stands out as one of the most significant oilseed crops, serving as an abundant source of biomass and vegetable oil for energy production and industrial applications. The plant is a very adaptable species that is remarkable with regard to its resistance to heavy metal levels that are not much higher than concentrated levels [44]. Its resilience to extreme temperature ranges and adaptability to varied climatic and soil conditions are key agronomic traits. Sunflowers are recognized for their tolerance to heavy metals, attributed to their rapid growth, substantial biomass, high translocation capacity, and ability to accumulate heavy metals, particularly in their fatty tissues. This characteristic makes them effective for heavy metal remediation. Research has demonstrated their capability in removing contaminants such as chromium, Copper, Cadmium, and Zinc [45]. Research has shown that the removal of heavy metals by sunflower plants in contaminated soil varies based on the germination duration (30-90 days) [46]. Studies have demonstrated the ability of sunflower plants to treat some pollutants from chemical elements in the form of nanoparticles This is based on the properties of nanoparticles such as their ease and speed of penetration into the plasma membrane of plant cells, thus facilitating their recruitment and inclusion within these cells. The direct stimulating effect of nanoparticle concentrations of Nano oxides on the germination of seeds of a number of plants, including sunflower, is due to their biomineralization and the ability of some plants to incorporate them as a growth-stimulating

element as a basic electron carrier through the electron transport chain. This is supported by the study conducted on sunflower plants on the positive effect of titanium oxide nanoparticles TiO_2 NPs on seedling growth [47]. In another study, it was found that foliar spraying with Nano zinc oxide pesticide at a concentration of 200 parts per million resulted in the highest oil yield per acre, indicating the ability of sunflower plants to incorporate nanoparticles [48].

The stimulating effect of nanoparticle concentrations of zinc oxide nanoparticles on seed germination and growth of sunflower plants is due to their bio mineralization and their ability to be incorporated as a growth-stimulating element [49]. The findings [50] suggest that magnesium nanoparticles enhance sunflower growth under drought conditions by boosting the antioxidant system, promoting the production of photosynthetic pigments, and increasing primary metabolite levels. In another study, it was found that sunflower plants have the ability to incorporate iron nanoparticles by increasing the level of phenols, anthocyanins, and antioxidant enzyme activity, in addition to increasing macro- and micronutrients [51]. The toxicity of nanoparticles (NPs) is mitigated by: Antioxidants that are primarily made in different organelles, including mitochondria, chloroplasts, peroxisomes, vacuoles, and the endoplasmic reticulum (ER). Their role in alleviating oxidative stress enhances the tolerance of plants to the toxicity induced by metal-based nanoparticles (MBNPs). This ultimately fosters better plant growth, development, and yield by stimulating the accumulation of phytonutrients and antioxidants within the plant system. Consequently, biological macromolecule and micromolecule homeostasis is maintained, leading to improved crop quality [52].

8. Phytoremediation using Sunflowers and their potential for bioenergy production

Sunflower-based phytoprocessing practices must account for environmental and human health risks, especially concerning metal accumulation in the plants' edible parts, which can compromise food safety. To mitigate these risks, effective biomass management strategies are essential, redirecting contaminated materials toward non-food applications like bioenergy production [53] (Fig. 4).

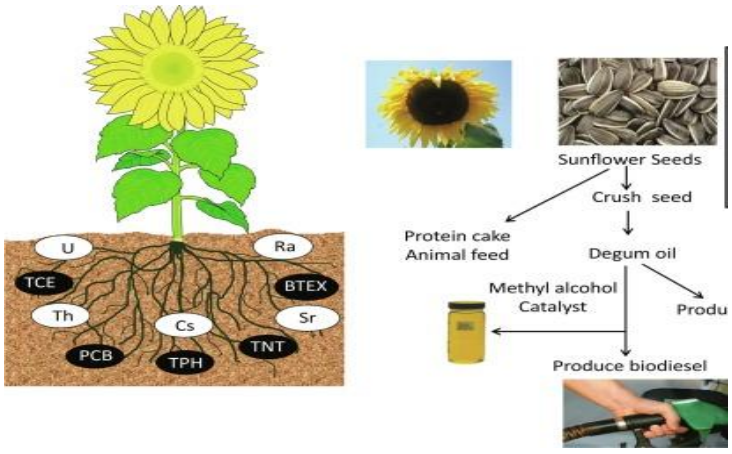


Figure 4: Phytoremediation by sunflower and bioenergy production [54]

