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Review

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**JERUSALEM ARTICHOKE (*HELIANTHUS TUBEROSUS* L.)
FOR PHYTOMANAGEMENT
OF POTENTIALLY TOXIC METAL-CONTAMINATED SOILS:
A CADMIUM-FOCUSED REVIEW****I. M. Zadarko, V. V. Husak**

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Soil contamination by potentially toxic metals (PTMs), particularly cadmium (Cd), is a persistent environmental problem because metals do not degrade and may enter food chains. This review assesses the evidence for using Jerusalem artichoke (*Helianthus tuberosus* L.) in the phytomanagement of PTM-contaminated soils, with emphasis on Cd. A systematic search of Scopus and Web of Science was followed by a narrative synthesis of eligible studies. The available evidence indicates that Cd tolerance, biomass production, accumulation, and root-to-shoot translocation vary substantially among genotypes and experimental conditions. Several studies report greater Cd retention in roots than in shoots, indicating low translocation and potential relevance to stabilization-oriented phytomanagement; however, root accumulation alone does not demonstrate long-term immobilization. Selected high-biomass genotypes may contribute to gradual phytoextraction when aboveground biomass is repeatedly harvested, but field-scale Cd mass-balance data remain limited. Soil pH, mixed-metal contamination, amendments, and plant-associated bacteria can modify plant growth and metal availability. Accordingly, *H. tuberosus* should be regarded as a candidate for long-term phytomanagement of slightly to moderately contaminated land unsuitable for food production rather than as a rapid decontamination technology. Biomass produced on contaminated sites must be excluded from food and feed chains and managed through a validated and regulated pathway.

Keywords: *Helianthus tuberosus* L., Jerusalem artichoke, phytoremediation, Cadmium, potentially toxic metals, phytostabilization, phytoextraction, PRISMA 2020.

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Топіамбур (*Helianthus tuberosus* L.) у фітоменеджменті ґрунтів, забруднених потенційно токсичними металами: огляд із акцентом на кадмій

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Забруднення ґрунтів потенційно токсичними металами, особливо кадмієм (Cd), є тривалою екологічною проблемою, оскільки метали не розкладаються та можуть потрапляти до трофічних ланцюгів. У цьому огляді оцінено доказову базу щодо використання топіамбура (*Helianthus tuberosus* L.) для фітоменеджменту ґрунтів, забруднених потенційно токсичними металами, з особливою увагою до Cd. Після систематичного пошуку в базах Scopus і Web of Science проведено нарративний синтез відібраних досліджень. Наявні дані свідчать, що толерантність до Cd, формування біомаси, накопичення металу та його переміщення з коренів до надземних органів істотно залежать від генотипу й умов експерименту. У низці досліджень Cd переважно накопичувався в коренях, що вказує на низьку транслокацію та потенційну придатність до стабілізаційно орієнтованого фітоменеджменту; однак саме по собі кореневе накопичення не доводить довготривалої іммобілізації Cd у ґрунті. Високобіомасні генотипи можуть сприяти поступовій фітоекстракції за регулярного збирання надземної біомаси, проте польових даних щодо повного балансу Cd поки недостатньо. На ефективність також впливають рН ґрунту, сумісне забруднення іншими металами, ґрунтові добавки та асоційовані з рослинами бактерії. Отже, *H. tuberosus* доцільно розглядати як кандидата для довготривалого фітоменеджменту слабо та помірно забруднених земель, непридатних або не призначених для вирощування харчової продукції, а не як засіб швидкого очищення. Забруднену біомасу слід виключити з харчового й кормового ланцюгів та спрямовувати лише на валідований і регульований шлях поводження.

Ключові слова: *Helianthus tuberosus* L., топіамбур, фіторемедіація, кадмій, потенційно токсичні метали, фітостабілізація, фітоекстракція, PRISMA 2020.

Introduction. Soil contamination with potentially toxic metals (PTMs) is a long-term environmental problem because metals and metalloids are persistent, non-biodegradable and capable of accumulating in soil-plant systems. Cadmium (Cd) is particularly important due to its mobility in soil, plant uptake, phytotoxicity and potential entry into food chains. The environmental relevance of Cd should therefore be interpreted within the broader context of PTM toxicity, soil chemistry, and bioavailability [2, 20, 29, 51].

Phytoremediation has been proposed as an environmentally compatible, comparatively low-cost approach for managing contaminated soils. Its main mechanisms include phytoextraction, phytostabilization,

rhizofiltration, phytovolatilization and plant-assisted immobilization. The concept has developed from early demonstrations of plant-based metal removal to more realistic phytomanagement strategies in which risk reduction, biomass production and long-term site stabilization are considered together [1, 8, 14, 26, 27, 34–39, 40, 43, 45].

The efficiency of phytoremediation depends on metal tolerance, root development, uptake capacity, root-to-shoot translocation and biomass production. Hyperaccumulators can reach very high shoot metal concentrations, but they often produce limited biomass. For this reason, high-biomass species combining moderate metal accumulation, strong tolerance, and potential for controlled

non-food management are increasingly considered for field-scale phytomanagement [10, 11, 21, 24, 33, 50].

Jerusalem artichoke (*Helianthus tuberosus* L.), also known as topinambur, is a perennial Asteraceae crop with rapid growth, vegetative propagation by tubers, high biomass productivity and adaptability to marginal environments. Its biomass and tubers are widely discussed in relation to bioenergy, inulin production and renewable industrial feedstocks, which makes the crop attractive for contaminated lands, where food production would be inappropriate [13, 17, 19, 22, 23].

The potential of *H. tuberosus* for PTM phytoremediation is supported by studies showing growth under Cd stress, Cd accumulation in roots and shoots, genotype-dependent performance, response to mixed-metal contamination and possible improvement through endophytic bacteria. Cd-focused evidence is especially important because Cd combines high environmental relevance with strong plant physiological effects [4–6, 12, 31, 32, 49].

This review aims to evaluate the evidence for the use of *H. tuberosus* in the phytomanagement of PTM-contaminated soils, with particular emphasis on Cd. The review focuses on genotype-dependent Cd tolerance and accumulation, organ-specific Cd partitioning, soil and rhizosphere factors, assisted remediation, biomass management, field feasibility, and remaining research gaps.

Materials and methods.

Review design. This review was designed as a systematic literature search followed by a narrative evidence synthesis to evaluate the potential of *Helianthus tuberosus* L. for the phytomanagement and phytoremediation of soils contaminated with potentially toxic metals (PTMs), with particular emphasis on cadmium (Cd). Reporting of the literature identification, screening, eligibility assessment, and study selection process was informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement and its explanation-and-elaboration document [42, 46]. The original PRISMA

statement was additionally consulted as methodological background [41].

The review focused primarily on experimental evidence directly concerning *H. tuberosus* exposed to Cd or other PTMs. Methodological publications, general reviews of phytoremediation and metal toxicity, and publications addressing Jerusalem artichoke biomass utilization were used as contextual sources to support interpretation but were considered separately from the primary experimental evidence.

