

# Role of *Zinnia elegans* in the Phytoremediation of Heavy Metal-Contaminated Soils: A Scientific Review

Kawther Hadi Abood, Sarah Hussein Al-Shammari, Rasha Adil Al-bakri

Department of Plant Production Technologies, Al-Mussaib Technical College, Al-Furat Al-Awsat Technical University, Iraq.

**Abstract** - One of the most common annual ornamental plants that have gained a growing popularity as a non-edible in phytoremediation of heavy metal contaminated soils is *Zinnia elegans* Jacq. Among its conceptual appeal is its rapid growth, lack of difficulty in growing, fibrous root structure, aesthetic appeal, and minimal direct food-chain hazard, making it conceptually suitable to remediation efforts in urban, peri-urban, roadside and abandoned sites. This is a critical synthesis of the recent literature on the role of *Z. elegans* in the uptake, tolerance, stabilization, and potentially extraction of toxic metals in contaminated substrates, especially one that was published in 2020 or later. The evidence that is available shows that *Z. elegans* is able to tolerate and accumulate economically significant metals like Pb and Cr in controlled conditions, as well as prompt adaptive responses in the form of augmented antioxidant activity, proline amassing, tissue-level structure adjustment, and biomass allocation changes. Recent research further postulates that humic substances, chelators, plant growth-promoting bacteria and optimal substrate management can enhance its remediation. Nevertheless, direct experimental evidence on *Z. elegans* is more limited than that that is available to support some more comprehensively studied ornamental species like *Tagetes*, *Canna* and *Nerium*. Thus the present scientific status of *Z. elegans* is optimistic yet in a transitional state: it can be taken as a prospective multifunctional decorative plant that has real potential of phytoremediation, particularly at aesthetically sensitive sites, but that is still to be better established in terms of field validation, as well as the standardization of bioconcentration and translocation behavior, and guidelines on biomass management upon harvest. On the whole, *Z. elegans* should be taken seriously in the future research on remediation of heavy metals in the environment as it controls the ecological usefulness with the popular acceptability and aesthetics.

**Keywords:** *Zinnia elegans*; ornamental plants; phytoremediation; heavy metals; lead; chromium; phytoextraction; phytostabilization; urban soils.

## 1. INTRODUCTION

One of the most enduring issues related to mining, start-up of industrial discharge, irrigation with sewage, traffic emission, battery waste, pigments, electroplating waste and unregulated urban development is the heavy metal contamination of soil. Heavy metals unlike most organic pollutants are not biodegradable, can stay longer and can be exchanged among soil, water, vegetation, animals and man. In case of contamination of agricultural or urban soils, the outcomes are the loss of soil quality, the decrease in the growth of plants, the ecological toxicity, and the potential transfer of metals, including Pb, Cd, Cr, Ni, Cu, and As, to the food chain (Yan et al., 2020; Bhat et al., 2022; Sharma et al., 2023; Aryal, 2024).

Traditional remediation approaches like excavation, soil replacement, vitrification, solidification, soil washing, and chemical immobilization can be quite efficient, but are expensive and disruptive, energy-consuming, and impractical to use on large or in part-occupied sites. This is why, phytoremediation has maintained a high scientific and practical interest as a green technology utilizing the use of plants and their rhizosphere to immobilize, extract, transform or trap under field conditions. Phytoremediation can take the form of phytoextraction, phytostabilization, rhizofiltration, phytovolatilization, or revegetation-based ecological restoration depending on the plant species, the contaminant chemistry and the management goal (Yan et al., 2020; Pouresmaieli et al., 2022; Tan et al., 2023; Acharya et al., 2025).

One significant advancement in this direction has been the increasing appreciation of the fact that ornamental plants can be used to address a significant practical issue in phytoremediation: most high-biomass or tolerant species cannot be used in city landscapes, whilst most food crops cannot be used due to concern over metal uptake posing a direct safety hazard. The ornamental plants are thus appealing since they will help in ecological restoration, aesthetic enhancement and reduces chances of direct dietary contact. Recent reviews have specifically included their application to contaminated urban scenery, roadside belts, green

zones around the urban edges, industrial buffer areas, and the urban space where aesthetics and social acceptance are significant in addition to the effectiveness of remediation (Capuana, 2020; Khan et al., 2021; Deepika and Haritash, 2023; Umer et al., 2023).

Here where ornament is important, a promising candidate yet to be assessed properly is *Zinnia elegans* Jacq. The plant is widely grown all over the world, is cheap, can be grown at any time of the year, can be grown by seed, is able to grow large amounts of above-ground biomass in warm conditions, and has largely been valued due to its colorful inflorescences. These properties are also important since not only metal tolerance is a requirement in any practical phytoremediation, but also social acceptance, vegetable culture, biomass handling, and the capacity to resettle vegetation to degraded areas. In recent years, the experimental studies have shown that *Z. elegans* are capable of tolerating and accumulating Pb and Cr under pot conditions, of responding to wastewater that contains mixed metals, as well as of displaying structural and biochemical changes during metal stress (Panda et al., 2020; Patel and Modi, 2020; Bahmanzadegan Jahromi et al., 2023; Ahsan et al., 2024).

Although this is promising, the evidence base of *Z. elegans* is still less than the literature on the more established ornamental phytoremediators, like marigold, canna or oleander. This renders a critical review scientifically helpful. An effective review must not merely hail the plant as a future hyperaccumulator but must review what is really known about its uptake behaviour, stress tolerance, remediation aspects, enhancement opportunities, constraints and feasible situations of use. This moderation is especially significant due to the fact that not all recent research about *Z. elegans* focuses on the issues of tolerance and survival, whereas others imply that meaningful accumulation may occur only in the context of certain amendment regimes or certain metals.

The objective of the current review is thus to present a scientific synthesis of the role of *Z. elegans* in the phyto-removal of the heavy metal-contaminated soil, which is rigorous in nature. The paper concentrates on the recent evidence, incorporates species-specific research with the general ornamental phytoremediation research, and assesses the plant in both mechanistic and practical ways. Pb and Cr receive special focus, as these are most directly examined in *Z. elegans*, yet Cu, Zn, Ag-stress responses, or arsenic-stress response settings and mixed-metal wastewater responses are also discussed as additional evidence.

