



Phytoremediation of Metal Nanoparticles from the Contaminated Water

Bodies: A Review



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Abstract

The increment of industrialization brings metal nanoparticles (MNPs) contamination and different waste materials into the world. These hazardous toxic substances may be accessible in water conditions. Water pollution with MNPs causes severe adverse impacts on a wide range of aquatic animals and plants. Phytoremediation is an eco-accommodating and practical measure for the elimination of toxic metals including MNPs from polluted water bodies. The assurance of a suitable plant species is the biggest perspective for productive phytoremediation. The utilization of water plants holds steep capability for the removal of normal and inorganic pollutions. Aquatic weeds like water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna minor*) water lettuce (*Pistia stratiotes L.*), and several other submerged plants are prominent metal accumulator plants that can be used for the removal of MNPs. The tremendous advancement of aquatic plants can add to the issue of water pollution; regardless, these plants can be utilized to handle other natural problems which are executed in today's life.

Keywords: Phytoremediation, Aquatic plants, Water contamination, Metal nanoparticles.

1. Introduction

A growing field is nanotechnology, and the new uses of nanomaterials depend on qualities related to their original size and other features. These nanomaterials provide new solutions for long-persisting issues, and their utilization has expanded significantly. Furthermore, nanomaterials exhibit diverse morphologies, such as nanoparticles, nanorods, nanoflowers, nanowires, nanosheets, and nanofibers [6-1], as shown in Fig. 1. These results in significantly unique ecological purposes and practices. The implementation of nanotechnology, along with inadequate management of nanomaterial practices, exacerbates the issue [7]. Unplanned

discharge of effluent, use in the soil in the procedure of pesticides, remediate, and so on. The practice of nanometals containing amendments in the soil related to fertilizers, compost, biosolids, etc., and polluted water utilized in farming are the main points of concern for toxicity. The entry of metal nanoparticles (MNPs) into the soil, sediments, and water exerts adverse results on plants and living organisms [8, 9]. The discharge of untreated wastewater or treatment effluents directly into the water comes with numerous nanometals, which harm the environment. These water bodies hold nanometals that go into the surface's part, create an unsettling way of transport, and show adverse effects [10-12]. The presence of

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unique properties containing physical, chemical, and optical MNPs is in high demand in many applications [13-16]. Noble MNPs can also be used to separate heavy metals [17].

The exposure of suspended MNPs in the air, which starts from the discharge, an exposure causes uncontrolled toxicological impacts on living beings as well as the water ecosystem. The unrestricted effort of nanoparticles can come indirectly in contact with the skin and swallowing in the body. When MNPs expand in the air, aquatic, and soil, they can experience a few potential changes such as dissolution, accumulation, and different responses with biomacromolecules, depending upon the things of both the nanoparticles and the accepted inidum [18, 19]. The nanoparticle's presence in plant production products, fertilizers, and waste treatment products such as sludges and biosolids causes soil toxicity.

Aquatic plants like *Vallisneria spiralis L.*, *Najas guadelupensis*, *Elodea canadensis*, *Pistia stratiotes L.*, *Riccia fluitans L.*, *Salvinia natans L.*, and *Limnobium laevigatum*) can quickly remove several contaminants from the water [20, 21]. The floating aquatic plants provide a high contact area with the surrounding water and enhancing their absorption capacity due to the direct contact of the plant body with the pollution medium [22, 23].

Therefore, aquatic plants are generally utilized in phytoremediation [24, 25]. Phytoremediation of MNPs can be considered a green and sustainable approach for environmental cleanup. It is a green, low-cost, ecologically sustainable, and socially acceptable technique [26-28]. It involves using plants to absorb and accumulate MNPs from contaminated soils or water. While phytoremediation offers several advantages, it is important to consider potential concerns related to secondary pollution. If the plants are not properly managed, harvested, or disposed of, there is a possibility of creating a secondary pollution issue. To ensure the sustainability of phytoremediation, it is crucial to implement proper management practices including monitoring and assessment, harvesting and disposal, risk assessment, and plant selection. By implementing these management practices, the risks of secondary pollution can be significantly reduced. Phytoremediation uses green plants to remove contaminated soil, water, and air pollutants. The advantages of phytoremediation include a high level of remediation that does not harm the environment; it is practical, eco-friendly, and provides the opportunity for more toxin removal from green plants [29] and testing the cleaning methods. The application of aquatic plants in phytoremediation positively affects expelling MNPs harmfulness from

the contaminated water in a characteristic manner, and now it is planned out everywhere in the world. They are standard safeguards for metals and nanometals contaminants.

This review offers a novel and comprehensive analysis of the current state of research on phytoremediation of MNPs from water bodies. This review explores the most recent advancements in the field, addressing key issues and providing a detailed understanding of the mechanisms involved in the phytoremediation process. In addition, it sheds light on a critical environmental issue and offers a potential solution for the removal of MNPs from contaminated water bodies. Some other reviews have focused on different aspects of phytoremediation, such as the use of microbes or the effects of nanoparticles on plants. This review focuses specifically on the use of plants for metal nanoparticle removal. Additionally, this review provides a critical analysis of the potential limitations and challenges associated with the use of plants for phytoremediation, which can serve as a valuable guide for future research in the field.

2. Sources of the metal nanoparticles

MNPs are widely used in various industrial applications, and their production has increased significantly in recent years [30-35]. As a result, the release of MNPs into the environment has become a major concern due to their potential adverse effects on human health and the environment. The primary sources of MNPs include industrial effluents, wastewater treatment plants, agricultural runoff, and atmospheric deposition. Industrial activities such as manufacturing, construction, and mining, are major sources of MNPs in the environment. During these processes, MNPs are released into the air or water as by-products, which can lead to the contamination of nearby water bodies and ecosystems. Additionally, the use of MNPs in consumer products, such as cosmetics, textiles, and electronics, has also contributed to their release into the environment.

Wastewater treatment plants are another significant source of MNPs, as they are not always designed to remove these particles effectively. MNPs in wastewater can accumulate in the biosolids produced during the treatment process, which are then used as fertilizers or disposed of in landfills, potentially leading to further environmental contamination. Agricultural runoff is another source of MNPs in the environment. The use of metal-based pesticides and fertilizers in agriculture can lead to the accumulation of MNPs in soil and water bodies. Atmospheric deposition, such as the release of MNPs from industrial emissions, also contributes to the presence of these particles in the environment. Understanding

the sources of MNPs is essential for effective environmental management and remediation strategies. Identifying and controlling these sources can help reduce the release of MNPs into the environment, which can have significant implications for human health and the environment.

MNPs are released into water bodies from various sources, including industrial activities, agricultural activities, atmospheric deposition, and wastewater treatment plants [36]. Copper (Cu), zinc (Zn), iron (Fe), nickel (Ni), titanium dioxide (TiO₂), and silver (Ag) nanoparticles are some of the most common types of MNPs that contribute to water body contamination [37].