A narrative synthesis was selected instead of a quantitative meta-analysis because the available studies differed substantially in plant genotype, experimental system, contaminant type and concentration, exposure duration, soil characteristics, measured plant organs, and reported endpoints. Particular attention was therefore given to the direction and consistency of effects, experimental context, metal partitioning among plant organs, biomass production, and the practical relevance of individual studies rather than to statistical pooling of heterogeneous datasets.

Information sources and search date.

The bibliographic search was conducted on 31 July 2026 using two major scientific databases: Scopus and the Web of Science Core Collection.

The search covered literature available in the databases up to 31 July 2026. No publication-year restriction was applied, allowing both earlier foundational studies and recent experimental evidence to be identified.

The primary search strategy was constructed around three groups of terms:

- terms identifying *H. tuberosus*;
- terms describing Cd and other potentially toxic metals;
- terms describing phytoremediation, metal accumulation, translocation, or related plant responses.

The principal search was designed to identify studies directly relevant to the soil-plant remediation function of Jerusalem artichoke. Additional contextual searches were conducted separately for Cd toxicity, hyperaccumulation, soil amendments and pH, plant-microbe-assisted phytoremediation, and

non-food utilization of *H. tuberosus* biomass. Contextual publications were used to interpret the primary findings but were not treated as primary *H. tuberosus* phytoremediation studies.

Search strategy. The following search string was applied to the title, abstract, and author keywords fields in Scopus:

Scopus search query

TITLE-ABS-KEY (("Helianthus tuberosus" OR "Jerusalem artichoke" OR topinambur) AND (cadmium OR Cd OR "heavy metal*" OR "potentially toxic metal*" OR lead OR Pb OR zinc OR Zn OR copper OR Cu OR nickel OR Ni OR mercury OR Hg OR chromium OR Cr) AND (phytoremediation OR phytoextraction OR phytostabilization OR accumulation OR "metal accumulation" OR translocation OR bioconcentration OR "bioconcentration factor" OR "translocation factor" OR tolerance)).

The Scopus search returned 43 records.

The same conceptual search strategy was adapted to the Topic (TS) field of the Web of Science Core Collection:

Web of Science search query

TS = (("Helianthus tuberosus" OR "Jerusalem artichoke" OR topinambur) AND (cadmium OR Cd OR "heavy metal*" OR "potentially toxic metal*" OR lead OR Pb OR zinc OR Zn OR copper OR Cu OR nickel OR Ni OR mercury OR Hg OR chromium OR Cr) AND (phytoremediation OR phytoextraction OR phytostabilization OR accumulation OR "metal accumulation" OR translocation OR bioconcentration OR "bioconcentration factor" OR "translocation factor" OR tolerance)).

The Web of Science search returned 55 records.

Thus, 98 bibliographic records were identified in the two databases before screening, consistent with the initial identification stage of the PRISMA workflow.

Supplementary contextual searches.

Supplementary contextual searches were conducted in Scopus and Web of Science Core Collection on 31 July 2026.

Because the primary *H. tuberosus* literature does not cover all mechanistic and

practical aspects required for interpreting phytoremediation performance, supplementary searches were conducted to obtain supporting literature on Cd toxicity, metal bioavailability, soil amendments, microorganisms, and biomass utilization.

These searches were conceptually separate from the primary evidence search and were not used to classify a publication as direct experimental evidence for *H. tuberosus* phytoremediation.

The following supplementary search combinations were used.

Cadmium toxicity and tolerance in plants ("cadmium toxicity" OR "cadmium stress" OR "Cd toxicity") AND (plant* OR crop*) AND (tolerance OR accumulation OR uptake OR translocation).

This contextual literature was used to interpret the physiological effects of Cd on plant growth and metal tolerance. Relevant background sources included publications on Cd toxicity and plant tolerance, for example [5].

Metal hyperaccumulation and phytoremediation (hyperaccumulat* OR phytoremediation OR phytoextraction OR phytostabilization) AND ("heavy metal*" OR "potentially toxic metal*" OR cadmium OR Cd).

This search was used to provide the conceptual framework for distinguishing classical hyperaccumulation, phytoextraction, phytostabilization, and high-biomass phytomanagement. Relevant methodological and conceptual sources included [1], [21], and [40].

Plant-microbe-assisted phytoremediation ("plant growth-promoting bacteria" OR PGPR OR rhizobacteria OR endophyte* OR "endophytic bacteria") AND (phytoremediation OR cadmium OR Cd OR "heavy metal*").

These sources were used to interpret the potential role of rhizospheric and endophytic microorganisms in plant growth, stress tolerance, and metal availability. Relevant general references included [15], [18], and [43].

Soil pH, Cd bioavailability, and amendments (cadmium OR Cd OR "heavy metal*") AND ("soil pH" OR amendment* OR biochar OR compost OR liming OR lime OR phosphate*) AND (bioavailability OR mobility OR immobilization OR mobilisation OR mobilization OR remediation).

This contextual search was used to support interpretation of soil-dependent Cd availability and the potential effects of organic and mineral amendments. Relevant references included [3], [2], [44], and [51].

Jerusalem artichoke biomass and non-food utilization ("Helianthus tuberosus" OR "Jerusalem artichoke") AND (biomass OR bioenergy OR bioethanol OR biogas OR biorefinery OR "renewable energy").

These sources were used exclusively to assess the potential non-food use of *H. tuberosus* biomass and were not considered evidence of metal-removal efficiency unless metal exposure was experimentally investigated. Relevant publications included [13], [19], [22], and [23].

Eligibility criteria. Studies considered part of the primary evidence base were required to meet the following eligibility criteria:

Inclusion criteria were: (i) original peer-reviewed experimental research; (ii) investigation of *Helianthus tuberosus* L. as the experimental plant species; (iii) exposure to Cd and/or at least one other potentially toxic metal; (iv) hydroponic, pot, greenhouse, soil, sludge-amended soil, or field experimental conditions; and (v) reporting of at least one outcome relevant to phytoremediation or phytomanagement, including plant tolerance, biomass production, metal concentration in plant tissues, root-to-shoot translocation, bioconcentration, metal uptake, total metal removal, effects of soil pH, effects of amendments, or plant-microbe interactions.

Studies examining mixed-metal contamination were eligible when Cd or other PTMs were quantified and the response of *H. tuberosus* could be evaluated separately.

Exclusion criteria were: (i) studies that did not investigate *H. tuberosus*; (ii) studies without exposure to potentially toxic metals;

(iii) studies addressing only food composition, inulin production, genetics, agronomic productivity, or bioenergy production without a metal-contamination component; (iv) studies dealing exclusively with other plant species; (v) publications without sufficient information to evaluate the experimental system or metal-related outcome; and (vi) duplicate publications reporting the same experimental dataset without additional relevant information.

Reviews, books, methodological guidelines, and broader phytoremediation publications were excluded from the primary evidence set but could be retained as contextual references when they provided information required for interpreting mechanisms, soil chemistry, remediation strategies, or biomass management.

This distinction was introduced to prevent general reviews and methodological publications from being counted as experimental evidence for the remediation capacity of *H. tuberosus*.

Study selection and PRISMA workflow. All records identified through Scopus and Web of Science were compiled before screening. The database searches yielded 98 records, including 43 records from Scopus and 55 records from Web of Science.