## 2. WHY ZINNIA ELEGANS? BOTANICAL AND FUNCTIONAL FEATURES RELEVANT TO PHYTOREMEDIATION

*Zinnia elegans* is a member of the Asteraceae family and it is commonly grown as an annual bedding trial in tropical, sub-tropical and warm-temperate areas. As a remediation aspect, some of the horticultural characteristics are desirable. It has a short seed germination time, grows quickly, roots form a fibrous network, and is capable of re-flowering when grown in the open field. It has been found to be particularly useful in contaminated soils where the establishment of the seasonal cover is urgently needed to mitigate dust movement, splash erosion and the aesthetic neglect. Practically, a visually acceptable phytoremediation plant is usually more likely to be cared about during multiple cycles compared to an unattractive remedial species (Capuana, 2020; Khan et al., 2021; Deepika and Haritash, 2023).

Another benefit is the non-edibility of *Z. elegans*. One of the issues raised repeatedly with phytoextraction is that food or forage crops can create contaminants in the agricultural routes. Ornamental species do not face a lot of this risk since they do not serve to feed human beings or animals. It is one of the reasons as to why ornamental phytoremediation has been advocated in contaminated urban, and peri-urban soils particularly where full decontamination is not possible, but where ecological cover is required. *Zinnia* is especially suitable in this strategy due to the availability of a market familiarity, visual variety, and short-cycle biomass, which can be removed during accumulation events (Khan et al., 2021; Umer et al., 2023; Zhakypbek et al., 2024).

The other viable benefit is the fact that the plant fits into maintained landscapes. *Z. elegans* may be planted in flower beds, strips, roundabouts, roadsides, institutional gardens, and industrial campuses as well as temporary revegetation systems. At these sites, it can be anticipated that phytoremediation can serve several purposes simultaneously: dust control, thermal control, aesthetic enhancement, and trapping of pollutants. *Zinnia* does not require exceptional ornamental value or unpopularity to be included in the landscaping of ordinary green spaces, as opposed to some hyperaccumulators whose capacity to accumulate metals may be moderate and not excessive (Capuana, 2020; Deepika and Haritash, 2023).

Physiologically, *Z. elegans* seems to be able to trigger a number of conventional defensive heavy-metal responses. Recent research shows that, at metal stress, the plant is capable of enhancing the levels of proline, antioxidant enzymes, and structural defense of the tissues, and some of the anatomical traits indicate efforts to preserve transport continuity and cell wall strength. Such reactions do not, in themselves, demonstrate high phytoextractive capacity, but they are suggestive that the species can endure contaminated substrates sufficiently long to be operationally applicable in a phytotreatment or phytotransferring system (Panda et al., 2020; Tugbaeva et al., 2022; Bahmanzadegan Jahromi et al., 2023; Ahsan et al., 2024).

Meanwhile, the plant cannot be romanticised. Ornamental plant can be able to withstand metals without being able to extract them effectively into harvestable shoots. The important question, however, is not on whether *Z. elegans* can survive contamination but on whether it can accumulate the contaminants in a manner and distribution pattern that can be consistent with the remediation target. Above-ground accumulation and repeated harvest would be useful in phytoextraction, whereas high root retention and rhizosphere immobilization could be desirable in phytostabilization. The existing evidence would indicate that *Z. elegans* can play a role in either of the strategies based on the metal that it is being exposed to, the amendment regime, and the soil-plant environment.

**Table 1. Functional characteristics of *Zinnia elegans* that support its use in phytoremediation-oriented landscape systems**

Trait	Relevance to remediation	Likely operational benefit	Selected support
Fast seasonal growth	Short establishment time on disturbed soil	Rapid vegetative cover, reduced dust and bare-soil exposure	Capuana, 2020; Panda et al., 2020
Non-edible ornamental species	Lower direct food-chain risk than edible crops	Suitable for urban and peri-urban sites	Khan et al., 2021; Deepika & Haritash, 2023
Fibrous root system	Good rhizosphere contact and soil stabilization potential	Supports phytostabilization and surface-soil interaction	Yan et al., 2020; Sharma et al., 2023
Publicly acceptable flowers	Combines remediation with visual landscaping	Higher social acceptance and easier municipal deployment	Capuana, 2020; Umer et al., 2023
Tolerance-related biochemical plasticity	Supports survival under Pb-, Cr-, Cu-, Zn-, and mixed-metal stress	Maintains growth long enough for capture/stabilization	Panda et al., 2020; Tugbaeva et al., 2022; Ahsan et al., 2024

### 3. MECHANISTIC BASIS: HOW *Z. ELEGANS* CAN INTERACT WITH HEAVY METALS

Remediation value of any plant species is dependent on a series of processes that start at the root soil interface. This process occurs in the following stages: exposure of the rhizosphere to metal ions or metal bearing particles, adsorption on root surfaces, uptake into apoplastic or symplastic pathways, complexation with organic ligands and either retention in roots or translocation to stems and leaves. These processes define how a plant will be a phytoextractor or a stabilizer depending on the balance between them. The present theory of phytoremediation points out that this balance is affected by transport proteins, root exudation, cell wall binding, vacuolar sequestration, antioxidant activity, and rhizosphere microorganisms (Yan et al., 2020; Sharma et al., 2023; El-Sappah et al., 2024; Acharya et al., 2025).

Not yet molecularly characterized to the same depth as in model hyperaccumulators, the best-characterised machinery in *Z. elegans* remains, however, the most well-documented in any organism, although recent work presents a convenient physiological representation. Panda et al. (2020) found an antioxidant system and performance alterations in plants in response to Cr stress, which is in line with oxidative-stress management. Bahmanzadegan Jahromi et al. (2023) were able to report alterations in antioxidant characteristics under Pb stress, which shows that a metal exposes the body to defense metabolism as opposed to instant physiological failure. Likewise, in a study by Ahsan et al. (2024) zinnia subjected to metal-contaminated wastewaters changed enzymatic and morphophysiological characteristics, suggesting a generalized stress adaptation system, and not a metal-specific one.