Cu nanoparticles are widely used in electronic devices, paints, and coatings, and their release into the environment can occur through industrial effluent and atmospheric deposition [37]. Zn nanoparticles are used in various products, including cosmetics, sunscreens, and surface coatings, and their release into the environment can occur through the use of these products or industrial activities [38]. Ni nanoparticles are used in the production of alloys, coatings, and catalysts, and their release into the environment can occur through industrial activities [36]. TiO₂ nanoparticles are widely used in the cosmetics industry and have been detected in wastewater treatment plants and natural water bodies [37].

Understanding the sources of MNPs is important for developing effective environmental management and remediation strategies. It can also aid in the development of regulations and policies that aim to control the release of MNPs into water bodies. Some of the techniques used to remediate metal nanoparticle contamination in water bodies include phytoremediation, bioremediation, and chemical remediation [36]. The utilization of MNPs in the different day-by-day use items like Ag NPs is getting numerous considerations like antimicrobial operators, cleansers, wastewater treatment, food stockpiling holders, food bundling materials, room splashes, paints, soaps, and shampoos [39]. Their untreated removal of MNPs into water causes poisonousness in aquatic bodies and soil. The water bodies may pollute by straightforwardly or indirectly releasing mechanical effluents and waste materials, which comprises MNPs that discharge contaminant climate in the surroundings. Nanoparticles can be unrestricted into the soil throughout manufacturing, farming, industrialized uses, or accidental leaks [40]. These MNPs cause toxicity. They respond with water and are connected with the natural way of life, and they are effectively retained in the cell layer [10], as shown in Fig. 1.

Presenting MNPs to complex aquatic situations brings about substance and physical modifications of

particles disintegration and oxidation—decreased responses will alter the first structure. Different mixtures, such as humic substances, proteins, and other small natural atoms, can cover or replace surface MNPs gathers, which are the center of potential coatings and molecule coatings. Such modifications are likely to control the course of things and the estimated toxicity of MNPs [41].

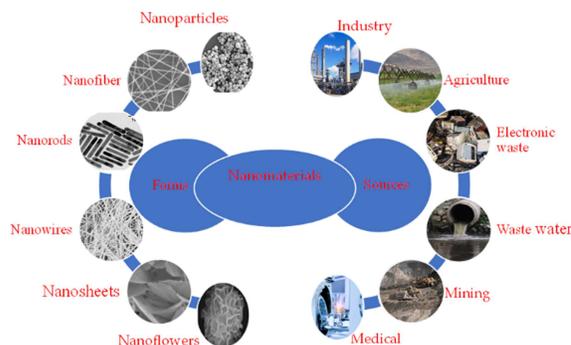


Fig. 1: Various morphologies of metal nanoparticles and their sources in water bodies.

3. Toxicity of metal nanoparticles

The varying effectiveness of metal and metal oxide NPs in phytoremediation can be explained by several factors. Firstly, metal oxide NPs exhibit greater surface reactivity and a stronger tendency to be absorbed by plants compared to pure MNPs. Furthermore, metal oxide nanoparticles possess attributes such as a large surface area, low solubility, minimal environmental effects, and the absence of secondary pollutants [42]. Secondly, metal oxide NPs can undergo redox reactions, leading to alterations in their chemical forms and toxicity. Moreover, the presence of metal oxide NPs can impact plant physiology, influencing growth patterns and nutrient absorption. Having a comprehensive understanding of these distinctions is essential for maximizing phytoremediation efficiency and evaluating the potential hazards associated with different types of nanoparticles.

3.1. Toxicity of metal nanoparticles on plants

Metal oxide nanoparticles of Zn, Ag, Ce, Ni, Cu, Ti, Al, and Fe are majority utilized in enterprises and are generally read for their effects on various plants. Seed development, plant progress, and biomass are the major indicators for evaluating the toxicity of trace elements in plants [43-46]. Numerous experiments have been reported on translocation, absorption, and harmfulness in plants. The accumulation and development of plants and MNPs impact are detected by way of the composition, concentration, and proportions of the deposited MNPs, which lie on the plant tissue and cell. MNPs

create a physical and chemical change in plants, which is carried on by their presence. In the dissolution, water-soluble as metal ions, MNPs play a character as interactors and catalysts.

The main property affecting plant root take-up of MNPs is molecule size. Surely, size determination exists in the take-up of MNPs by plants. It has accounted, however, for conflicting outcomes in the collected works. For *Lemna minor*, the diameter of the fronds or leaves can range from 10-80 millimeters. The reduction in the number of fronds can be between 0.005 to 0.04. There is also a slowing of growth and chlorosis (yellowing) of the leaves. The number ranges in this case are referring to the size and magnitude of the observed changes in the plant's physical characteristics and growth patterns [47]. For *Cymodocea nodosa*, the size of the leaves is specified as having a diameter of 35, but it is not clear what unit is being used (it could be millimeters or centimeters, for example). The range of the observed decrease in length of leaves is between 0.0002 to 0.2, but again, the unit is not specified. Additionally, there is an induction of an oxidative stress indicator (H_2O_2), which is a measurement of the plant's response to stress, as well as changes in the activity of antioxidative enzymes and the presence of fewer actin and tubulin filaments. These measurements and indicators provide information about the plant's physiological responses to different stimuli or conditions.

Isoetes japonica and *Oenanthe javanica* presented 1.8 mg/L TiO_2 NPs, and nanotube TiO_2 shapes more than 17 d (enlightenment not announced). Bioaccumulation of Ti is broken down for the complete body. After 17 days, the total amount of Ti that had been collected in *O. javanica* under the entry of TiO_2 NPs and the acceptance of TiO_2 NPs was 489.1 mg/g. The total body Ti of *I. japonica* was 54.5 mg/g before the addition of TiO_2 NPs and 155.2 mg/g after the addition of TiO_2 NPs. It did not clarify to represent contrasts in the gathering of TiO_2 NPs and TiO_2 NPs; however, the difference may lie in their distinct morphologies, where the route of TiO_2 NPs at destinations of contact constrained the opportunity of disguise. *O. javanica* survived the translocation of Ti, with Ti aggregation being 424.4 mg/g (roots) and 64.7 mg/g (shoots) under the presentation of TiO_2 NPs. In contacts to TiO_2 NPs Ti focuses were lower: 73.6 mg/g (roots) and 5.9 mg/g (shoots). Since TiO_2 NPs mixes are ineffectively dissolvable, scientists have considered the association and bioaccumulation of TiO_2 NPs to be determined by nanoframes. They have not performed disintegration examinations [48]. Furthermore, these studies examined how the morphology and exposure location of engineered

nanoparticles (ENPs) can impact their bioaccumulation by aquatic plants [48].