Duplicate checking was performed before screening, and 36 duplicate records were removed, leaving 62 unique records for title and abstract screening.

Title and abstract screening was performed by one reviewer using the predefined inclusion and exclusion criteria. Because study selection was conducted by a single reviewer, no formal procedure for resolving disagreements between reviewers was applicable. At this stage, 5 records were excluded because they did not address *Helianthus tuberosus*, potentially toxic metals, or outcomes relevant to phytoremediation, phytomanagement, metal accumulation, root-to-shoot translocation, or plant tolerance.

Consequently, 57 reports were sought for full-text retrieval and eligibility assessment. The retrieved full texts were evaluated against the predefined eligibility criteria. Following

full-text assessment, six reports were excluded because they did not provide sufficient direct evidence concerning *H. tuberosus* exposure to potentially toxic metals or did not report outcomes relevant to phytoremediation, metal accumulation, translocation, tolerance, or phytomanagement.

The remaining 51 reports met the eligibility criteria and were included in the narrative evidence synthesis. The complete study-selection process is summarized in Figure 1 according to the PRISMA 2020 flow-diagram framework [42, 46].

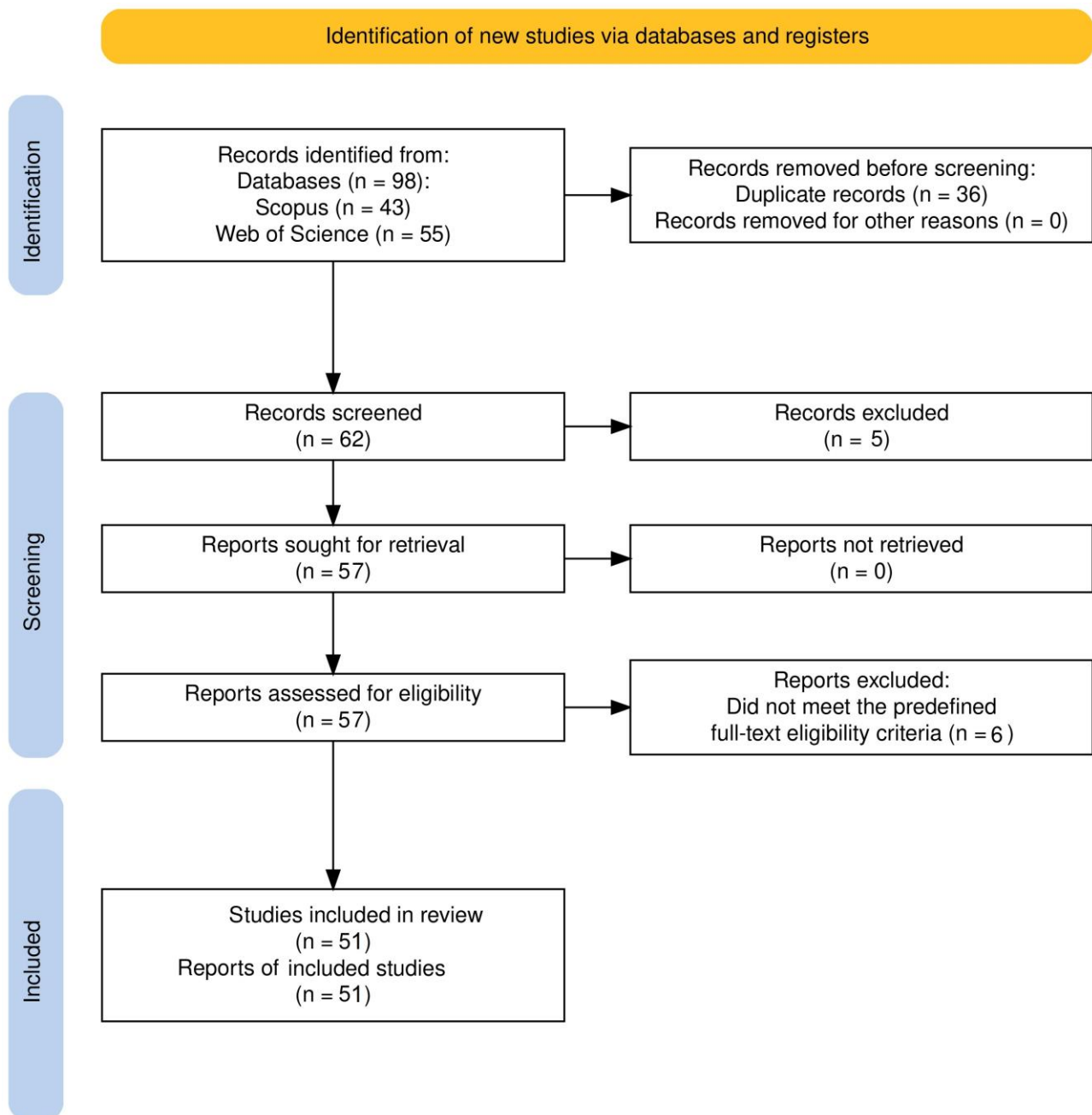


Figure 1. PRISMA 2020 flow diagram of the literature search and study-selection process

A total of 98 records were identified through Scopus ($n = 43$) and Web of Science ($n = 55$). After removal of 36 duplicate records, 62 unique records underwent title and abstract

screening, of which 5 were excluded. Fifty-seven reports were retrieved and assessed for full-text eligibility. Six reports were excluded

at the full-text stage, leaving 51 studies for inclusion in the narrative evidence synthesis.

Data extraction. For each eligible primary study, data were extracted into a structured evidence table. The following information was recorded where available:

- bibliographic information and publication year;
- experimental country or location;
- *H. tuberosus* cultivar, genotype, or accession;
- experimental system (hydroponic, pot, greenhouse, sludge-amended soil, or field study);
- characteristics of the soil or growth substrate;
- target metal or mixture of metals;
- metal concentration and, where reported, chemical form;
- exposure duration;
- soil pH and other relevant physicochemical characteristics;
- amendment treatments;
- microbial inoculation or endophyte treatments;
- plant survival and growth response;
- root, shoot, leaf, stem, and tuber biomass;
- metal concentrations in individual plant organs;
- bioconcentration or bioaccumulation factors;
- root-to-shoot translocation factors;
- total amount of metal accumulated or removed, where calculable;
- reported statistical significance;
- major experimental limitations.

Where studies reported only tissue metal concentration without biomass data, the results were interpreted as evidence of accumulation but not automatically as evidence of effective phytoextraction. Similarly, preferential accumulation of Cd in roots was interpreted as evidence of restricted root-to-shoot translocation and potential relevance to stabilization-oriented phytomanagement rather than as direct proof of long-term phytostabilization.

This distinction was applied consistently throughout the evidence synthesis.

Assessment of study quality and applicability. Because the eligible literature included heterogeneous hydroponic, pot, greenhouse, and field experiments, study quality and applicability were evaluated qualitatively rather than by applying a single numerical score.

Each primary study was assessed according to the availability and clarity of the following methodological characteristics: presence of an appropriate control treatment; clear identification of plant genotype or cultivar; reported contaminant concentrations and exposure duration; description of the experimental substrate or soil; biological replication; organ-specific determination of metal concentrations; biomass measurements; reporting of root-to-shoot partitioning; statistical analysis; and relevance of the experimental system to field-scale phytomanagement.