The control of antioxidants plays a pivotal role since the indirect oxidative injury can be usually caused by the disruption of electron transport, membrane integrity, and redox homeostasis by the presence of heavy metals. Plants respond to it with enzymes that include superoxide dismutases, catalases and peroxidases, and non-enzymatic compounds that include proline, phenolics and compatible solutes. In the case of *Z. elegans*, the rise in proline and antioxidant activity during the conditions of Cr and Pb exposure make it possible to interpret the fact that the species is able to preserve metabolic activity during contaminant stress, at least in the moderate limits of contamination. Remediation is only possible in such tolerance, as quick-death plants cannot offer valuable contaminant removal or stabilization (Panda et al., 2020; Bahmanzadegan Jahromi et al., 2023; Ahsan et al., 2024).

Structural adjustment can also be of importance. Tugbaeva et al. (2022) demonstrated that lignification of axial organs in *Z. elegans* was boosted by copper stress. Though such work was not presented as a phytoremediation trial, it is extremely relevant due to the fact that strengthened cell walls can serve as metal binding protective sink and may restrain uncontrolled cellular damage. Singh et al. (2024) also identified the anatomical and physiological response of *Z. elegans* seedlings to AgNO<sub>3</sub> and ZnSO<sub>4</sub> and their nanoparticle analogs, thus stating that the adaptation to stress in the species involves both tissue-level modifications and those in photosynthetic activity.

One very important interpretation is that tolerance is not necessarily equal to high extraction efficiency. The tolerance of a contaminant by a species can be by avoidance of metals by roots or by fortification of apoplastic barriers, which is advantageous to phytostabilization but not to shoot-based phytoextraction. Thus, bioconcentration factor, translocation factor, biomass productivity and harvestable metal load must be considered as a unit. The available literature on *Z. elegans* indicates that the plant is capable of accumulating some metals and retaining acceptable biomass in the conditions of stress, yet the extent of extractable removal highly depends on the type of contaminant, the condition of the substrate, and the strategy of amendments (Patel and Modi, 2020; Panda et al., 2020; Deepika and Haritash, 2023).

#### 4. DIRECT EVIDENCE FOR THE PHYTOREMEDIATION POTENTIAL OF *Z. ELEGANS*

##### 4.1 Lead (Pb)

The problematic urban and industrial soil contaminants include lead due to its persistence, effective sorption in soil, and serious health effects. The fact of *Z. elegans* phytoremediation of Pb is encouraging, albeit quite small in size. According to Patel and Modi (2020), *Z. elegans* accumulated in high concentrations of Pb in contaminated soil, and the authors mentioned that the species is an excellent bioaccumulator of Pb in their laboratory study. Although the research was brief, it was a valuable indicator to show that the plant is capable of uptaking lead as opposed to simply surviving in its presence.

A more mechanistic input was made by Bahmanzadegan Jahromi et al. (2023), who assessed *Z. elegans* in Pb contaminated soils and demonstrated that the antioxidant properties varied significantly following the contamination and amendment treatments. Their contribution is significant in two ways. It shows first that zinnia is able to provoke a quantifiable biochemical defense program in Pb stress. Second, it demonstrates that amendments of remediation behavior are possible or can include humic acid and DTPA, which can modify the dynamics of metal availability and uptake. It implies that the phytoremediation performance of *Z. elegans* cannot be evaluated just under the unamended soil conditions.

The Pb case is also reinforced by recent research involving the integration of plants and useful microorganisms. The *Z. elegans* and *Bacillus* sp combination was more effective than the plant alone in reducing the concentration of Pb in contaminated soil; the combined treatment exhibited a significant reduction in soil Pb after 60 days (Febiola et al. 2025). This is consistent with the larger phytoremediation body of literature that indicates that plant growth-promoting bacteria might increase root development, metal mobilization or immobilization equilibrium, stress tolerance, and rhizosphere activity. In the case of Pb-contaminated soils, in other words, existing data indicate that *Z. elegans* can be particularly effective when included in an assisted phytoremediation system in place of a plant-only intervention (Boorboori et al., 2022; Khilji et al., 2024; Febiola et al., 2025).

It still needs a scientifically skeptical interpretation. Lead is not also well mobile in soil, and high apparent uptake in pot samples does not necessarily mean high field-scale removal. In non-meaningful shoot concentrations, total metal removal is only determined by harvestable biomass per unit area and repetition of cropping cycles. Therefore, the existing Pb literature favorably deems *Z. elegans* as an acceptable ornamental prospective to Pb phytoremediation research, but not as a more or less ubiquitous field solution.

##### 4.2 Chromium (Cr)

Chromium especially hexavalent chromium is a very toxic toxicant relating with tanning, metal finishing, pigments, and industrial effluents. The chromium research by Panda et al. (2020) is one of the information-rich species-specific studies on *Z. elegans*. The authors conducted an experiment in a pot with different concentrations of graded Cr(VI) to test growth, root morphology, flowering characteristics, biochemical stress markers and metal accumulation. The experiment revealed that *Z. elegans* could grow in an environment with chromium stress though the adverse impact was felt at higher contamination rates.

Among the fascinating findings by Panda et al. (2020) was the fact that Cr stress increased flowering, which could also indicate the stress-induced life-cycle adaptation instead of enhanced vigor. More importantly, the plant exhibited rises in antioxidant enzymes enzyme activities and proline content, and this authenticated that chromium evoked a physiological defence mechanism. There were real uptake plants that accumulated chromium in plant tissues, which showed that they did not merely

avoid chromium. The authors came to the conclusion that *Z. elegans* can be used in chromium phytoremediation, although the process shows high potential in the moderate and low level of contamination.