Salvinia natans was exposed to 1, 10, 20, and 50 mg/L ZnO NPs for 7 days together with 44 mg/L $ZnSO_4$ [49]. Zn accumulation following ZnO NP exposures was from 0.45 to 3.65 mg/g in leaves, 0.33 to 2.97 mg/g in flushed roots, and 0.49 to 8.18 mg/g in unflushed roots. Zn bioaccumulation after $ZnSO_4$ exposure was 4.28 mg/g in leaves, 3.82 mg/g in flushed roots, and 3.64 mg/g in unflushed roots. When compared to releases of 50 mg/L ZnO NPs, the results indicated that $ZnSO_4$ had a larger potential for bioaccumulation. The concentration of adsorbed MNPs was demonstrated by the fact that bioaccumulation was stronger from presentation to ZnO NPs than to $ZnSO_4$ due to unflushed roots. ENPs adsorption on root surfaces is shown by the huge differences in bioaccumulation between washed and unflushed attaches exposed to ZnO NPs. Because ZnO NP agglomerates had settled to the bottom of the experiment jar after 7 days, no suspended ZnO NPs could be identified in the testing suspension media. Additionally, ZnO NPs in suspension were discharged because of adsorption to root surfaces.

The disintegration investigation affirmed the nearness of disintegrated Zn in the suspension of ZnO NPs exposures. Hence, Zn aggregation was likely the outcome of ZnO NPs and the absorption and disguise of breaking down Zn structures, with the last procedure dominating. Entirely, the disguise of ZnO NPs was improbable considering the development of huge agglomerates up to 1.6 mm in size, unreasonably huge for a cell disguise. Despite being more substantial in the leaves on average, the zinc concentration of the washed roots and leaves did not differ significantly. Such results may be improperly interpreted as evidence of the dynamic translocation of zinc from the roots to the leaves. *Salvinia species* keep contaminants out of the water through their leaves just like they do through their roots [50]. The information on Zn bioaccumulation recommends that the procedure is legitimately identified with presentation fixation and that the take-up rate for broke up Zn is more significant than that for the nanoparticles. Changes repressed the take-up of ZnO NPs; for example, agglomeration [51] by *Landoltia punctata* accumulated approximately 700 mg/g Cu in the fronds and 800 mg/g Cu in the roots afterwards exposure to 1 mg/L CuO NPs for 14 d. The plants were exposed to 0.2 mg/L or 0.6 mg/L dissolved Cu ($CuCl_2$) in the same study. The bioaccumulation of Cu from the 0.2 mg/L exposure was around 100 mg/g (fronds) and 300 mg/g (roots), whereas the 0.6 mg/L exposure produced 500 mg/g (fronds) and 700 mg/g (roots). Even though the results point to a higher absorption rate for CuO NPs, it is challenging to draw

comparisons because CuCl_2 and CuO NP exposure concentrations were different. The bioaccumulation from CuO NPs openings likely came about because of the take-up of dissolvable Cu (based on disintegration discoveries), adsorption of CuO NPs, and possibly their disguise. The discoveries further proposed transportation of Cu and CuO NPs from the roots to the leaves, yet there is a need for attentive, as this plant's leaves are equipped for engrossing supplements from the general climate.

Generally, the take-up of disintegrated Cu has all the assigns of being the primary driver of CuO NPs bioaccumulation, considering the discoveries [52]. Besides, it can likewise result from the amassing of both broken-up and particulate Cu structures [53]. Curiously, the findings of Shi *et al.* [51] vary from others [52], because it accounted for the amassing of CuO NPs to be higher than CuCl_2 openings [51, 54]. The exposure doses of CuCl_2 (0.2 mg/L, 0.6 mg/L) and CuO NPs (1 mg/L) varied, though, and this may have caused an underestimation of the potential for soluble Cu accumulation. It also makes it impossible to accurately compare the accumulation of soluble Cu and CuO NPs.

3.2. Toxicity of metal nanoparticles on animals

The entry of MNPs into animal and human bodies can be conceivable through various ports. Lots of anthropogenic ways made it possible for MNPs entry into the bodies. The neural uptake of breathed in nanoparticles may be restricted by the blood-cerebrum barrier and olfactory nerves [55]. Nanoparticles (particularly of a metallic sort) tend to quickly enter the circulatory framework [56]. In this method, once in the circulatory system, the transportation of nanomaterials can happen around the body and be used up by organs and tissues, including the bone marrow, cerebrum, heart, spleen, liver, kidneys, and sensory system [56, 57]. Despite the above realities, data is small on the conduct of nanoparticles in the body [58]. Under follows a concise conversation on the important ports of nanoparticle transport and hidden components in the active being.

The expansion of nanotechnology in the food and horticulture segments has drawn in open considerations over the past decade. Either intentionally or accidentally adding nanomaterials to food or unexpectedly presented through movement [59] in numerous food and agribusiness items. Thus, worries over natural and human well-being emerge as the spread of nanomaterials extends, attributable to nanomaterials' kind of physicochemical properties [60].

The worries over natural well-being are an immediate outcome of the collaboration of nanomaterials utilized as nanomanures, nanopesticides, and

immobilized nanosensors. The basic physiochemical characteristics of the nanomaterials determine their behavior and outcome to a large extent. Furthermore, the consistency of the conduct and outcome of nanomaterials is restricted by the multidimensional nature of natural settings. The complex interaction between nanotechnology, biology, and ecology makes it challenging to monitor and trace the flow of nanomaterials [61]. Although the comprehensive technique has recommended understanding the interaction between nanomaterials and the bioecosystem. A convincing assessment of ecological nanotoxicity is necessary to read the biotic and abiotic circumstances in an associated biological system [62]. To illustrate the challenges and possible testing procedures involved in evaluating the risks linked to nanomaterials, we present the example of aluminum nanoparticles in relation to human digestion. The tests conducted during the early stages of digestion were not altered in simulated saliva.

Molecule accumulation may happen whenever during the assimilation procedure; however, all together in stomach liquid for the most part. Aluminum NPs start to disintegrate and discharge aluminum particles in stomach liquid incompletely. Likewise, nonparticulate structures are shaped all over again from free particles. A similar routine applies to Ag NPs. Ag colloids are interconnected blends of different species that are kept on the surface of any media [63, 64]. This triggers the arrival of Ag particles as both guilty parties for poisonousness [65, 66].

It observed that embryonic development in amphibians shows a weak lethal effect at high concentrations in embryos at the early stage. CuO NPs, TiO_2 NPs and ZnO NPs did not incite incipient organisms to pass yet performed teratogenic effects, especially on the digestive tract when fixations were greater than 50 mg/L. ZnO NPs set off the maximum extreme effects on the intestinal obstruction, promoting the entry of MNPs into connective tissue. The teratogenicity of TiO_2 NPs was weak and may have been hidden by physiological effects. However, broken-down particles coming from CuO NPs could be liable for some effects, not ZnO [67]. The assessment of the negative impacts of TiSiO_4 nanoparticles estimated to be smaller than 50 nm demonstrated a mortality rate of less than 11% in *Pelophylax perezii tadpoles (Rana perezii)*. On the other hand, melanin and lactate both experienced significant effects, leading to an increase in oxidative pressure. TiSiO_4 NPs had a significant impact on these species [68].