Particular caution was applied when extrapolating results from hydroponic or short-term controlled experiments to field conditions. Controlled studies were considered valuable for identifying physiological responses, genotype differences, and mechanisms of Cd uptake, whereas field studies were assigned greater practical relevance for evaluating biomass productivity, soil effects, mixed-metal exposure, and operational feasibility.

No study was excluded solely because of a lower level of field applicability; instead, methodological limitations were considered during interpretation of the strength of the evidence.

Evidence synthesis. Because of substantial heterogeneity in experimental design, genotype, contaminant concentration, exposure duration, soil characteristics, plant organs analysed, and reported outcomes, quantitative meta-analysis was not considered appropriate.

The evidence was therefore synthesized narratively and organized into the following thematic domains:

- genotype-dependent Cd tolerance, biomass production, and Cd accumulation;

- Cd partitioning among roots, shoots, leaves, stems, and tubers and its implications for phytoextraction versus stabilization-oriented management;
- effects of soil pH, co-contaminants, and mixed-metal exposure;
- plant–microbe-assisted remediation and the effects of beneficial endophytic or rhizospheric microorganisms;
- effects of soil amendments and manipulation of metal bioavailability;
- field feasibility, biomass management, residue safety, and long-term phytomanagement.

Particular emphasis was placed on distinguishing metal concentration in plant tissues from total metal removal. Evidence for phytoextraction was considered stronger when studies reported both biomass production and tissue metal concentration, allowing the amount of metal removed in harvested biomass to be estimated. Evidence based solely on tissue concentration was not interpreted as sufficient to demonstrate effective field-scale decontamination.

Similarly, evidence of root-dominated Cd accumulation was interpreted as indicating limited translocation to harvestable shoots and potential suitability for stabilization-oriented management, but not as direct evidence that Cd mobility or bioavailability in soil had been permanently reduced.

Results and discussion.

Characteristics of the included primary studies. The available primary evidence on *Helianthus tuberosus* under potentially toxic metal exposure comprises a heterogeneous range of experimental systems, including hydroponic experiments, controlled soil studies, mixed-metal treatments, sewage-sludge-amended soils, and field-scale investigations. Cadmium represents the most consistently investigated target metal, although individual studies have also examined Zn, Cu, Ni, Pb, Cr, Hg, Fe, and Mn, either separately or as components of mixed-metal contamination [4, 6, 12, 31, 32, 49].

Experimental designs differed substantially with respect to plant genotype or cultivar, contamination level, exposure

duration, growth substrate, soil properties, and the endpoints used to evaluate plant responses. Cd-focused studies included both controlled exposure experiments evaluating cultivar-specific tolerance and root-to-shoot translocation and soil-based experiments assessing genotype-dependent biomass production and Cd accumulation [6, 32]. Other investigations expanded this evidence base by examining plant responses to combined Cd and Zn exposure in association with endophytic bacteria, the influence of pH under mixed-metal contamination, and metal uptake under sewage-sludge-amended field conditions [12, 31, 49].

The most frequently reported outcomes included plant growth and biomass production, metal concentrations in roots and aboveground tissues, root-to-shoot translocation, genotype-dependent variation in metal accumulation, and responses to environmental or biological modifiers. In particular, Cd-focused experiments demonstrated substantial genotype dependence in tolerance, biomass production, and metal accumulation, whereas mixed-metal studies showed that uptake patterns can change with soil or solution chemistry [6, 31, 32]. Field-oriented evidence further indicates that cultivar choice and biomass productivity are important determinants of metal uptake under more complex soil conditions [49].

The heterogeneity of experimental designs, exposure systems, and reported endpoints limits direct quantitative comparison among studies and supports the use of narrative rather than pooled statistical synthesis. Importantly, metal concentration in plant tissues should not be interpreted as a stand-alone measure of remediation efficiency. Effective phytoextraction depends on the interaction between tissue metal concentration and harvestable biomass, whereas interpretation of stabilization-oriented effects additionally requires information on metal mobility and bioavailability within the soil–root system [1, 21, 40].

Accordingly, *H. tuberosus* is more appropriately evaluated as a high-biomass phytomanagement crop than as a classical

metal hyperaccumulator. Its remediation potential should be assessed using a combination of biomass production, metal accumulation, organ-specific partitioning, tolerance under prolonged exposure, and the quantity of metal that can ultimately be removed from or immobilized within the contaminated system [21, 24, 50].

The primary studies most directly relevant to the evaluation of *H. tuberosus*

under PTM contamination are summarized in Table 1. Collectively, they provide evidence for genotype-dependent Cd tolerance and accumulation, restricted root-to-shoot Cd translocation in some cultivars, modification of plant performance and metal distribution by endophytic bacteria, and substantial effects of pH and mixed-metal conditions on metal uptake [6, 12, 31, 32].

1. Selected key primary studies evaluating *Helianthus tuberosus* under PTM exposure

Research focus	Exposure system/metals	Main finding	Interpretation	References
1	2	3	4	5
Cd accumulation and translocation	Cd; hydroponic exposure; cultivars N2 and N5	Cd tolerance and accumulation were genotype-dependent; Cd accumulated mainly in roots, with TF below 1.	Supports genotype screening and indicates restricted root-to-shoot Cd translocation and potential suitability for stabilization-oriented management; root retention alone does not demonstrate phytostabilization	[6]
Cd phytoextraction in soil	Cd-contaminated soil; genotypes NY2 and NY5	NY5 showed higher biomass and greater Cd accumulation than NY2.	High-biomass genotypes may increase total Cd accumulation in plant biomass; effective Cd removal additionally requires harvesting and removal of contaminated biomass from the site.	[32]
Endophyte-assisted tolerance	Cd and Zn; cultivars VR and D19; PGP endophytes	Selected <i>Pseudomonas</i> and <i>Serratia</i> strains improved growth and affected Cd distribution.	Selected bacterial inoculants improved plant growth and altered Cd distribution under controlled conditions; their field effectiveness remains to be validated.	[12]
Mixed-metal uptake and pH	Cd, Cu, Fe, Mn, Ni, Zn, Pb; pH gradients	Growth and uptake were controlled by pH and metal load; several metals were more readily translocated than Cd/Pb.	Field application requires pH-sensitive management and site-specific risk assessment.	[31]
Sewage-sludge-amended field soil	Cr, Ni, Cu, Zn, Cd, Pb; six-year field experiment	Sludge dose increased yield and metal uptake; varietal differences were observed.	Provides field-scale evidence that biomass yield and cultivar choice and biomass yield are important determinants of field performance.	[49]

1	2	3	4	5
Hg-contaminated soil	Hg; non-food energy crop approach	Genotype-dependent tolerance and remediation potential were reported.	The study demonstrates genotype-dependent Hg tolerance and accumulation, extending the evidence for <i>H. tuberosus</i> beyond Cd. Conclusions concerning Cd should be based on Cd-specific studies.	[4]

Genotype-dependent Cd tolerance and accumulation. Genotype is one of the most important determinants of Cd response in *Helianthus tuberosus*. Available experimental evidence demonstrates substantial variation among cultivars and genotypes in their ability to maintain growth under Cd exposure and to accumulate Cd in plant tissues. Consequently, the remediation potential of *H. tuberosus* should not be interpreted as a uniform species-level characteristic but rather as a genotype-dependent trait that requires screening of individual plant materials before field application [6, 32].