Mechanistically speaking, the chromium data are useful as it demonstrates the duality of the *Z. elegans* when contaminated: the plant cannot be viewed as a delicate decoration that cannot survive, nor as a hyperaccumulator with no drawback to the growth rate. Rather, it takes a more realistic intermediate ground, where practical use can be made of tolerance, ornamentality, as well as bio-mass, but performance is highly dependent on the intensity of contamination. Such a species profile, in fact, is what can be helpful in controlled landscapes, where a total extraction is not as significant as a cover over time, partial removal, and risk avoidance (Panda et al., 2020; Deepika and Haritash, 2023; Acharya et al., 2025).

#### 4.3 Copper, zinc, silver-related stress, and mixed-metal wastewater

Despite the fact that Pb and Cr are the most experimentally examined contaminants in *Z. elegans* phytotransformation experiments, other metals and mixed-metal states may be taken into consideration in the recent studies that provide valuable context. As depicted by Tugbaeva et al. (2022), copper stress promoted lignification in the axial organs of *Z. elegans*, which indicates the existence of a structural defense mechanism that can facilitate the sequestration or compartmentalization of excess Cu. This result is applicable in the sense that lignification may provide cell wall adhesion as well as strengthening tissues against injury that is caused by metal.

Singh et al. (2024) contrasted the reaction of *Z. elegans* and *Tagetes erecta* seedlings to both AgNO<sub>3</sub> and ZnSO<sub>4</sub>, as well as to their nanoparticles. Their research established that the ionic metal salts had greater toxicity than the respective nanoparticles and the two ornamentals were not similar in the physiological and anatomical response. The significant implication presented herein to the current overview is that *Z. elegans* may be still educative even when not the best-performing organism in the comparison: it shows a quantifiable tolerance, species-specific anatomical plasticity, and practical usefulness in the contamination case of emerging materials and mixed metal exposure.

Ahsan et al. (2024) used zinnia to further elaborate on the evidence by studying zinnia in the presence of varying metal-hoarded wastewaters. Their findings revealed that wastewater quality affected the biomass of the plants, pigments, enzymatic antioxidants and other morphophysiological parameters. The moderately contaminated or treated waters caused less harm than those with higher metal concentrations, which suggested that *Z. elegans* could be deployed in the remediation-based irrigation or polishing systems only when the quality of the wastewater is tracked. The work is of particular significance to developing nations and water-deficient areas in which ornamental landscaping is likely to become more dependent on reclaimed water. In this regard, zinnia may be used as a landscape crop, as well as a biological indicator of wastewater appropriateness.

The more generalized version of these works is that *Z. elegans* cannot be judged through single-metal pot experiments exclusively. Actual polluted locations tend to contain numerous metals, variable supply, interacting pH effects and non-metal stressors which can be salinity or unsound soil structure. Thus, the documented plasticity of zinnia on the receiving side of Cu, Zn, Ag-related treatments, and metal-contaminated wastewater has in its favor an opportunity to qualify as a component of integrated remediation landscapes, though it cannot yet be conclusively demonstrated that it is a universal high capacity extractor.

#### 4.4 Arsenic-related restoration contexts and ecological reconstruction

The direct arsenic literature on *Z. elegans* is relatively limited in the recent past although the species is found in the wider Asteraceae-based restoration studies. Meng et al. (2025) established the positive effects of no till-reseeding with the Asteraceae plants on the arsenic contaminated mining sites and reported that *Z. elegans* exhibited positive biomass behaviors in the arsenic stressed system in their system. Though this was not a pure phytoextraction experiment but a community- and restoration-based study, the study remains significant because real-world remediation often relies on ecological reconstruction as opposed to metal extraction on individual species.

The restoration-based evidence indicates that *Z. elegans* can be applicable to the locations where such goals as quick coverage, community reconstruction, aesthetic recovery, and partial contamination control have to be achieved. The overall ecological aspect is usually undervalued in the discussion of phytoremediation that at times only looks at tissue concentration levels. A plant potentially useful in severe disturbed locations, however, can be functionally useful despite not being the most competitive accumulator of metals in an absolute sense because it can survive, contribute biomass, enhance the landscape, and be a part of revegetation pathways (Capuana, 2020; Meng et al., 2025).

**Table 2. Representative recent studies directly relevant to heavy metal remediation by *Zinnia elegans***

Study	Metal / stressor	Experimental system	Main observation	Interpretive value
Panda et al. (2020)	Cr(VI)	Pot experiment	<i>Zinnia</i> tolerated moderate Cr, accumulated Cr, and showed higher antioxidant enzymes and proline under stress	Strongest direct evidence for Cr-related tolerance and uptake
Patel & Modi (2020)	Pb	Contaminated soil exposure	Reported high Pb bioaccumulation in <i>Z. elegans</i>	Supports lead uptake potential
Bahmanzadegan Jahromi et al. (2023)	Pb	Pb-contaminated soil with DTPA and humic acid	Amendments modified antioxidant responses and improved remediation-related behavior	Shows amendment-sensitive Pb remediation potential
Ahsan et al. (2024)	Mixed metals in wastewater	Irrigation with metal-hoarded wastewaters	Growth, pigments, and enzymatic traits changed with wastewater quality	Relevant to reclaimed-water and mixed-stress settings
Singh et al. (2024)	Ag and Zn salts / nanoparticles	Seedling physiological–anatomical comparison	Species-specific responses indicated tolerance plasticity and structural adaptation	Useful for understanding stress biology under novel metal forms
Febiola et al. (2025)	Pb	Plant–bacteria bioremediation trial	<i>Zinnia</i> + <i>Bacillus</i> sp. reduced soil Pb more than plant-only treatment	Supports assisted phytoremediation
Meng et al. (2025)	As-contaminated mining area	No-till reseeded with Asteraceae plants	<i>Z. elegans</i> maintained favorable biomass in restoration context	Supports use in ecological reconstruction, not only extraction

## 5. ENHANCEMENT STRATEGIES FOR IMPROVING THE PHYTOREMEDIATION PERFORMANCE OF *Z. ELEGANS*

A phytoremediation plant can hardly perform excellently based on species identity. The results can change based on soil pH, organic matter, redox state, rhizosphere flora, metal speciation, and age of plants. This is more so in the case of ornamental plants whose growth would be restricted to visual standards in case they are to be utilized in open landscapes or in those that were under management. Based on this, the most promising future direction of *Z. elegans* is probably the improvement-enhanced phytoremediation as opposed to the deployment of plants.