Warm-blooded animals and mainly people presented to MNPs can enter the body with inward breath, and many works concerning clinical effects have been distributed [56, 57]. MNPs can also enter the body

through the skin. In every situation, the MNPs' size permits endocytosis to enter a cell and transcytosis to infiltrate several cells gradually. This allows MNPs to reach the apprehensive closures of the olfactory epithelium during inhalation, and then the axons proceed to the olfactory bulbs in the cerebral cortex where they affect neurons. Differently, MNPs entered the lungs, found blood, and attempted to clear the blood-brain barrier. They can also reach various organs like the bone marrow, lymph nodes, the spleen, or the heart. Studies have demonstrated that MNPs (magnetic nanoparticles) can induce inflammation, prooxidant activity, concentrated pressure, and alterations in mitochondrial distribution. These effects were found to be dependent on the type of MNPs used [56, 57].

Zebrafish is undoubtedly a decent model for MNPs contemplates. In any case, other fish species, for example, trout, are likewise to an excessive range utilized. The effects of TiO₂ NPs were investigated in trout hepatocytes. For that, the effects researched concerned nanomaterials utilized, for example, C₆₀ fullerene, MWNTs, SWNTs, with or without a characterized work, and TiO₂ NPs estimating 5-200 nm. Examinations verified that they discovered these substances demonstrating Ecotoxicological effects. In every circumstance, a few analyses uncovered a nearness of Co build-ups, which did not enter the MNPs constitution but found their beginning in the creation continuing. Follow components were maybe liable for poisonous effects. Systems, for example, an encouraging means of transportation connected to the nearness of MNPs, could build a toxic reaction like just presentation to similar atoms in the fluid arrangement [69].

Despite the wide range of materials that make up nanoparticles [70], only a small number of them are being employed extensively, putting the environment at risk of exposure. As a result, these materials were primarily investigated for their effects on various plant species. Certain MNPs, like single-walled carbon nanotubes and fullerene, have undergone extensive research to identify the mechanisms underlying their nanotoxicity. On the other hand, under exposure to single-walled carbon nanohorns, enhanced growth, as well as accelerated seed germination for several organs of maize, tomato, rice, and soybean, have been observed [71]. According to [72], nanoparticles have been produced in recent years for use in agriculture as nanopesticides and nanofertilizers, as well as nanocarriers for pesticides and fertilizers. Nanoparticles of chitosan were utilized to contain herbicide, due to which the efficacy of herbicide was seen to be boosted considerably [73]. Mesoporous silicon nanoparticles have also been utilized to transfer DNA, proteins, and

other substances to plants as metalloidal nanoparticles [74]. Nanoparticles, such as nanozeolite (the fundamental building blocks of silicate (SiO₄) and aluminates (AlO₄) tetrahedrons), hydrogels (composed of various polymers such as chitosan and alginate), which improve soil quality, and nanosensors are used in agriculture (for monitoring plant and soil health [75]). Silica nanoparticles are not hazardous to plants; however, some authors have noted a toxic effect because of changes in the pH of the media after the addition of the nanoparticles. Silica nanoparticles can reduce the phytotoxicity of chromium (VI) in *Pisum sativum* (L.) seedlings [76]. Several studies on the effects of metal and metal oxide nanoparticles on plants have demonstrated a toxic effect on plants, whereas a small number of studies have also indicated their beneficial role in enhancing plant growth parameters and productivity [77-79].

Research data on size, concentration, zeta potential, uptake by types of plants and impacts on the plant are required to evaluate whether the metal and metal oxide nanoparticles pose a concern to plant species and the environment. In particular, the zeta potential is a very accurate indicator of the coagulation and reactivity of nanoparticles in solution. Zeta potential, which represents the combined electric potential of all ions and particles in solution, is affected by variations in pH and ionic strength [80]. Plants are subject to a variety of physiological, morphological, and genotoxic alterations because of nanoparticle exposure. Consequently, it is crucial to understand the function of specific nanoparticles to employ nanotechnology in agriculture effectively [81].

3.3. Toxicity of metal nanoparticles on humans

The lungs, skin, and gastrointestinal systems of animals and people serve as three major entry points for distinctive or anthropogenic nanoparticles into the body, as may be inferred from their continual touch interaction with the condition. Nanoparticles can enter an animal or human body through a variety of ports. As it may, infusions and inserts can likewise be other potential courses of nanoparticle passage explored [58, 82]. Strikingly, the blood-mind hindrance and olfactory nerves may interfere with the neuronal take-up of breathed in nanoparticles [55]. Similarly, the movement of interstitially introduced elements through the lymphatic system and their subsequent confinement in the lymph nodes has been reported [83]. Nanoparticles (particularly of the metallic sort) tend to quickly enter the circulatory framework. Once in the circulatory system, nanomaterials can travel throughout the body and enter organs and tissues like the bone marrow, liver, kidneys, spleen, and the sensory system [56, 57].

Despite the above realities, data is small on the conduct of MNPs in the body [58].

The physical barrier between the mind and veins known as the blood-cerebrum obstacle consists of a negative electrostatic charge. This boundary helps explicitly in limiting the entrance of specific substances. The cationic particles increase the blood-brain barrier's absorption through charge balance, whereas the anionic obstruction can also help stop usually anionic atoms. Numerous types of exploration have concentrated on this course with the completion goal of medication conveyance to the mind. Furthermore, several irritants and circulatory conditions (such as hypertension) were thought to increase the blood-brain barrier's susceptibility to absorption, which would eventually allow the nanoparticles to reach the sensory system [41].

Numerous actual nerve endings can be seen in the nasal and tracheobronchial regions. The disguising of the inhaled nanoparticles from the olfactory mucosa through the olfactory nerves in the olfactory bulb is supported by comprehensive reports. In the rodent, inward breaths of nanomagnesium oxide 30 nm and nanocarbon 20–30 nm [55] were accounted for. The translocation of the breathed in nanoparticles to the olfactory bulb was additionally proved. Furthermore, nanoparticles can likewise be translocated into more profound cerebrum structures.

About 300 million alveoli make up a human lung's inner surface area, which ranges from 75 to 140 m². This huge apparent territory goes about as the primary section entryway for breathed in particles. After an inward breath, nanoparticles first collaborate in the respiratory tract with the coating liquid made of proteins and phospholipids. The strong material can arrive at the gas trade surfaces off the chance that it is circular with widths less than 10 mm. Due to gravitational settling, capture efforts, and impaction, the respiratory tract can store the elements that are farthest away. Most particle parts having a littler width can be more influenced by dissemination, and these can be amassed in the alveoli and littler aviation routes. Littler width strands can enter the lung; however, the strands with a highly long viewpoint proportion stay on the high aviation routes. By the way, straight, long strands can enter profoundly into the alveolar district held there due to the much slower procedure of freedom by the alveolar macrophages [82].

As a result, the fluid air contact moistened the particles and moved them towards the epithelium [41]. Within sight of past irritation, esophageal epithelial cells can absorb nanoparticles following contact. It typically takes a few hours for the bronchial epithelial cells to transport the mucous layer covering the lungs particles into the throat using their cilia. If a significant number of oxidative

mixtures are breathed in, the protective cell reinforcements of the physiological fluid layer may get exhausted.