Controlled Cd-exposure experiments showed cultivar-dependent differences in both Cd tolerance and accumulation, indicating that genetic variation can substantially influence plant performance under metal stress [6]. Similar differences were observed in Cd-contaminated soil, where genotype NY5 showed greater biomass production and higher Cd accumulation than NY2 [32]. These results demonstrate that selection of suitable genotypes can influence not only tissue Cd concentrations but also the total amount of Cd accumulated in plant biomass.

This distinction is particularly important when phytoremediation performance is evaluated. High metal concentration in plant tissues does not necessarily correspond to high remediation efficiency if plant growth is strongly inhibited. Conversely, a genotype maintaining relatively high biomass under Cd stress may accumulate a greater total mass of Cd even when its tissue concentration is moderate. Therefore, the most informative assessment should integrate tissue Cd concentration with biomass production rather than evaluate either parameter independently.

Where sufficient data are available, Cd accumulation should preferably be expressed as total metal mass per plant, per unit harvestable biomass, or per unit land area.

The importance of biomass maintenance is also supported by the physiological effects of Cd toxicity. Cadmium is a non-essential element that can adversely affect photosynthesis, mineral nutrition, water relations, membrane integrity, antioxidant metabolism, and root development. These effects can suppress biomass formation and thereby reduce the practical usefulness of otherwise Cd-accumulating plants [5, 10, 11, 25, 47, 48]. Accordingly, Cd tolerance should be considered together with accumulation capacity when candidate *H. tuberosus* genotypes are selected.

From a phytomanagement perspective, this genotype × biomass interaction may represent one of the principal advantages of *H. tuberosus*. Classical metal hyperaccumulators can achieve exceptionally high tissue metal concentrations, but low biomass production may limit the total amount of contaminant that can be removed per unit area. High-biomass species may follow a different strategy, in which moderate metal concentrations are partly compensated by greater biomass production and repeated harvesting [1, 24, 50]. However, for *H. tuberosus*, this potential should be demonstrated through Cd mass-balance measurements rather than inferred from biomass production alone.

An important limitation of the current evidence is that genotype comparisons have been conducted using a relatively restricted set of cultivars and experimental conditions. The superior performance of one genotype in a

particular hydroponic or soil experiment cannot therefore be assumed to persist across different soil types, Cd concentrations, climates, or management systems. Wider genotype-by-environment testing is required to identify plant materials that consistently combine Cd tolerance with sustained biomass production and high total Cd accumulation.

Overall, the available evidence supports genotype selection as a prerequisite for the use of *H. tuberosus* in Cd-contaminated soils. Candidate genotypes should be evaluated according to a combination of Cd tolerance, biomass stability under exposure, tissue Cd accumulation, and total accumulated Cd mass. Metal partitioning among roots, shoots, and tubers represents an additional critical selection criterion because it determines whether accumulated Cd remains predominantly belowground or becomes available for removal in harvestable biomass.

Root-to-shoot partitioning and remediation function. The distribution of Cd among plant organs is a critical determinant of the potential remediation function of *Helianthus tuberosus*. Evidence from Cd-exposure experiments indicates that Cd may accumulate preferentially in roots, with lower concentrations or limited transfer to aboveground tissues. In particular, cultivar-based experiments reported root-dominated Cd accumulation and root-to-shoot translocation factor (TF) values below 1, demonstrating restricted movement of Cd from belowground to aboveground plant organs [6].

This pattern has important implications for the interpretation of phytoremediation performance. Preferential retention of Cd in roots may reduce its transfer to stems and leaves and may therefore be compatible with stabilization-oriented phytomanagement. However, root accumulation alone should not be regarded as direct evidence of successful phytostabilization. Phytostabilization implies a reduction in contaminant mobility, bioavailability, leaching, erosion-mediated transport, or other pathways of environmental dispersion within the soil-root system. Demonstrating these effects requires measurements of soil Cd fractions and

contaminant mobility over time in addition to plant tissue concentrations [1, 28].

The distinction is particularly important because a low translocation factor describes metal partitioning within the plant but does not directly quantify changes in the contaminated soil. Therefore, findings of $TF < 1$ should be interpreted as evidence of restricted root-to-shoot Cd transfer and potential suitability for stabilization-oriented management, rather than as proof that *H. tuberosus* permanently immobilizes Cd in soil. Long-term field measurements of bioavailable and mobile Cd fractions would be required to confirm such a function.

Conversely, effective phytoextraction requires sufficient transfer of Cd into harvestable biomass followed by physical removal of that biomass from the contaminated site. Soil-based experiments with *H. tuberosus* indicate that selected genotypes can combine relatively high biomass production with substantial Cd accumulation, supporting the possibility of gradual Cd extraction through repeated harvesting [32]. Nevertheless, the presence of Cd in aboveground tissues should not itself be equated with effective soil decontamination. The relevant endpoint is the cumulative mass of Cd removed from the site over successive harvests, which depends on both tissue Cd concentration and harvestable biomass [1, 26].

Accordingly, phytoextraction and stabilization-oriented phytomanagement should not be treated as mutually exclusive or fixed species-level properties of *H. tuberosus*. The relative importance of each function is likely to depend on genotype, Cd concentration and bioavailability, soil properties, exposure duration, and harvest regime. A genotype characterized by strong root retention may be more appropriate where the principal management objective is to limit contaminant transfer and maintain vegetation cover, whereas genotypes combining substantial shoot biomass with greater Cd transfer to aboveground tissues may be more suitable for gradual phytoextraction [21, 26].

Assessment of *H. tuberosus* should therefore include organ-specific measurements

rather than a single whole-plant Cd concentration. Cd concentrations and biomass should ideally be quantified separately for roots, stems, leaves, and tubers. This is particularly relevant for Jerusalem artichoke because tubers represent a substantial component of belowground biomass and may constitute an additional reservoir of accumulated Cd. Without separate measurements of tuber contamination, it is difficult to establish the complete distribution of Cd within the plant or to evaluate the risk associated with retaining, harvesting, or unintentionally redistributing contaminated tubers.

A complete assessment of remediation performance should combine organ-specific Cd concentrations with corresponding biomass data and, where possible, changes in soil Cd pools before and after cultivation. For extraction-oriented systems, this would permit calculation of the cumulative Cd mass physically removed through harvested biomass. For stabilization-oriented systems, plant measurements should be complemented by changes in mobile or bioavailable soil Cd fractions. Such an approach would distinguish true contaminant removal or reduced environmental mobility from simple redistribution of Cd between soil and plant compartments.

Overall, the available evidence suggests that the remediation function of *H. tuberosus* should be interpreted along a continuum between stabilization-oriented phytomanagement and gradual phytoextraction, rather than assigned a single fixed label. Root-dominated accumulation supports the potential for restricting aboveground Cd transfer, whereas effective phytoextraction requires sufficient Cd allocation to harvestable tissues and repeated biomass removal. Determining which function predominates under field conditions requires integrated measurements of plant-organ partitioning, biomass production, soil Cd bioavailability, and cumulative Cd mass balance.