A chelating/availability-modifying-substance enhancement route is one of the possible improvements. Bahmanzadegan Jahromi et al. (2023) proved that *Z. elegans* behavior under the influence of DTPA and humic acid changed according to the contaminated soil with Pb. Chelating agents have the potential to raise metal solubility and availability to plants, though they pose a risk to the environment when mobilized metals are washed out of the rhizosphere. Humic materials can be more moderate in nature, and occasionally enhance the availability of metals and root health. As a result, such amendments as zinnia application ought to be strictly regulated according to the remediation goal: to achieve as much uptake as possible when it is possible to

harvest it, or to decrease mobility when stabilization is desirable (Awad et al., 2021; Bahmanzadegan Jahromi et al., 2023; Tamma et al., 2025).

The second pathway involves using organic amendments like compost, biochar or engineered organic materials. Widespread ornamental phytoremediation research demonstrates that organic supplements are capable of boosting the introduction and development of plants and altering the biomass. Awad et al. (2021) showed that organic material modified the effectiveness of heavy metal phytoextraction in ornamental systems, and even more recent reviews reiterate the concept of amendment based phytoremediation as one of the most feasible approaches to enhance plant performance without reducing their survival. This biomass-stimulating role can be valued as much as any physiological change in tissue concentration when applied to examples such as zinnia, an annual plant that needs to generate removable shoot biomass in order to be used in phytoextraction (Awad et al., 2021; Pouresmaieli et al., 2022; Acharya et al., 2025).

The third way is microbial assistance. The co-culture of *Z. elegans* and *Bacillus* sp. described by Febiola et al. (2025) demonstrates how bacteria can enhance the results of remediation. Broadly, growth-promoting rhizobacteria in plants and arbuscular mycorrhizal fungi are capable of enhancing plant root surface area, plant nutrient status, plant stress signaling, and plant metal partitioning. As has been demonstrated repeatedly by reviews, microbial partners have been shown to change plants, that would otherwise be marginal tolerant to operational usefulness, particularly when they deal with contaminated soils of poor fertility or unstable structure. Despite the fact that the study of zinnia-specific microbiome is still in its initial stages, the existing evidence points to this direction with strong support (Boorboori and Zhang, 2022; Khilji et al., 2024; Febiola et al., 2025).

The fourth path is the design of mixed or sequential ornamental systems. Zinnia can be used with more highly accumulating ornamentals or with tree species that provide perennial cover and root deeper. Comparative ornamental research on marigold and sunflower, e.g. indicates that various species are superior in diverse metals or management objectives. This implies that *Z. elegans* can be most useful as an element of an ornamental remediation palette but not as an all-purpose solution. Mixed ornamental systems are also suggested to be more acceptable by the general population in highly visible landscapes, and to redistribute the functions of remediation between root depths and growth patterns (Madanan et al., 2021; Biswal et al., 2022; Sharma and Mathur, 2023; Chunwichit et al., 2025).

**Table 3. Management strategies that can enhance or refine Zinnia-based heavy metal phytoremediation**

Strategy	Expected effect	Potential advantage for <i>Z. elegans</i>	Caution / limitation
Humic substances / chelators	Increase or regulate metal availability	May improve Pb uptake and physiological performance	Excess mobilization may increase leaching risk
Compost / biochar / organic matter	Improve substrate quality and biomass	Supports establishment, survival, and removable biomass production	May reduce availability too much for phytoextraction if not balanced
Plant growth-promoting bacteria	Enhance rhizosphere activity and stress tolerance	Can improve Pb remediation and plant vigor	Performance may be site-specific and inoculum-dependent
Arbuscular mycorrhizal fungi	Modify uptake, root retention, and antioxidant defense	Useful for tolerant ornamental systems on degraded soils	Species-specific compatibility must be validated
Mixed ornamental planting	Distribute remediation functions among species	Improves aesthetics, resilience, and landscape value	Makes attribution of removal efficiency more complex

## 6. POSITIONING *Z. ELEGANS* AMONG ORNAMENTAL PHYTOREMEDIATORS

The scientific argument of *Z. elegans* is made more apparent when compared to more familiar ornamental phytoremediators. Although reviews of ornamental plants indicate that zinnia has frequently been the subject of less direct attention of field and greenhouse work than other ornamental plants, marigolds (*Tagetes* spp.), canna, *Mirabilis*, oleander, and various ornamental trees all have received more direct attention. These species are often mentioned due to the combination of a moderate biomass, tolerance, or high accumulation of a certain contaminant (Capuana, 2020; Khan et al., 2021; Deepika and Haritash, 2023).

*Z. elegans* seems to have a middle position between these species. It is extremely applicable to seasonal decorative use and in the urban rehabilitation of visual aspects and has direct measures of Pb and Cr uptake. But its published field-scale data is still limited, and its translocation phenotype has not as yet been described with similar uniformity as in a few marigold experiments. This does not make it any less important but determines its scientific status at the present time. *Zinnia* is promising, plausible, and operationally appealing, however, under-validated as compared to the best ornamental phytoremediation species (Madanan et al., 2021; Biswal et al., 2022; Sharma and Mathur, 2023; Khilji et al., 2024).

Aesthetic versatility is one of the greatest comparative advantages of *Zinnia*. A remediation plant installed in front of the buildings should be acceptable by the municipalities, households, and institutions. In this case, *Zinnia* usually has an upper hand over the plants which are either aesthetically rough or limited to only a few periods throughout the year. Also, the presence of annual ornamentals permits repeated short remediation cycles, which may be a valuable option where a harvested biomass should be taken off on a regular basis. In moderate contamination where single-time extraction is not viable, repeated-cycle ornamental system might be a better alternative to a single high-accumulator planted once (Capuana, 2020; Umer et al., 2023).