Be that as it may, nanoparticle entrance through the skin in the body may incorporate three potential infiltration pathways, specifically, intracellular, intercellular and follicular. The three layers of human skin are the epidermis, subcutaneous dermis, and dermis. The outer layer of the epidermis layer corneum is composed of a keratinized layer of dead cells that is 10 mm thick and is typically difficult to penetrate by ionic mixtures and dissolvable water particles. The epidermis surface is typically seen to be quite finely organized, exhibiting a flaky appearance with pores for sweat, sebaceous organs, and hair follicle locations. Infiltration of nanoparticles through the corneum layer has also been demonstrated. Hair follicles, flexing skin, and fractured skin can all be key section routes for nanoparticles. Toxicological examinations are broad on TiO₂ because of its noteworthy practice in the beautifying agent industry. The most significant measure of covered TiO₂ was discovered confined in the upper piece of the layer corneum.

3.4. Nanoparticles effect on the food chain

They begin from the essential maker (plants) to the consumers of the tertiary level (animals and insects). At each progressive level, nanoparticles mirror their inclusion by entering their metabolic pathway through active and inactive means of transportation. Holbrook *et al.* [84] and Lin *et al.* [85] show their destructive impact in the real striking order. Their lesser proportions offer vast surface territory that presents them with the high potential to convey harmful materials, for example, lipophilic toxins and substantial metals [86], to enter the food chain. Fig. 2 describes the development of nanoparticles in the environment.

Other than fish, bivalve molluscs are observed as top predators, basically in the benthic food web. They are frequently utilized as bio-pointers in aquatic biological systems. A few investigations have inspected the metal amassing, and its impacts on these organisms, including subcellular distribution [87, 88], as suspension feeders and bivalves are in danger of ENPs presentation. For their upgraded procedures of cell disguise of individual particles in the small scale and nano-size range, their physiological framework is defenseless to ENPs uptake. For example, the bivalves *Mytilus edulis* and *Crassostrea virginica* catch and hold regular particles <100 μm in size during specific seasons, making collected ENPs s exceptionally accessible for uptake. As investigated by [89], bivalve mollusks are remarkable model creatures for getting the danger and impacts of ENPs on sea-going spineless

creatures. In vivo and in vitro investigations show that ENPs may emphasize going on the insusceptible framework, and agglomerates and totals translocated from the gill to the stomach-related organ prompt intracellular take-up and oxidative stress [90, 91]. These make these living beings delicate in expanding ENPs pollution. Because of their food web situation, a significant savage creature experiences trophic exchange examines.



Fig. 2: Movement of nanoparticles in the environment.

4. Impact of metal nanoparticles on plants

4.1. Morphological changes

According to Olkhovych *et al.* [92], the uncertain impact observed was caused by Zn and Cu NPs on *Pistia stratiotes L.* growth, which holds inhibitory action. In the 7-day interval of observation, no change was noticed in the plants, but in the expansion of plant weight seen altogether exploratory variations on the fourteenth day of the trial, the increase in the number of leaves and roots on a single plant came after that., with this, it may cause leaves staining from dull green to light green shading was observed in variations with of Zn NPs and double arrangement of Zn and Cu NPs, which may demonstrate the collapse of chlorophyll, simultaneously, the exceptional development of parallel Branch in these variations examined. Plants developed within sight of Cu NPs remained green, however, indicating turgor misfortune in mesophilic cells. Other than that, the darkening and dying of real roots followed by restraint of recent development viewed. The collaborative activity of Cu and Zn NPs was demonstrated by the effect of the two-fold production of MNP on *Pistia stratiotes L.* plants. Plants from this variety, therefore, had the most notable leaf development, light green coloring, unusual turgor of the leaf cells, and a low increase in number of roots.

4.2. Physiological changes

The utilization of dissimilar MNPs has taken a massive job in the physiology of harvest plants. In a roundabout way, it might impact the physiological boundaries by converting the progress of responsive peroxidase, catalase, oxygen species, chlorophyll, superoxide dismutase movements, and phenol and leaf protein substances. Krishnaraj *et al.* [93] revealed that Ag NPs rewarded *B. monnieri* plants with higher protein -sugar substances and lower absolute phenol substances, peroxidase and catalase, action. By removing reactive oxygen species from plant cells, the use of TiO₂ NPs at lower concentrations (200 mg/mL) increases the chlorophyll, peroxidase catalase, superoxide dismutase activities, and malondialdehyde substance on *Lemna minor* compared to mass. However, at higher concentrations (500 mg/mL), the TiO₂ NPs significantly damage the cell layer in the living media. The toxicity of MNPs in plants includes leaves necrosis, root reduction, harvest extension and biomass reduction, as shown in Fig. 3.

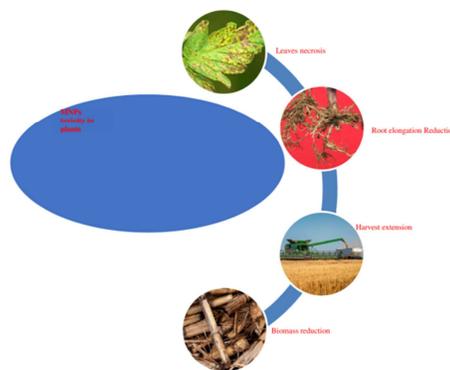


Fig. 3: Metal nanoparticles toxicity in plants.

5. Removal of metal nanoparticles from aquatic ecosystems

In the process of phytoremediation, heavy metals from contaminated soil, water, and air are removed using plants. Due to their potential to harm the environment, MNPs are one class of contaminant that has attracted more attention lately. It has been observed that aquatic plants are useful in the phytoremediation of MNPs in aquatic environments. By a range of routes, including industrial effluent, agricultural runoff, and consumer products, MNPs can enter aquatic habitats. Due to their small size and large surface area, which might enable their uptake and accumulation in the biota, they can pose a serious hazard to aquatic animals and ecosystems once released.

Aquatic plants may filter out MNPs from water in a variety of ways. MNPs sticking to the surface of plants is one of the main ways. This happens because of the plant's surface having functional groups like carboxyl, hydroxyl, and amino groups. Via a process known as phytostabilization, which includes immobilizing metals in plant tissue to stop their migration to other parts of the environment, MNPs can also collect in the tissue of plants.

Several aquatic plant species have been found to be efficient at removing MNPs from the environment. For instance, it has been discovered that *Lemna minor*, sometimes known as duckweed, is efficient at removing Cu, Ag, and Au NPs from aqueous environments. In lab tests, it was discovered that the plant *Azolla caroliniana* could purge up to 99% of Cu NPs from water. Several variables can affect how well aquatic plants can remove MNPs from the environment. These factors include plant type, metal nanoparticle type and concentration, environmental physicochemical characteristics, and exposure time. The possible toxicity of the MNPs to the plants themselves must also be considered, as exposure to high quantities might result in diminished growth and even death.