Effects of soil properties, amendments, and microorganisms. The

remediation performance of *Helianthus tuberosus* cannot be interpreted independently of the physicochemical and biological properties of the soil–rhizosphere system. Metal uptake by plants is controlled not only by total contaminant concentration but also by metal speciation, bioavailability, soil pH, organic matter, sorption processes, co-occurring elements, and rhizosphere activity. Consequently, similar total Cd concentrations may result in different plant responses and metal-uptake patterns under different soil conditions [2, 51].

Among these factors, soil pH is particularly important for Cd availability. In general, decreasing pH tends to increase Cd solubility and the proportion of metal potentially available for plant uptake, whereas increasing pH can enhance sorption and reduce Cd mobility. However, the magnitude of this effect depends on other soil properties, including organic matter content, clay mineralogy, cation-exchange capacity, and the presence of competing ions. Therefore, soil pH should not be considered as an isolated predictor of Cd uptake but as part of the broader chemical environment controlling metal availability [2, 51].

Experimental evidence specific to *H. tuberosus* further demonstrates that pH and contaminant composition can strongly modify plant growth and metal accumulation. Under mixed-metal exposure involving Cd together with Cu, Fe, Mn, Ni, Zn, and Pb, changes in pH and metal loading affected both biomass production and the uptake and translocation of individual elements [31]. These observations are particularly relevant to field phytomanagement because contaminated soils commonly contain mixtures of metals rather than Cd alone. Interactions among co-contaminants may modify metal availability, plant toxicity, and uptake patterns, making direct extrapolation from single-metal hydroponic experiments to field conditions inappropriate.

The importance of complex soil conditions is also supported by field evidence from sewage-sludge-amended soils, where metal uptake and biomass production varied

with sludge application rate and cultivar [49]. Such findings emphasize that practical remediation performance results from the interaction among contaminant load, soil properties, plant material, and biomass response rather than from the accumulation capacity of the species alone.

Soil amendments provide a potential means of modifying these interactions. Organic and mineral amendments, including liming materials, phosphates, composts, and biochar, can alter soil pH, sorption capacity, metal speciation, and consequently the mobility and bioavailability of Cd and other PTMs [3, 44]. Their effects, however, should not automatically be considered beneficial for every remediation objective. Amendments that strongly immobilize Cd may be appropriate where reduction of contaminant mobility and plant stress is the principal objective, but the same treatment may decrease Cd uptake into harvestable tissues and therefore limit phytoextraction.

Accordingly, amendment selection should be linked explicitly to the intended remediation function. For stabilization-oriented phytomanagement, amendments may be used to decrease Cd mobility, improve soil conditions, and support plant establishment. For phytoextraction-oriented management, excessive immobilization may be counterproductive if it substantially reduces the amount of Cd available for uptake. Evaluation of amendment effectiveness should therefore include measurements of both plant responses and changes in mobile or bioavailable soil Cd fractions rather than relying solely on changes in total soil Cd concentration [3, 44].

Biological interactions within the rhizosphere represent another potentially important component of *H. tuberosus*-based phytomanagement. Plant-associated microorganisms can influence root development, nutrient acquisition, stress responses, and metal availability, thereby modifying both plant tolerance and metal distribution. Broader phytoremediation research has demonstrated that plant growth-promoting rhizobacteria and endophytic

bacteria can affect metal uptake and plant performance through several mechanisms, including modification of nutrient availability, production of plant-growth-regulating compounds, changes in rhizosphere chemistry, and enhancement of stress tolerance [15, 16, 18, 30].

Evidence directly involving *H. tuberosus* indicates that selected endophytic bacteria can modify plant responses under Cd and Zn exposure. In particular, selected *Pseudomonas* and *Serratia* strains were associated with improved plant growth and changes in metal distribution, although the magnitude and direction of these effects depended on the plant cultivar and bacterial treatment [12]. These findings support the potential value of plant-microbe combinations but also demonstrate that microbial effects cannot be generalized across all cultivars or environmental conditions.

The available microbial evidence should therefore be interpreted cautiously when considering field application. Effects demonstrated under controlled experimental conditions may not persist in heterogeneous field soils, where microbial survival, competition with indigenous communities, soil chemistry, climatic conditions, and contaminant concentrations may alter inoculant performance. Consequently, bacterial inoculation should not be presented as a universally effective enhancement of *H. tuberosus* phytoremediation. Instead, compatible cultivar-microorganism combinations should be evaluated under site-specific conditions before field-scale implementation [12, 30].

Taken together, these findings indicate that *H. tuberosus*-based remediation should be regarded as an integrated soil-plant-microbe system rather than a plant-only intervention. Soil pH, metal bioavailability, co-contamination, amendment-induced changes in soil chemistry, microbial interactions, and plant genotype jointly determine biomass production and metal uptake. Management strategies should therefore be developed for specific sites and remediation objectives rather than transferred directly from controlled

experiments or from one contaminated soil to another.

For practical application, the sequence of decision-making should begin with characterization of total and bioavailable Cd, soil pH, organic matter, and co-contaminants. Amendment or microbial treatments should then be selected according to whether the intended objective is stabilization-oriented management or gradual phytoextraction. Their

effectiveness should ultimately be assessed through changes in soil metal availability, plant biomass, organ-specific metal accumulation, and, where extraction is intended, the cumulative amount of Cd removed in harvested biomass.

The principal determinants identified across next Sections and their practical implications are summarized in Table 2.

2. Evidence-based determinants of Cd phytomanagement by *Helianthus tuberosus* and their practical implications

Determinant	Evidence-based interpretation	Practical implication	References
Genotype-dependent Cd tolerance	Cultivars and genotypes differ in their ability to maintain growth and accumulate Cd under exposure.	Genotype screening should precede field application; species-level generalization should be avoided.	[6, 32]
Biomass-dependent Cd accumulation	High biomass may compensate for moderate tissue Cd concentrations and increase total accumulated Cd mass.	Evaluate biomass yield together with tissue Cd concentration; where possible, report total Cd mass per plant or unit area.	[2, 32]
Root-to-shoot Cd partitioning	Cd may be retained predominantly in roots, resulting in low root-to-shoot translocation in some cultivars.	Root retention indicates potential for stabilization-oriented management but does not by itself demonstrate long-term phytostabilization.	[6]
Soil pH and mixed-metal effects	Cd uptake and plant growth are strongly influenced by pH, metal mixture, and soil chemistry.	Site-specific assessment of Cd bioavailability and co-contaminants is required before selecting a remediation strategy.	[3, 31]
Microbial assistance	Selected endophytic bacteria can improve plant growth and modify Cd distribution under controlled conditions.	Cultivar–microorganism combinations should be tested locally; controlled-study effects should not be assumed to persist under field conditions.	[12, 30]
Soil amendments	Organic and mineral amendments may change Cd mobility and plant availability depending on their properties and soil conditions.	Amendment selection should correspond to the intended remediation objective: Cd immobilization where stabilization is intended, or maintenance of sufficient Cd availability where gradual extraction is intended.	[1, 44]

Field feasibility and biomass management. Translation of experimental evidence on *Helianthus tuberosus* into field-scale phytomanagement requires greater caution than interpretation of results obtained

under hydroponic or controlled soil conditions. Field soils are spatially heterogeneous and may differ substantially in pH, organic matter content, contaminant speciation, metal bioavailability, co-contaminants, microbial

communities, and seasonal environmental conditions. Consequently, plant performance and metal uptake observed under controlled conditions should not be assumed to occur with the same magnitude under field conditions.