There is a strong case in the combination of phytoremediation to benefit from restoration of the environment whilst producing clean energy named bioenergy. The potential of plants to clean contaminated soil and water comes as demand in alternative energy mounts and plants can be used to provide biomass to convert into bioenergy. The procedure results in renewable energy, and this comes with a lot of benefits. In this regard, biofuels become an alternative source of energy to the fossil fuel, which is efficient in the implementation of phytoremediation. Nevertheless, it is important to analyze the quality of these biofuels and decide on the suitability of different energy crops for biofuel production and the clean-up of metal polluted sites, before the field-scale processes are implemented [55]. Among tested crops, sunflower has shown excellent performance due to its beneficial characteristics for both phytoremediation and bioenergy generation [56]. Significant efficacy in accumulating metal pollutants in the aboveground parts of the plants was exhibited by sunflowers, whereby bioconcentration and translocation factors ranged between 0.81 and 0.94. These efficiencies were markedly enhanced by the application of *Bacillus aryabhattai*, which elevated the bioconcentration and translocation factors to greater than 1 across all tested metals qualifying the sunflower as a hyperaccumulator species. The post-remediation sunflower residues with the built-up of metals possessed calorific values between 17.01 and 18.04 MJ/kg and were thermochemically treated under pyrolysis. This produced about 22.3 percent metal-free bio-oil, and 51.6 percent of biochar. The findings indicate possible sunflower plants as a great agent in phytoremediation process besides being used as a renewable energy source [57].

9. Challenges and future trends

To maximize the potential of sunflowers in phytoremediation of pollutants, several critical challenges need to be tackled. Soil conditions, the variability of climate and so on are environmental factors that influence the efficiency of remediation significantly. Genetic engineering presents promising possibilities for improving metal tolerance and accumulation in sunflower varieties, while also addressing adaptation to environmental variability. Furthermore, investigating the use of soil amendments like biochar, compost, and beneficial microorganisms can boost plant growth and enhance metal uptake, ultimately increasing their capacity to mitigate pollutants **[34]**.

10. Conclusions

Phytoremediation represents an innovative and eco-friendly strategy for addressing environmental Contaminants. By utilizing the natural abilities of plants, such as highly effective pollutant-accumulators like sunflowers, this method can restore polluted sites while aiding overall improvements in environmental conditions. Its versatility in managing a wide array of pollutants, including nanopollutants, underscores its ability to adapt to diverse environmental challenges. Aligning with ecological principles, phytoremediation minimizes reliance on chemical treatments, thereby lowering the chances of unforeseen negative impacts. Additionally, this approach fosters biodiversity and fortifies ecosystem resilience, delivering significant environmental benefits. Advancing research into the processes and factors that impact plant's effectiveness, especially in dealing with Nano pollutants, could pave the way for developing more precise and efficient phytoremediation techniques.

11. References

[1] Bhat, M. A., Gedik, K., & Gaga, E. O. (2023). Environmental impacts of nanoparticles: pros, cons, and future prospects. In *Synthesis of bionanomaterials for biomedical applications* (pp. 493-528). Elsevier. https://doi.org/10.1016/B978-0-323-91195-5.00002-7

[2] Mishra, M. (2019). Effect of accumulation of nanoparticles in soil health-a concern on future. *Frontiers in Nanoscience and Nanotechnology*. https://doi.org/10.15761/FNN.1000181

[3] Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., ... & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University-Science*, *34*(3), 101865. https://doi.org/10.1016/j.jksus.2022.101865