The removal of MNPs from aquatic environments can be performed using phytoremediation, which employs aquatic plants. This method can be used to remove a variety of toxins, is affordable, and is good for the environment. To examine the long-term effects of this approach on aquatic ecosystems and to optimize the use of aquatic plants in phytoremediation, additional research is required. There have been broad investigations to improve our acceptance of the conduct and poisonousness of MNPs. Several usages and dumping of MNPs will be released directly into water bodies, which cause toxicity in them [94-96]. The two strategies used today for MNPs removal from aquatic bodies are chemical and biological methods.

5.1. Chemical methods

5.1.1. Aquatic colloids

well-known definition by the International Union of Pure Applied Chemistry (IUPAC) the International Union of Pure Applied Chemistry's well-known definition (IUPAC), aquatic colloids are materials with dimensions below 1 μm . The colloids consist of organic (like polysaccharides and humic substances) and inorganic (like metal oxides silicon oxide, Al, Fe, Mn) and bacteria and viruses. The MNPs act together with aquatic colloids and, in that way, them in the sediment and aggregate position. This points out that the aim of the nanoparticle can be overwhelmed by attributes and the centralization of colloids. It accounted for that in oceanic waters furthermore estuarine, the thickness of aquatic colloids is

outstandingly low. Again, the nanoparticle distribution is likewise low because of the high accumulation tendency. This expanded the sedimentation rate at fluid frameworks with top ionic qualities [97]. The MNPs concentrations are typically between 1 and 10 g/L in naturally occurring water, which also contains oxides of Ti, Zn, Ce, and Ag [97]. As for communication between the colloid and MNPs, humic substances coat the external of the MNPs and balance out their surface charge, limiting the opportunity of the total [98], as appeared for carbon nanotubes (CNTs), for example [99]. Then again, fibrils raise this probability across mechanisms [100]. The principal elements or belongings of the MNPs that altogether impact their conduct in characteristic water frameworks like substance piece, mass, molecule thickness, surface territory, size dispersion, surface charge, surface corruption (the probable shell and topping operators), strength and solvency of the MNPs [97].

5.1.2. Surface Plasmon resonance

It is another phenomenon displayed by MNPs, which can be utilized to locate poisonous material. Different metallic and non-metallic MNPs can be used for natural clean-up, and they come in a variety of shapes and sizes. For instance, it can use other single metal MNPs, bimetallic MNPs, and carbon base nanomaterials; thus, forward, because MNPs exhibit stronger reactivity to redox-acceptable pollutants and (I) can diffuse or penetrate a contaminating zone where microparticles cannot.

5.1.3. Benth scale experiment

Chalew *et al.* [101] mimicked regular wastewater treatment strategies in a seat scale, and explored, them to calculate the expulsion proficiency of MNPs under traditional treatment conditions. The analysts spiked nano-sized Ag, ZnO, and TiO₂ particles into tests of groundwater, surface water, engineered freshwater, manufactured freshwater containing NOM, and tertiary wastewater gushing.

Turbidity and all-out natural carbon evacuation dictated the ideal alum portion for each kind of water and NP. They watched 2–20%, 3–8%, and 48–99% of spiked Ag, TiO₂ also, and ZnO NPs, separately, stay in the gushing after the treatment process. Also, MNPs can deliver disintegrated particles coming about because of the draining of the NP material into the water. These broken-up particles are an extra worry as they can continue in complete water. The best evacuation of disintegrated particles was watched for TiO₂ and the most exceedingly terrible expulsion for ZnO.

5.1.4. Metal salts

The pre-hydrolyzed forms of Al^{3+} and Fe^{3+} , hydrolyzing metals forms broadly used as coagulants in aquatic and treatment of wastewater [102]. Several studies have looked into the effectiveness of removing NPs from SiO_2 NPs using alum or iron coagulants, CuO NPs [103], and Ag NPs [104] semiconductor wastewater [105], also like the two most marketed MNPs, nano- TiO_2 [106-108] and carbon NPs, counting fullerene [99] and CNTs [109]. The drawbacks of chemical methods are that they are not eco-friendly and cost-effective. It affects the health conditions of aquatic bodies, especially living organisms, which directly affects our food chain also. It involves water health conditions. These methods will not be used to clean significant surface area. Even dangerous, handling of these methods may take a reactive phase.

5.2. Biological methods

The biological methods have been arranged based on the bioremediating system activated by using different terrestrial and aquatic plants/species to remove contaminants from soil/water situations [110].

Plants, microbes, and animals can all be used in biological soil remediation techniques. Particularly phytoremediation has grown in popularity because of its affordability and sustainability. Plants can take up, degrade, or alter pollutants, effectively sanitizing the soil. It has been demonstrated that using this technique to remove heavy metals, hydrocarbons, and other contaminants from polluted soils is effective [111].

Overall, biological remediation methods offer a sustainable and cost-effective approach to reducing the impact of pollutants on the environment. However, the effectiveness of these methods can be influenced by several factors, such as the type and concentration of contaminants, the type of organism used, and environmental conditions. Further research is needed to optimize the use of biological methods and to assess their long-term effects on the environment.

6. Uptake and phytoremediation of metal nanoparticles by plants

6.1. Uptake and mechanism of metal nanoparticles by aquatic plants

The MNPs may move to other plant sections, such as above-water or deeper-rooted shoots, after getting beyond the cell film's barrier. The apoplastic pathway has been proposed by the majority of studies, in which ENPs first enter the cell divider's pores before diffusing into the gap between the divider and the

plasma layer or passing through the intercellular space without touching the cell film [112].

The observed communication of MNPs in the plant cell and the plasma membrane at developed concentrations caused its injury [113]. In plants, MNPs enter through root junctions, and acceptance and translocation go through many physicochemical barriers. The plant cell wall is the prime circle it must cross and pass over. Cellulose makes up the cell wall which restricts the bigger elements of MNPs and allowance to get in small particles into it; due to the configuration of the plant cell wall membrane, the entry of MNPs is possible. The size avoidance limit for plant cell dividers is between 5 to 20 nm [114]. It has accounted for a portion of the MNPs to stimulate the enlargement of bigger cellular pores dividers, which further encourages the passage of massive nanoparticles [115]. The nanoparticles may travel through endocytosis [116], and further, through simplistic transport, they might move to various plant tissues [117]. As of late, [118] have suggested a numerical model which demonstrates a lipid trade component for nanoparticle transportation inside plant cells. The investigation confirmed that scale and zeta possibilities of size are vital in deciding the means of nanoparticle transport within the plant, as shown in Table 1.