Nevertheless, field-oriented evidence indicates that *H. tuberosus* possesses several characteristics relevant to long-term management of contaminated land. Its capacity to produce substantial biomass and to grow on marginal or non-food land may be advantageous where conventional agricultural production is undesirable. A long-term experiment on sewage-sludge-amended soil further showed that biomass production and metal uptake depend on cultivar and contamination conditions, confirming that field performance results from interactions among plant material, soil properties, and contaminant loading rather than from species identity alone [49].

For practical application, the remediation objective should be defined before cultivation begins. Where the principal objective is stabilization-oriented phytomanagement, evaluation should focus on successful plant establishment, persistence of vegetation cover, reduction of erosion or contaminant dispersion, and changes in mobile or bioavailable Cd fractions. By contrast, where gradual phytoextraction is intended, the relevant endpoint is the cumulative amount of Cd physically removed from the site in harvested biomass over successive growing seasons. Tissue Cd concentration alone is insufficient to demonstrate effective remediation because performance depends on both metal concentration and harvestable biomass [1, 7, 9, 40].

This distinction also affects harvesting strategy. Aboveground biomass containing Cd must be removed from the site if phytoextraction is the intended objective; otherwise, senescence and decomposition may return part of the accumulated metal to the soil. Harvest monitoring should therefore include biomass yield together with organ-specific metal concentrations so that the quantity of Cd removed during each harvest can be estimated. Where stabilization-oriented management is

prioritized, harvesting intensity may differ, but monitoring of plant tissues and soil Cd availability remains necessary to determine whether the system is reducing environmental exposure rather than merely redistributing the contaminant.

Biomass management represents an additional practical challenge. Plant material produced on soils contaminated with Cd or other PTMs should not automatically enter conventional food or feed chains. This issue is particularly important for *H. tuberosus* because its tubers are normally used for food, feed, propagation, and industrial purposes. Where the crop is grown for phytomanagement, contaminated tubers and other plant material should therefore be kept separate from conventional agricultural products and managed in a way that prevents unintended redistribution of accumulated metals.

Jerusalem artichoke has been investigated extensively as a feedstock for bioethanol, biogas, renewable energy, and broader biorefinery applications [13, 19, 22, 23]. These studies demonstrate the technological versatility of *H. tuberosus* biomass under conventional production conditions. However, they do not directly demonstrate that biomass contaminated with Cd or other PTMs can safely enter the same processing pathways. Bioenergy or industrial utilization should therefore be regarded as a potential biomass-management option that requires separate validation, rather than as an automatically safe end use for phytoremediation biomass.

Any proposed processing route should account for the fate of accumulated metals. Thermal, biological, or industrial processing may reduce biomass volume or recover useful energy and materials, but it does not necessarily eliminate Cd from the system. Metals may remain concentrated in ash, digestate, solid residues, or other by-products. Accordingly, evaluation of contaminated biomass processing should include metal concentrations and, where possible, a mass balance across the biomass, final products, and residues before reuse or disposal. The currently

available *H. tuberosus* bioenergy literature supports the feasibility of biomass conversion but does not by itself establish the environmental safety of processing Cd-contaminated material.

Tuber management requires particular consideration because *H. tuberosus* is vegetatively propagated. Tubers remaining in the soil may contribute to plant persistence, while harvested tubers may provide a pathway for contaminated material to leave the managed site if they are inadvertently used for food, feed, or propagation. Field-management protocols should therefore include monitoring of tuber metal concentrations, controlled handling of harvested tubers, and measures to prevent unintended movement of contaminated propagules.

Overall, the field feasibility of *H. tuberosus* depends not only on its capacity to tolerate and accumulate Cd but also on whether the entire management system can be controlled effectively. Practical implementation should integrate site characterization, selection of suitable plant material, a clearly defined remediation objective, monitoring of soil and plant Cd, appropriate harvesting, control of tuber movement, and a validated pathway for handling contaminated biomass. To translate these considerations into a testable field-management approach, Table 3 summarizes a proposed sequence of site characterization, genotype selection, remediation-objective definition, soil and rhizosphere management, monitoring, harvesting, and contaminated-biomass control.

3. Proposed field implementation and monitoring framework for *Helianthus tuberosus* on Cd-contaminated soils.

Step	Recommended action	Purpose/evaluation criterion	Supporting evidence/References
1	2	3	4
1. Site characterization	Determine total and bioavailable Cd, soil pH, organic matter, major soil properties, and relevant co-contaminants before planting.	Establish baseline contamination and determine whether stabilization-oriented management or gradual phytoextraction is a realistic objective.	[3, 51]
2. Genotype selection	Screen available <i>H. tuberosus</i> genotypes under site-relevant Cd concentrations and soil conditions.	Select material combining Cd tolerance, sustained biomass production, and appropriate organ-specific Cd partitioning.	[6, 32]
3. Definition of the remediation objective	Define whether the principal objective is stabilization-oriented phytomanagement, gradual phytoextraction, or a combination of both.	Ensure that subsequent soil management, harvesting, and monitoring are consistent with the intended remediation function.	[2, 40]
4. Soil and rhizosphere management	Adjust soil conditions only where justified by site-specific data; consider liming materials, organic/mineral amendments, phosphates, or biochar according to the intended remediation objective.	Modify Cd mobility and plant stress without assuming that reduced bioavailability is beneficial for phytoextraction.	[1, 31, 44]

1	2	3	4
5. Microbial assistance, where applicable	Test compatible endophytic or rhizospheric microorganisms under site-specific conditions before field-scale application.	Determine whether microbial inoculation improves biomass production, Cd tolerance, or metal distribution under realistic soil conditions.	[12, 30]
6. Plant and soil monitoring	Measure biomass and Cd concentrations separately in roots, stems, leaves, and tubers; monitor total and bioavailable soil Cd during cultivation.	Distinguish plant accumulation from actual contaminant removal or reduced Cd mobility and establish a Cd mass balance.	[26, 40]
7. Harvest management	When phytoextraction is targeted, remove Cd-containing harvestable biomass from the site and record biomass yield and tissue Cd concentrations for each harvest.	Quantify cumulative Cd mass physically removed from the contaminated site rather than relying on tissue concentration alone.	[2, 32]
8. Tuber and propagation control	Monitor tuber Cd concentrations and prevent unintended movement or reuse of contaminated tubers outside the managed site.	Reduce the risk of contaminated material entering food, feed, or propagation pathways and limit uncontrolled vegetative spread.	Evidence is currently limited; this should be treated as a management recommendation and research priority.
9. Contaminated biomass management	Exclude contaminated biomass from food and feed chains. Any proposed energy or industrial processing route should include measurement of Cd and other PTMs in products, by-products, and residues.	Prevent secondary redistribution of contaminants and determine whether a proposed biomass-processing pathway is environmentally acceptable.	Current <i>H. tuberosus</i> bioenergy sources support biomass-processing potential, but do not directly establish safe processing of Cd-contaminated biomass: [18, 19]
10. Long-term performance assessment	Repeat soil and plant monitoring over multiple growing seasons.	Demonstrate cumulative Cd removal, reduction in mobile/bioavailable Cd, or another measurable reduction in environmental risk.	[22, 40]