[4] Priya, A. K., Muruganandam, M., Ali, S. S., & Kornaros, M. (2023). Clean-Up of Heavy Metals from Contaminated Soil by Phytoremediation: A Multidisciplinary and Eco-Friendly Approach. *Toxics*, *11*(5), 422. https://doi.org/10.3390/toxics11050422

[5] Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. *Heliyon*, *10*(19). https://doi.org/10.1016/j.heliyon.2024.e38683

[6] DalCorso, G., Fasani, E., Manara, A., Visioli, G., & Furini, A. (2019). Heavy metal pollutions: state of the art and innovation in phytoremediation. *International journal of molecular sciences*, *20*(14), 3412. https://doi.org/10.3390/ijms20143412

[7] Mahardika, G., Rinanti, A., & Fachrul, M. F. (2018). Phytoremediation of heavy metal copper (Cu2+) by sunflower (Helianthus annuus l.). In *IOP conference series: earth and environmental science* (Vol. 106, No. 1, p. 012120). IOP Publishing. http://dx.doi.org/10.1088/1755-1315/106/1/012120

[8] Kaonda, M.K.M. and Chileshe, K. (2023) Assessment of Sunflower (Helianthus annuus L.) for Phytoremediation of Heavy Metal Polluted Mine Tailings—A Case Study of Nampundwe Mine Tailings Dam, Zambia. Journal of Environmental Protection, 14, 481-492. https://doi.org/10.4236/jep.2023.147028

[9] Qadir, M., Hussain, A., Shah, M., Hamayun, M., Al-Huqail, A. A., Iqbal, A., & Ali, S. (2024). Improving sunflower growth and arsenic bioremediation in polluted environments: Insights from ecotoxicology and sustainable mitigation approaches. *Heliyon*, *10*(12), e33078. https://doi.org/10.1016/j.heliyon.2024.e33078

[10] Yan A, Wang Y, Tan SN, Mohd Yusof ML, Ghosh S, Chen Z. Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. Frontiers in plant science. 2020 Apr 30;11:359. https://doi.org/10.3389/fpls.2020.00359

[11] Ashraf S, Ali Q, Zahir ZA, Ashraf S, Asghar HN. Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. Ecotoxicology and

environmental safety. 2019 Jun 15;174:714-27. https://doi.org/10.1016/j.ecoenv.2019.02.068

[12] Dutournie P, Jeguirim M, Khiari B, Goddard ML, Jellali S. Oilve mill wastewater form a pollution to green fells, agricultural water source, and bio-fertilizer. Part 2 : Water recovery. Water., 2019; 11(4): 768. https://doi.org/10.3390/w11040768

[13] Rehman, M. Z. U., Rizwan, M., Ali, S., Ok, Y. S., Ishaque, W., Saifullah, Nawaz, M. F., Akmal, F., & Waqar, M. (2017). Remediation of heavy metal contaminated soils by using Solanum nigrum: A review. *Ecotoxicology and environmental safety*, *143*, 236–248. https://doi.org/10.1016/j.ecoenv.2017.05.038

[14] Hasan MM, Uddin MN, Ara-Sharmeen I, F. Alharby H, Alzahrani Y, Hakeem KR, Zhang L. Assisting phytoremediation of heavy metals using chemical amendments. Plants. 2019 Aug 21;8(9):295. https://doi.org/10.3390/plants8090295

[15] Patel NA, Khan MD, Shahane S, Rai D, Chauhan D, Kant C, Chaudhary VK. Emerging pollutants in aquatic environment: source, effect, and challenges in biomonitoring and bioremediation-a review. Pollution. 2020 Jan 1;6(1):99-113. https://doi.org/10.22059/poll.2019.285116.646

[16] Yahya RT, Qaddawi ZT, Rasheed AA, Sultan SJ. Effect of diode laser rays in stimulating anthocyanin pigment levels in radish (*Raphanus sativus* L.) plant tissues. Journal of Applied and Natural Science. 2024;16(3):1158. https://doi.org/10.31018/jans.v16i3.5779