Due to MNPs entries, the oxidative burst was observed with the chloroplast and mitochondria transport chains. MNPs take-up mechanisms are likely a direct result of the physiological, anatomical, and assorted morphological variety of higher aquatic plants. A diverse uptake mechanism shows morphological contrasts between the vascular pattern and contrasts in roots [117, 119]. MNPs mostly refer to the "uptake" mechanism and their by-products, which show up inside the cells and tissues of aquatic plants through a passive and active process. The plants' uptake of adsorbed MNPs and dissolved forms of metals show bioaccumulation. Bioaccumulation comprises a significant procedure during the exchanges of MNPs with plants. Since it can indicate toxicological effects, suppose the contamination's fixation increases a specific edge. Information on the take-up energy of MNPs by aquatic plants is inadequate, irrespective of prior research [117, 120, 121]. However, it is key to the perspective that decides the bioaccumulation, bioavailability, and destructiveness of MNPs.

The nanoparticles get to enter through plants' roots, then the MNPs are absorbed on the root walls. Plant roots have an unpleasant wall because of the nearness of root hairs, which can emit adhesive or else little atoms, for example, natural acids. Commonly, a negative charge can be seen on the root surface. These highlights result in MNPs with positive surface

charges that have been absorbed and accumulated on the root surface [46]. MNPs must pass through a series of physiological root barriers, starting at the surface and trying to make their way down to the xylem vessels, including the fingernail skin, cortex, endodermis, and Casparian strip on the root surface. Finally, move upward to the shoots via the xylem. Overall, root plays a vital role in transporting MNPs in the aerial portions of plants from contaminated bodies. Fig. 4 shows metal nanoparticles interaction with the plant.

Whether MNPs can saturate the root surface, or cuticles yet obscure. Furthermore, the root surface cuticle arrangement is like those of the leaf surface cuticle. The root tips of primary and auxiliary roots are formed by the immature cuticle skin surrounding the root hairs; MNPs can therefore enter the epidermis directly in these areas [47]. In higher plants, there are two separate critical pathways by which MNPs can be transported and taken up by roots as they approach the root epidermis. In the apoplastic pathway, MNPs first enter the pores of the

cell dividers before diffusing into the space between the cell dividers.

The plasma film can also pass through the intercellular gap without penetrating the cell layer. This suggests that MNPs in plant roots take an apoplastic pathway. One is MNPs' infiltration of the cytoplasmic region and cell layer. The other is how MNPs are transported to surrounding cells after entering by plasmodesmata.

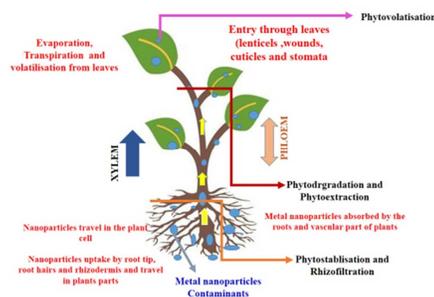


Fig. 4: The uptake and migration of the metal nanoparticles through different parts of the plant.

Table 1: MNPs accumulation paths by aquatic plants

| Plants | NPs types | Uptake detection method | NPs characteristic | Water exposure | Uptake pathway | Ref. |
|------------------------------|------------------|---|--|--|-------------------------------------|-------|
| <i>Lemna minor</i> | TiO ₂ | TEM, SEM | 275–2398 nm; SSA 50 m ² /g; 0.01–10 mg/L | Growth medium Steinburg. pH 5.5; CaCO ₃ 166 mg/L | Adsorption (no internalization) | [53] |
| <i>Myriophyllum simulans</i> | Au | STEM, EDX and SEM; TEM, z –14.1 mV; 250 g/L | 4 nm; spherical. z –14.1 mV; 250 g/L | Well/borehole water; pH 7.1; TOC 8.56 mg/L; CaCO ₃ 107 mg/L; conductivity 210 mS/cm | Internalization (tissue) | [119] |
| <i>Egeria densa</i> | Au | STEM, EDX and SEM; TEM, EDX | 4 nm; spherical. z –14.1 mV; 250 g/L | Well/borehole water; pH 7.1; TOC 8.56 mg/L; CaCO ₃ 107 mg/L; conductivity 210 mS/cm | Adsorption (no internalization) | [119] |
| <i>Azolla caroliniana</i> | Au | STEM, EDX, SEM; TEM, | 4 nm; spherical; z –14.1 mV; 250 g/L | Well/borehole water; pH 7.1; TOC 8.56 mg/L; CaCO ₃ 107 mg/L; conductivity 210 mS/cm | Internalization (cellular) | [119] |
| <i>S. tabernaemontani</i> | Cu | TEM | 38.7 nm; SSA 12.84 m ² /g; z –2.8 mV | Hoagland's medium | Cellular and tissue internalization | [53] |
| <i>Salvinia natans</i> | ZnO | ICP-OES | 25 nm; uncoated; SSA 90 m ² /g; 1–10 mg/L | OECD growth medium; pH 6.5 | Adsorption | [49] |
| <i>S. tabernaemontani</i> | CdS QDs | TEM | 4.3 nm; z –9.8 mV | Hoagland's medium | Cellular and tissue internalization | [53] |

6.2. Phytoremediation of metal nanoparticles using aquatic plants

Aquatic plants, such as water hyacinth, duckweed, and water lettuce, have also been used in the phytoremediation of water contaminated with heavy metals, pesticides, and other pollutants. These plants can absorb and accumulate contaminants, effectively removing them from water [122]. It fits them for taking fundamental enhancements from the environment so that they could emerge from the same process from the water bodies [119].

In recent years, there has been growing interest in the use of phytoremediation to remove NPs from contaminated environments. Phytoremediation of

NPs can occur through a variety of mechanisms. For example, some plants can uptake and accumulate NPs in their tissues, which can then be harvested and removed from the environment. Other plants can break down NPs through chemical or biological processes, converting them into less toxic forms or releasing them into the atmosphere. Additionally, plants can help stabilize NPs in the soil, reducing their potential to leach into groundwater or become airborne.

However, the use of phytoremediation for NPs is still in its early stages, and more research is needed to fully understand the potential of this approach. Some of the challenges associated with using phytoremediation for NPs include the variability in plant species and their ability to uptake or degrade

NPs, the potential for NPs to accumulate in plant tissues and enter the food chain, and the risk of unintended consequences, such as the release of toxic breakdown products. Nevertheless, phytoremediation shows promise as a cost-effective and sustainable approach to addressing NP contamination in the environment. Many NPs, including Ag, Au, TiO₂, ZnO, and Al₂O₃, are metallic [123]. Recent publications suggest that NPs are hazardous to a variety of creatures, but because these reports only include freshwater species and species employed in regulatory testing, further research is required [124]. There are a few, rare reports on higher (vascular) plants. In this context, CuNP were shown to be toxic to *Phaseolus radiatus* (mung bean) and *Triticum aestivum* (wheat), while Ag NP at 500 and 100 mg L⁻¹ resulted in 57% and 41% decreases in plant biomass and transpiration in *Cucurbita pepo* (zucchini) [125]. Ag NPs also showed toxic effects on *Lemna gibba* exposed to Ag NPs over 7 days [125].

Another method for phytoremediation to remove these substances from the atmosphere is the discovery that NPs, which originate from environmental particulate matter deposition, enter the leaf surface [126]. It has also been observed that the effectiveness of this technique of phytoremediation is morphology-dependent, as various types of leaves can accumulate metallic NPs to varying degrees based on features like peltate trichomes and hypodermis [126].