The major comparative limitation of *Z. elegans* is the restricted quantity of field tests showing the mass of contaminants eliminated per hectare or over numerous seasons. To make a plant species make the transition between promising species to recommended species, future research needs to measure biomass-normalized removal, metal sequestration, reproducibility across a range of soils, and safety after harvest. To put it briefly, the literature now validates the use of *Z. elegans* as a plausible candidate, although not a conclusive benchmark ornamental phytoextractor.

**Table 4. Practical strengths, limitations, and appropriate use scenarios for *Zinnia elegans* in heavy metal phytoremediation**

Dimension	Strengths	Limitations	Best-fit scenarios
Ecological role	Provides rapid vegetative cover and supports revegetation	Not a proven universal hyperaccumulator	Moderately contaminated soils requiring cover and risk reduction
Landscape value	High ornamental appeal and public acceptance	Seasonal; may require repeated replanting	Roadsides, campuses, institutional gardens, buffer strips
Remediation function	Useful for Pb and Cr research; adaptable under mixed-metal stress	Field data on removal efficiency remain limited	Pilot trials, urban phytostabilization, assisted phytoextraction
Management compatibility	Easy seed-based establishment and harvestable biomass	Biomass handling becomes a contamination-management issue	Short-cycle remediation with periodic removal
Innovation potential	Compatible with microbial and amendment-assisted systems	Needs standardized protocols and multi-season validation	Integrated ornamental remediation systems

## 7. BIOMASS HANDLING, ENVIRONMENTAL SAFETY, AND POST-HARVEST MANAGEMENT

One of the weaknesses that have been observed repeatedly in the practice of phyto remediation is the propensity to concentrate on plant uptake but the neglect on the post-harvest mechanism. A serious remediation plan that includes *Z. elegans* should have a biomass management plan since metal-bearing shoots cannot be simply composted or disposed of in normal green waste. The latest reviews note that post-phytoremediation biomass itself constitutes a secondary waste stream, which might need to be controlled disposed of, subjected to thermal treatment, recovered value, or some other forms of specialized processing based on the type and concentration of the metals (Liu and Tran, 2021; Tan et al., 2023; Mukherjee et al., 2025).

This is of particular concern to decorative annuals. They have the plus over not having to harvest the shoots once, but the downside is that with every harvest, contaminated biomass has to be produced which needs to be handled safely. In the context of municipal or institutional adoption, this implies that the concept of phytoremediation must be adopted as waste logistics are initially developed. The environmental benefits realized on the soil could be cancelled by subsequent contamination routes unless such planning is done.

There is also a need of risk communication. Since zinnia is a common garden plant the society might not necessarily realize that the plants planted on polluted soil should not be planted into residential vegetable gardens, fed to livestock or disposed uncontrollably. As such, the future application of *Z. elegans* in remediation must comprise not just agronomic procedures but labeling, harvest management procedures, and location-specific safety recommendations.

## 8. RESEARCH GAPS AND FUTURE DIRECTIONS

The initial significant area of research gap is the minimal amount of field trials on a long-term basis. The majority of direct evidence of *Z. elegans* has been of pot studies or short controlled experiments. These are useful in screening tolerance and mechanistic response, but they cannot adequately represent the field heterogeneity, seasonal and weather variability, stratification of root-zone, and repeated periods of harvest. Zinnia needs to be tested at contaminated field plots, roadside belts, post-industrial green spaces, and mine-affected sites under realistic management conditions in the future (Capuana, 2020; Deepika and Haritash, 2023; Meng et al., 2025).

The second gap is related to quantitative performance measures. Numerous reports present physiological stress indicators, although they lack sufficient information on bioconcentration factor, translocation factor, total metal removal per plant, or total removal per unit area. These mass-balance values are required in remediation planning. A plant that is of good antioxidant performance and low extractable metallic performance may be more appropriate to stabilization rather than extraction. Consequently, further zinnia studies ought to provide a combined approach of tissue distribution, biomass yield, and metal mass removal and not as individual research.

The third gap is that cultivar-level analysis is required. Zinnia is exemplified with many cultivars which vary in height, branching, root formation, biomass formation, and flower characteristics. It is quite possible that the performance of phytoremediation is different among cultivars but it has not been well established. Selecting cultivar diversity may enable the identification of lines that will be more advantageous in phytoextraction, stabilization, wastewater polishing or high-biomass landscape rehabilitation.

A fourth disproportion is molecular validation. The recent reviews of the behavior of plant heavy metals focus more on transporter regulation, detoxification pathways, transcriptomics and signaling networks. There has been more physiological than molecular research on Zinnia. Combining omics, rhizosphere microbiology, and ion-transport studies would take the species beyond descriptive tolerance experiments and make it predictive remediation biology (El-Sappah et al., 2024; Mohamed et al., 2025; Acharya et al., 2025).

Lastly, mixed ornamental systems should be considered in future research studies. Remediation plants are commonly combined in the real green-space design, and not applied in monoculture as it is done in real green-space design. It would then be useful to experiment with *Z. elegans* using marigold, canna or appropriate ornamental shrubs and trees and measure the ability of mixtures of species to collect contaminants, improve substrates, support biodiversity and aesthetic appearance. This would put the science of phytoremediation in closer touch with the landscape practice realities.

## 9. CONCLUSION

The existing literature justifies the use of *Zinnia elegans* as a scientifically plausible ornamental plant in heavy metal phytoremediation research, especially in the systems that are worried about Pb and Cr and locations that are aesthetically sensitive. The particular species has a combination of fast colonization, nonedible biomass, aesthetic value, and quantifiable physiological resistance to various heavy metal stressors. Recent research has indicated it is capable of toxic metal accumulation, acting as an antioxidant and structural defence, and it has some advantages to be helped using humic substances, chelators, beneficial bacteria, and proper substrate management.