[17] Abid, N., Khan, A. M., Shujait, S., Chaudhary, K., Ikram, M., Imran, M., ... & Maqbool, M. (2022). Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review. *Advances in colloid and interface science*, *300*, 102597. https://doi.org/10.1016/j.cis.2021.102597

[18] . Raut, S. S., Singh, R., & Lekhak, U. M. (2024). Naturally occurring nanoparticles (NONPs): a review. *Next Sustainability*, *3*, 100037. https://doi.org/10.1016/j.nxsust.2024.100037

[19] Aflakian, F., Mirzavi, F., Aiyelabegan, H. T., Soleimani, A., Navashenaq, J. G., Karimi-Sani, I., ... & Vakili-Ghartavol, R. (2023). Nanoparticles-based therapeutics for the management of bacterial infections: A special emphasis on FDA approved products and clinical trials. *European Journal of Pharmaceutical Sciences*, *188*, 106515. https://doi.org/10.1016/j.ejps.2023.106515

[20] Morabito, K., Shapley, N. C., Mello, C., Calvert, P., & Tripathi, A. (2009). Nanoparticles and their applications in ultraviolet protection: a review. *Anal. Chem*, *1*, 1-10.

[21] Altammar, K. A. (2023). A review on nanoparticles: characteristics, synthesis, applications, and challenges. *Frontiers in microbiology*, *14*, 1155622. https://doi.org/10.3389/fmicb.2023.1155622

[22] Arora, R., Roy, T., & Adak, P. (2024). A review of the impact of nanoparticles on environmental processes. In *BIO Web of Conferences* (Vol. 86, p. 01001). EDP Sciences. https://doi.org/10.1051/bioconf/20248601001

[23] Wang, X., Yang, X., Chen, S., Li, Q., Wang, W., Hou, C., Gao, X., Wang, L., & Wang, S. (2016). Zinc Oxide Nanoparticles Affect Biomass Accumulation and Photosynthesis in Arabidopsis. *Frontiers in plant science*, *6*, 1243. https://doi.org/10.3389/fpls.2015.01243

[24] Jan, N., Majeed, N., Ahmad, M., Ahmad Lone, W., & John, R. (2022). Nano-pollution: Why it should worry us. *Chemosphere*, *302*, 134746. https://doi.org/10.1016/j.chemosphere.2022.134746

[25] Gao, Y., Yang, T., & Jin, J. (2015). Nanoparticle pollution and associated increasing potential risks on environment and human health: a case study of China. *Environmental science and pollution research international*, *22*(23), 19297–19306. https://doi.org/10.1007/s11356-015-5497-0

[26] Rajput, V. D., Minkina, T., Sushkova, S., Tsitsuashvili, V., Mandzhieva, S., Gorovtsov, A., ... & Gromakova, N. (2018). Effect of nanoparticles on crops and soil microbial communities. *Journal of Soils and Sediments*, *18*(6), 2179-2187. https://doi.org/10.1007/s11368-017-1793-2

[27] Gohar, F., Iqbal, U. Z., Khan, M. B., Rehman, F., Maryam, F. S. U., Azmat, M., ... & Shahid, M. U. (2024). Impact of nanoparticles on plant growth, development and physiological processes: A comprehensive review. https://doi.org/10.20944/preprints202410.0780.v1

[28] Rajwade, J. M., Oak, M. D., & Paknikar, K. M. (2024). Copper-based nanofungicides: The next generation of novel agrochemicals. In *Nanofungicides* (pp. 141-168). Elsevier. https://doi.org/10.53555/jaz.v44iS5.3481

[29] Roy, B., Murugesan, K., Mathanmohun, M., & Sathian, B. (2023). Impact of nanoparticles on human health and disease. *Nepal journal of epidemiology*, *13*(4), 1294–1297. https://doi.org/10.3126/nje.v13i4.61245