The phytoremediation is (i) non-invasive, (ii) eco-friendly, (iii) cost-effective, (iv) productive (v) more financially practical than other ordinary strategies, (vi) straightforwardly applicable in situ, (vii) freely accepted (as it gains ubiquity as a "green and clean" option in contrast to concoction medicines) [110, 127]. Moreover, (viii) phytoremediation can treat, simultaneously, locales damaged by more than one kind of toxic substance [128]. Among the impediments and additional confinements of phytoremediation, the principle is: (I) restricted resilience of a plant to the contaminations (especially for high focuses); (ii) low proficiency when the damaged soil layer expands profoundly in the dirt profile, being not available to the roots; (iii) tedious and slower than non-biological techniques; (iv) the contaminated condition, just as the atmosphere ought to permit the development of the plants (site-explicit conditions); (v) the toxin could be not bioavailable; (vi) once gathered, the treatment of the harmed tissues can be dangerous, and it now and again requires their burning or the removal in landfill [127]. It characterized phytoremediation as the utilization of plants to remediate soil and water from contaminants. This green innovation requires moderately minimal effort and is supposed of suitable for contaminant

remediation in numerous water biological systems [129]. It is well-arranged based on the physical and biological procedures (Fig. 5) [130]: (1) Water control: Use of plants to take up vast volumes of water to control the relocation of subsurface water. (2) Phytodegradation: take-up of a natural contaminant by the plant by decay through metabolic procedures inside the plant. (3) Phytextraction: take-up of a contaminant by plant roots and the translocation into the above-ground level of the plant; the contaminant is expelled by gathering the plants. It applies most regularly this innovation to soil or water pollutants with metals. (4) Phytostabilization (rhizofiltration): Restriction of a contaminant by consumption and gathering by roots, adsorption onto the root surface, or precipitation inside the root zone. (5) Phytovolatilization take-up of a contaminant by a plant, with the arrival of the contaminant or an altered structure to the air through transpiration. (6) Rhizodegradation: the breakdown of a contaminant in the dirt through a microbial action that is improved by the nearness of the dynamic root zone. Otherwise called improved rhizosphere biodegradation.

Various aquatic species have been recorded to take up metals for capacity in aeronautical (over the ground, above water) and lowered and subterranean tissues; furthermore, different sea-going plants immobilize metals on root surfaces and in residue encompassing roots. Moreover, microorganisms related to the plant rhizosphere assume a noteworthy job in phytoremediation with the capability of aquatic plants.

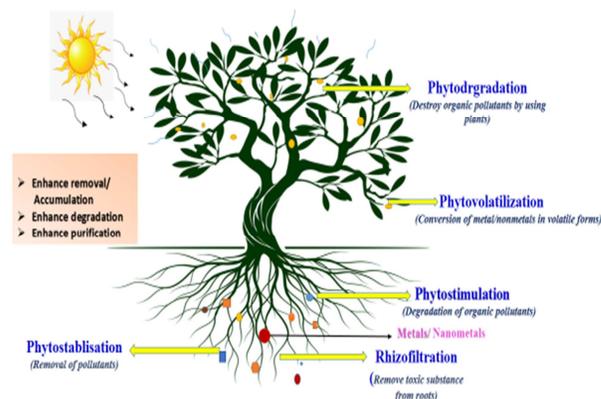


Fig. 5: Phytoremediation process.

7. The future perspective of metal nanoparticles phytoremediation

The use of phytoremediation, which is both eco-friendly and sustainable, has become a promising method for resolving different types of pollution. As

time progresses, it is becoming more apparent that phytoremediation has the potential to counter the challenges posed by MNPs. MNPs have been extensively utilized in different industries due to their distinct characteristics. However, their release into the environment has raised concerns regarding their potential negative impact on human health and ecosystems.

Phytoremediation has a promising future in addressing metal nanoparticle pollution due to its various benefits. With the progress in genetic engineering methods, there is a potential to improve plants' inherent remediation capabilities. By modifying the genes responsible for metal absorption, transportation, and conversion, researchers can develop hyperaccumulator plants that are optimized for effective metal nanoparticle elimination. These genetically engineered organisms could be customized to flourish in different settings and demonstrate greater metal resistance and absorption abilities.

The combination of nanotechnology and phytoremediation has the potential to improve the effectiveness of metal nanoparticle removal. This can be achieved by using nanoparticles like iron oxide or zero-valent iron to immobilize or break down metal pollutants. Additionally, phytoremediation can play a crucial role in restoring biodiversity, which in turn supports ecosystem services such as carbon sequestration and water purification.

Although phytoremediation for MNPs holds great promise, there are several obstacles that must be overcome to fully realize its potential. It is imperative to implement rigorous risk assessment protocols to assess the possible ecological and human health risks that may arise from the use of phytoremediation methods. Furthermore, it is crucial to establish robust regulatory frameworks to ensure the responsible and safe use of genetically modified plants and the continuous monitoring of phytoremediation initiatives. Additionally, a more profound comprehension of the intricate interplay between MNPs and plants is necessary to optimize phytoremediation strategies. Variables like nanoparticle size, shape, and concentration can significantly influence phytoremediation efficiency.

8. Conclusions

Research has established that certain aquatic plants can be utilized for removing MNPs from water and other contaminants. Key removal mechanisms encompass adherence to the root surface, internal uptake and storage within the root, absorption by microorganisms in the rhizosphere, and attachment to dissolved and suspended organic matter originating from the plant. The effectiveness of these mechanisms is known to vary depending on the plant species and local environmental conditions, such as

pH and natural organic matter content. Aquatic plants like *Eichhornia crassipes*, *T. angustifolia*, and *Elodea canadensis* and *Phragmites* are known for pollutant removal and are very effectively used in phytoremediation. The conduct and expected impacts of ENPs on plants inside real aquatic situations. Many of the data in research papers address the impact caused by MNPs in water. Future examinations must be led on plants and built nanoparticles under common conditions where plant-water-silt associations are concentrated as a coordinated unit. Such work must think about occasional varieties in physicochemical properties of the influenced water, alongside the impacts of different sources of info (e.g., acidic precipitation, composts, pesticides, street salt). Writing is meager concerning phytoremediation under such conditions. A wide range of aquatic plant types, including submerged, new, and coasting species utilized for the phytomanagement of contaminants. Naturally, cooperations among plants and MNPs vary with plant species. When applying plants for phytoremediation of degraded water and deposits. Numerous investigations have tended to the capacity of a solitary plant-animal variety for its phytoremediation potential. As it may, synergetic impacts from at least two species in a similar framework (lake, built wetland, etc.) would better copy field conditions, as these species become together normally and may work synergistically for ideal remediation of MNPs-influenced water.

Data availability

No datasets were generated or analyzed during the current study.

Declarations

Conflict of Interest: The authors declare that they do not have any conflict of interest.

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