Meanwhile, the evidence base is still smaller than in the case of certain other ornamental phytoremediators. This is why, *Z. elegans* can now be considered to be a highly-promising candidate but not a completely valid and universal solution. Its best short-term applications are pilot-scale projects, urban and peri-urban revegetation, short-cycle ornamental remediation, and research programs aimed at designing a balance between visual landscape quality and the reduction of ecological risk.

To sum up, *Z. elegans* should be given a better frontline position in aesthetical phytoremediation science. Its functional appeal is already obvious; the only thing left to do is to transform that appeal into more rigorous field results, standard measures of performance and safe biomass handling procedures. When these gaps are sealed, zinnia can have a place amongst the most helpful ornamental species to incorporate remediation and landscape restoration in the polluted conditions.

## REFERENCES

- [1] Acharya, A., Bellaloui, N., Pilipovic, A., Perez, E., Maddox-Mandolini, M., & Fuente, H. D. L. (2025). Current assessment and future perspectives on phytoremediation of heavy metals. *Plants*, 14(18), 2847. <https://doi.org/10.3390/plants14182847>
- [2] Ahsan, M., Younis, A., Raheel, M., Khalid, I., Abbas, H. T., Ashraf, W., Mihoub, A., Radicetti, E., Saeed, M. F., Ali, S., Valipour, M., & Jamal, A. (2024). Morpho-physiological and enzymatic responses of zinnia (*Zinnia elegans* L.) to different metal hoarded wastewaters. *Journal of Soil Science and Plant Nutrition*, 24, 2910–2923. <https://doi.org/10.1007/s42729-024-01717-w>
- [3] Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. *Heliyon*, 10(19), e38683. <https://doi.org/10.1016/j.heliyon.2024.e38683>
- [4] Awad, M., El-Desoky, M. A., Ghallab, A., Kubes, J., Abdel-Mawly, S. E., Danish, S., Ratnasekera, D., Islam, M. S., Skalicky, M., Brestic, M., Baazeem, A., Alotaibi, S. S., Javed, T., Shabbir, R., Fahad, S., Rahman, M. H., & El Sabagh, A. (2021). Ornamental plant efficiency for heavy metals phytoextraction from contaminated soils amended with organic materials. *Molecules*, 26(11), 3360. <https://doi.org/10.3390/molecules26113360>
- [5] Bahmanzadegan Jahromi, M. J., Abdossi, V., Samavat, S., Mohammadi Torkashvand, A., & Mozafari, H. (2023). New approach of antioxidant properties of *Zinnia elegans* using bioremediation of Pb-contaminated soils. *Bioremediation Journal*, 27(4), 345–362. <https://doi.org/10.1080/10889868.2022.2087592>
- [6] Bhat, S. A., Bashir, O., Ul Haq, S. A., Amin, T., Rafiq, A., Ali, M., Américo-Pinheiro, J. H. P., & Sher, F. (2022). Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. *Chemosphere*, 303(Pt 1), 134788. <https://doi.org/10.1016/j.chemosphere.2022.134788>
- [7] Biswal, B., Singh, S. K., Patra, A., & Mohapatra, K. K. (2022). Evaluation of phytoremediation capability of French marigold (*Tagetes patula*) and African marigold (*Tagetes erecta*) under heavy metals contaminated soils. *International Journal of Phytoremediation*, 24(9), 945–954. <https://doi.org/10.1080/15226514.2021.1985960>
- [8] Boorboori, M. R., & Zhang, H.-Y. (2022). Arbuscular mycorrhizal fungi are an influential factor in improving the phytoremediation of arsenic, cadmium, lead, and chromium. *Journal of Fungi*, 8(2), 176. <https://doi.org/10.3390/jof8020176>
- [9] Capuana, M. (2020). A review of the performance of woody and herbaceous ornamental plants for phytoremediation in urban areas. *iForest - Biogeosciences and Forestry*, 13, 139–151. <https://doi.org/10.3832/ifer3242-013>
- [10] Chunwichit, S., Phusantisampan, T., Thongchai, A., Taerprayoon, P., Avakul, P., Kubola, J., Pichtel, J., & Meeinkuirt, W. (2025). Role of soil amendments on phytoremediation potential of marigolds on cadmium and zinc co-contaminated soil. *Archives of Agronomy and Soil Science*, 71(1), 1–22. <https://doi.org/10.1080/03650340.2025.2518266>
- [11] Deepika, & Haritash, A. K. (2023). Phytoremediation potential of ornamental plants for heavy metal removal from contaminated soil: A critical review. *Horticulture, Environment, and Biotechnology*, 64(5), 709–734. <https://doi.org/10.1007/s13580-023-00518-x>
- [12] El-Sappah, A. H., Zhu, Y., Huang, Q., Chen, B., Soaud, S. A., Abd Elhamid, M. A., Yan, K., Li, J., & El-Tarabily, K. A. (2024). Plants' molecular behavior to heavy metals: From criticality to toxicity. *Frontiers in Plant Science*, 15, 1423625. <https://doi.org/10.3389/fpls.2024.1423625>
- [13] Febiola, R. R., Prasetyawati, E. T., & Nirwanto, H. (2025). The potential of *Zinnia elegans* and *Bacillus* sp. as lead (Pb) bioremediation agents. *Jurnal Bioteknologi & Biosains Indonesia*, 12(2), 231–240. <https://doi.org/10.55981/jbbi.2025.13482>
- [14] Khan, A. H. A., Kiyani, A., Mirza, C. R., Butt, T. A., Barros, R., Ali, B., Iqbal, M., & Yousaf, S. (2021). Ornamental plants for the phytoremediation of heavy metals: Present knowledge and future perspectives. *Environmental Research*, 195, 110780. <https://doi.org/10.1016/j.envres.2021.110780>
- [15] Khilji, S. A., Waseem, M., Tariq, S., Jabeen, S., Jamal, A., Alomrani, S. O., Javed, T., & Riaz, A. (2024). Microbe assisted phytoremediation of heavy metal contaminated soil by using African marigold (*Tagetes erecta* L.). *Plant Stress*, 11, 100369. <https://doi.org/10.1016/j.stress.2024.100369>
- [16] Liu, Z., & Tran, K.-Q. (2021). A review on disposal and utilization of phytoremediation plants containing heavy metals. *Ecotoxicology and Environmental Safety*, 226, 112821. <https://doi.org/10.1016/j.ecoenv.2021.112821>
- [17] Madanan, M. T., Shah, I. K., Varghese, G. K., & Kaushal, R. K. (2021). Application of Aztec marigold (*Tagetes erecta* L.) for phytoremediation of heavy metal polluted lateritic soil. *Environmental Chemistry and Ecotoxicology*, 3, 17–22. <https://doi.org/10.1016/j.encco.2020.10.007>
- [18] Meng, D., Qiu, J., Huang, P., Li, W., Li, Z., & Li, H. (2025). Positive effects of no-till reseeded with Asteraceae plants on the remediation of arsenic-contaminated mining areas: Tolerance evaluation, community reconstruction, and soil health impacts. *Journal of Environmental Management*, 128001. <https://doi.org/10.1016/j.jenvman.2025.128001>
- [19] Mohamed, H. I., Ullah, I., Toor, M. D., Tanveer, N. A., Ahmed, N., Naeem, M., Alatawi, A., El-Sabrou, A. M., Saffari, V. R., Alamri, S., & Ibrahim, M. F. M. (2025). Heavy metals toxicity in plants: Understanding mechanisms and developing coping strategies for remediation: A review. *Bioresources and Bioprocessing*, 12, 95. <https://doi.org/10.1186/s40643-025-00930-4>
- [20] Mukherjee, S., Leri, A. C., Bandaranayaka, C., Vázquez Núñez, E., Barros, R., Khan, A. H. A., Zhou, P., Zhang, T., Bernal, M. P., Clemente, R., & Bolan, N. (2025). Sustainable management of post-phytoremediation biomass. *Energy, Ecology and Environment*, 10, 675–709. <https://doi.org/10.1007/s40974-025-00364-w>
- [21] Panda, A., Patra, D. K., Acharya, S., Pradhan, C., & Patra, H. K. (2020). Assessment of the phytoremediation potential of *Zinnia elegans* L. plant species for hexavalent chromium through pot experiment. *Environmental Technology & Innovation*, 20, 101042. <https://doi.org/10.1016/j.eti.2020.101042>
- [22] Patel, E., & Modi, N. (2020). The bioaccumulation study of *Zinnia elegans* L.: Bioaccumulating high concentrations of lead (Pb) from contaminated soils. *Journal of Advanced Scientific Research*, 11(4), 344–346.
- [23] Poursmaieli, M., Ataei, M., Forouzandeh, P., Azizollahi, P., & Mahmoudifard, M. (2022). Recent progress on sustainable phytoremediation of heavy metals from soil. *Journal of Environmental Chemical Engineering*, 10(5), 108482. <https://doi.org/10.1016/j.jece.2022.108482>
- [24] Rahman, S. U., Qin, A., Zain, M., Mushtaq, Z., Mehmood, F., Riaz, L., Naveed, S., Ansari, M. J., Saeed, M., Ahmad, I., & Shehzad, M. (2024). Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review. *Heliyon*, 10(6), e27724. <https://doi.org/10.1016/j.heliyon.2024.e27724>
- [25] Sharma, J. K., Kumar, N., Singh, N. P., & Santal, A. R. (2023). Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment. *Frontiers in Plant Science*, 14, 1076876. <https://doi.org/10.3389/fpls.2023.1076876>
- [26] Sharma, M., & Mathur, J. (2023). Phytoaccumulation of zinc from contaminated soil using ornamental plant species *Helianthus annuus* L. and *Tagetes erecta* L. *International Journal of Phytoremediation*, 25(10), 1289–1305. <https://doi.org/10.1080/15226514.2022.2149692>
- [27] Singh, Y., Tripathi, S. N., Pandey, P., Tripathi, A., Arif, N., Yadav, V., Gaur, S., & Chauhan, D. K. (2024). Comparative physiological and anatomical responses of *Tagetes erecta* L. and *Zinnia elegans* Jacq. seedlings to AgNO<sub>3</sub> and ZnSO<sub>4</sub> metals and their nanoparticles. *Industrial Crops and Products*, 212, 118378. <https://doi.org/10.1016/j.indcrop.2024.118378>
- [28] Tan, H. W., Pang, Y. L., Lim, S., & Chong, W. C. (2023). A state-of-the-art of phytoremediation approach for sustainable management of heavy metals recovery. *Environmental Technology & Innovation*, 30, 103043. <https://doi.org/10.1016/j.eti.2023.103043>