[30] Wallbanks, S., Griffiths, B., Thomas, M., Price, O. J., & Sylvester, K. P. (2024). Impact of environmental air pollution on respiratory health and function. *Physiological reports*, *12*(16), e70006. https://doi.org/10.14814/phy2.70006

[31] Su ZH, Xu ZS, Peng RH, Tian YS, Zhao W, Han HJ, Yao QH, Wu AZ. Phytoremediation of trichlorophenol by phase II metabolism in transgenic Arabidopsis overexpressing a Populus glucosyltransferase. Environmental science & technology. 2012 Apr 3;46(7):4016-24. https://doi.org/10.1021/es203753b

[32] Nedjimi B. Germination characteristics of Peganum harmala L.(Nitrariaceae) subjected to heavy metals: Implications for the use in polluted dryland restoration. International Journal of Environmental Science and Technology. 2020 Apr;17(4):2113-22. http://dx.doi.org/10.1007/s13762-019-02600-3

[33] Liu S, Yang B, Liang Y, Xiao Y, Fang J. Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. Environmental Science and Pollution Research. 2020 May; 27:16069-85. https://doi.org/10.1007/s11356-020-08282-6

[34] Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. *Heliyon*, *10*(19). https://doi.org/10.1016/j.heliyon.2024.e38683

[35] Sylvain, B., Mikael, M. H., Florie, M., Emmanuel, J., Marilyne, S., Sylvain, B., & Domenico, M. (2016). Phytostabilization of As, Sb and Pb by two willow species (S.

viminalis and S. purpurea) on former mine technosols. *Catena*, *136*, 44-52. https://doi.org/10.1016/j.catena.2015.07.008

[36] Masindi V, Muedi KL. Environmental Contamination by Heavy Metals [Internet]. Heavy Metals. In Tech; 2018. Available from: https://doi.org/10.5772/intechopen.76082

[37] Mahar, A., Wang, P., Ali, A., Awasthi, M. K., Lahori, A. H., Wang, Q., et al. (2016). Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. *Ecotox. Environ. Safe.* 126, 111–121. https://doi.org/10.1016/j.ecoenv.2015.12.023

[38] Awa SH, Hadibarata T. Removal of heavy metals in contaminated soil by phytoremediation mechanism: a review. Water, Air, & Soil Pollution. 2020 Feb;231(2):47. https://doi.org/10.1007/s11270-020-4426-0

[39] Ali H, Khan E, Sajad MA. Phytoremediation of heavy metals—concepts and applications. Chemosphere. 2013 May 1;91(7):869-81. https://doi.org/10.1016/j.chemosphere.2013.01.075

[40] Jacob JM, Karthik C, Saratale RG, Kumar SS, Prabakar D, Kadirvelu K, Pugazhendhi A. Biological approaches to tackle heavy metal pollution: a survey of literature. Journal of environmental management. 2018 Jul 1;217:56-70. https://doi.org/10.1016/j.jenvman.2018.03.077

[41] Awa SH, Hadibarata T. Removal of heavy metals in contaminated soil by phytoremediation mechanism: a review. Water, Air, & Soil Pollution. 2020 Feb;231(2):47. https://link.springer.com/article/10.1007/s11270-020-4426-0

[42] DalCorso G, Fasani E, Manara A, Visioli G, Furini A. Heavy metal pollutions: state of the art and innovation in phytoremediation. International journal of molecular sciences. 2019 Jul 11;20(14):3412. https://doi.org/10.3390/ijms20143412

[43] Brandt R, Merkl N, Schultze-Kraft R, Infante C, Broll G. Potential of vetiver (Vetiveria zizanioides (L.) Nash) for phytoremediation of petroleum hydrocarbon-contaminated soils in Venezuela. International journal of phytoremediation. 2006 Dec 1;8(4):273-84.