Research gaps and priorities. Despite the promising experimental evidence, several important knowledge gaps continue to limit strong conclusions regarding the practical use of *Helianthus tuberosus* on Cd-contaminated soils. Current studies demonstrate that Jerusalem artichoke can tolerate Cd exposure, accumulate Cd, and maintain substantial biomass under certain conditions; however, the available evidence is not yet sufficient to define the crop as a broadly validated field-scale phytoremediation technology. In particular, conclusions derived from hydroponic and controlled soil experiments require confirmation under heterogeneous field conditions.

One major priority is broader genotype-by-environment evaluation. Cd-focused studies have demonstrated substantial differences among *H. tuberosus* genotypes in tolerance, biomass production, and Cd accumulation, but only a limited range of genetic material has been investigated [6, 32]. Future studies should compare a wider range of cultivars and genotypes across contrasting soil types, Cd concentrations, pH conditions, and climatic environments. Such experiments should identify genotypes that maintain stable biomass production and predictable Cd partitioning rather than extrapolating the performance of individual cultivars across sites.

Another major limitation is the lack of complete Cd mass balances. Tissue Cd concentrations characterize accumulation but do not demonstrate how much contaminant is actually removed from the soil. Future studies should therefore combine Cd concentrations in roots, stems, leaves, and tubers with corresponding organ biomass, harvest frequency, and measurements of total and bioavailable soil Cd before and after cultivation. For extraction-oriented systems, the most informative endpoint should be the cumulative mass of Cd physically removed from the site over successive harvests rather than tissue concentration alone. For stabilization-oriented systems, plant measurements should be complemented by

changes in mobile or bioavailable soil Cd fractions.

Greater attention is also required for tuber contamination and vegetative persistence. Tubers represent a substantial component of belowground biomass and may constitute an additional reservoir of accumulated Cd. Because they are normally used for food, feed, propagation, and industrial purposes, contaminated tubers may also represent a pathway for unintended movement of Cd-containing plant material outside the remediation site. Future experiments should therefore quantify tuber Cd concentrations separately from root and shoot concentrations and evaluate appropriate strategies for harvesting, containment, and prevention of uncontrolled vegetative spread.

Integrated, multi-season field experiments represent a further research priority. Existing studies commonly evaluate individual components of the remediation system separately, whereas practical phytomanagement requires simultaneous consideration of soil chemistry, plant genotype, microbial interactions, amendments, harvesting, and changes in contaminant availability over time. Microbial treatments that improve plant performance under controlled Cd exposure should be validated in heterogeneous field soils, where their effectiveness may be modified by indigenous microbial communities, contaminant levels, and environmental conditions [12]. Similarly, the effects of pH and mixed-metal contamination observed experimentally indicate that field performance cannot be predicted from total Cd concentration alone [31].

The role of soil amendments also requires evaluation tailored to the intended remediation objective. Liming materials, phosphates, composts, biochar, and related amendments can alter Cd mobility, bioavailability, and plant stress, but the desired effect differs between remediation pathways. Immobilization may be advantageous for stabilization-oriented phytomanagement, whereas excessive reduction of Cd availability may limit uptake where gradual

phytoextraction is intended. Future studies should therefore evaluate amendment performance using both plant-based indicators and changes in mobile or bioavailable soil Cd fractions rather than assuming that reduced metal uptake necessarily represents improved remediation [44].

Another unresolved issue is the safe management and possible valorization of contaminated biomass. Although *H. tuberosus* has considerable potential as a feedstock for bioenergy and biorefinery applications [22, 23], these studies do not establish that Cd-contaminated biomass can safely enter conventional processing pathways. Future research should therefore determine the fate of Cd during combustion, anaerobic digestion, fermentation, or other processing technologies and quantify metals in ash, digestate, solid residues, and other by-products. Biomass valorization should only be considered environmentally beneficial when contaminant redistribution and residue management are explicitly addressed.

More broadly, future studies should focus on whether cultivation of *H. tuberosus* produces a measurable reduction in environmental risk over time. Plant accumulation alone does not demonstrate remediation if Cd is merely transferred temporarily from soil to plant tissues or subsequently returned to the site. Long-term experiments should determine whether repeated cultivation reduces mobile or bioavailable Cd, decreases the total Cd pool through biomass removal, limits contaminant dispersion, or otherwise reduces exposure pathways. Such endpoints are necessary to distinguish successful phytomanagement from simple contaminant redistribution.

A methodological limitation of the present review should also be acknowledged. Study selection and eligibility assessment were performed by a single reviewer, which may have increased the risk of selection error or reviewer bias. This limitation should be considered when interpreting the completeness of the included evidence base.

Future research should therefore move from isolated proof-of-concept experiments

toward integrated field-scale validation. The most informative experimental designs would combine genotype selection, site characterization, organ-specific Cd partitioning, soil Cd bioavailability, amendment and microbial treatments, repeated harvesting, complete Cd mass balance, and contaminated-biomass management within the same multi-season framework. Such studies would make it possible to determine under which conditions *H. tuberosus* is most appropriate for stabilization-oriented phytomanagement, when it can contribute to gradual phytoextraction, and when its application is unlikely to provide meaningful environmental benefit.

Conclusions. *Helianthus tuberosus* L. is a promising high-biomass crop for the phytomanagement of Cd-contaminated soils, but its remediation performance is strongly influenced by genotype and site conditions. The available evidence demonstrates variation among cultivars in Cd tolerance, biomass production, metal accumulation, and root-to-shoot translocation. Preferential Cd retention in roots may support stabilization-oriented management, whereas gradual phytoextraction requires sufficient transfer of Cd to harvestable biomass followed by its repeated removal from the contaminated site.

The effectiveness of *H. tuberosus* also depends on soil pH, Cd bioavailability, co-contaminants, amendments, and plant-microbe interactions. These factors should be managed according to the intended remediation objective and evaluated under site-specific conditions. Remediation performance should therefore be assessed using organ-specific Cd concentrations, biomass production, and cumulative Cd removal rather than tissue concentration alone.

A major practical limitation is the management of contaminated biomass, including tubers. Biomass produced on Cd-contaminated land should be excluded from food and feed chains, while potential bioenergy or industrial uses require separate evaluation of Cd transfer into products, by-products, and residues. Overall, current evidence supports *H. tuberosus* more strongly

as a candidate for long-term, site-specific phytomanagement than as a rapid Cd decontamination technology. Future multi-season field studies should focus on genotype

selection, soil Cd bioavailability, root–shoot–tuber partitioning, repeated harvesting, cumulative Cd removal, and safe biomass management.

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