- [29] Tamma, A. A., Lejcuś, K., Fiałkiewicz, W., & Marczak, D. (2025). Advancing phytoremediation: A review of soil amendments for heavy metal contamination management. *Sustainability*, 17(13), 5688. <https://doi.org/10.3390/su17135688>
- [30] Tugbaeva, A., Ermoshin, A., Wuriyangan, H., Maleva, M., Borisova, G., & Kiseleva, I. (2022). Copper stress enhances the lignification of axial organs in *Zinnia elegans*. *Horticulturae*, 8(6), 558. <https://doi.org/10.3390/horticulturae8060558>
- [31] Umer, S., Abbas, Z., Aziz, I., Hanif, M., Abideen, Z., Mansoor, S., Hamid, N., Ali, M. A., & Al-Hemaid, F. M. (2023). Potential of ornamental trees to remediate trace metal contaminated soils for environmental safety and urban green space development. *Sustainability*, 15(11), 8963. <https://doi.org/10.3390/su15118963>
- [32] Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science*, 11, 359. <https://doi.org/10.3389/fpls.2020.00359>
- [33] Zhakypbek, Y., Kossalbayev, B. D., Belkozhayev, A. M., Murat, T., Tursbekov, S., Abdalimov, E., Pashkovskiy, P., Kreslavski, V., Kuznetsov, V., & Allakhverdiev, S. I. (2024). Reducing heavy metal contamination in soil and water using phytoremediation. *Plants*, 13(11), 1534. <https://doi.org/10.3390/plants13111534>