[44] Murphy, D. J. (2025). Agronomy and Environmental Sustainability of the Four Major Global Vegetable Oil Crops: Oil Palm, Soybean, Rapeseed, and Sunflower. *Agronomy*, *15*(6), 1465. https://doi.org/10.3390/agronomy15061465

[45] Zhao, X., & Li, G. (2025). *Impact of Single and Mixed Heavy Metal Contamination on Accumulation Patterns and Organ Distribution in Sunflowers* (No. EGU25-8466). Copernicus Meetings. https://doi.org/10.5194/egusphere-egu25-8466

[46] Adejube AA, Anteyi A, Garba FH, Oyekunle OA, Kudaisi FO. Bioremediating activity of sunflower (Helianthus annuus L.) on contaminated soil from Challawa Industrial Area, Kano-State Nigeria. International Journal of Agriculture and Earth Science. 2017;3(5):1-1.

[47] Day S, Özgen Y. Titanium dioxide nano particles improving impact on sunflower seedling's emergence performance. Ant J Bot. 2023;7(2):108-11. https://doi.org/10.30616/ajb.1270434

[48] Bakheit, B. R., Ali, E. A., Omar, A. A., & Hamed, H. A. (2022). Impact of Planting Methods and Foliar Spraying with Zinc Dioxide Nanoparticles on the Seed and Oil Yields of Sunflower. *Assiut Journal of Agricultural Sciences*, *53*(3), 1-13. https://doi.org/10.21608/ajas.2022.127476.1115

[49] Alamery, A. A., & Ahmed, N. A. (2020). Effect of biofertilizers and zinc nano particles on growth, yield and oil percentage of sunflower (Helianthus annuus L.). Plant Archives, 2020, Vol. 20, No. 2, 4648-4652. https://share.google/PKiUK8jk331ujGJF6

[50] Fatemi, A., Moaveni, P., Daneshian, J., Mozafari, H., & Ghaffari, M. (2022). Magnesium nanoparticles improve grain yield, oil percentage, physiological, and biochemical traits of sunflower (Helianthus annuus L.) under drought stress. *Journal of Agricultural Science and Technology*, *24*(3), 665-678. http://jast.modares.ac.ir/article-23-44376-en.html

[51] Gupta A, Bharati R, Kubes J, Vachova P, Popelkova D, Mahawar L, et al. Ferric oxide nano-priming enhances photosynthetic and physicochemical properties of sunflower (Helianthus annuus L.) microgreens. Plant Soil Environ. 2024;70(11):702-711. https://doi.org/10.17221/272/2024-PSE

[52] Ali S, Mehmood A, Khan N. Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. Journal of Nanomaterials. 2021;2021(1):6677616. https://doi.org/10.1155/2021/6677616

[53] Prasad, M. N. V. (2024). Bioremediation and bioeconomy potential of sunflower (Helianthus annuus L.). In *Bioremediation and Bioeconomy* (pp. 367-381). Elsevier. https://doi.org/10.1016/B978-0-443-16120-9.00020-0

[54] Wijekoon, W., Priyashantha, H., Gajanayake, P., Manage, P., Liyanage, C., Jayarathna, S., & Kumarasinghe, U. (2025). Review and Prospects of Phytoremediation: Harnessing Biofuel-Producing Plants for Environmental Remediation. *Sustainability*, *17*(3), 822. https://doi.org/10.3390/su17030822

[55] Marques, A. P., Paulo, A., & Caetano, N. S. (2024). Assessment of the potential of sunflower grown in metal-contaminated soils for production of biofuels. *Sustainability*, *16*(5), 1829. https://doi.org/10.3390/su16051829

[56] Zehra, A., Sahito, Z. A., Tong, W., Tang, L., Hamid, Y., Khan, M. B., ... & Yang, X. (2020). Assessment of sunflower germplasm for phytoremediation of lead-polluted soil and production of seed oil and seed meal for human and animal consumption. *Journal of Environmental Sciences*, *87*, 24-38. https://doi.org/10.1016/j.jes.2019.05.031

[57] Amabogha, O. (2022). *Combining phytoremediation with bioenergy production; exploring options for sustainable remediation* (Doctoral dissertation, Middlesex University). ISO 690