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Biology-Botany

Efficient plant species for the phytoremediation of copper-contaminated soils

Plantas eficientes para a fitorremediação de solos contaminados com cobre

Marcela Pinto Barbosa Vassar[I],
Fabiola de Sampaio Rodrigues Grazinoli Garrido[I], **Fábio Souto Almeida**[I]

[I] Universidade Federal Rural do Rio de Janeiro, Seropédica, RJ, Brasil

ABSTRACT

This study aimed to identify plant species and their physiological traits relevant to the ancient technique of soil remediation known as phytoremediation, applied to copper-contaminated soils. Publications from 2000 to 2025 were reviewed using the English and Portuguese terms 'copper,' 'phytoremediation,' 'copper phytoremediation,' 'fitorremediação de cobre,' and 'contaminação por cobre.' The search was conducted across major scientific databases, including the CAPES Periodicals Portal, Scopus, and Google Scholar. Articles were filtered for those addressing techniques and species employed in the phytoremediation of copper-contaminated areas during the study period. The review identified 51 plant species from 22 families, including 14 natives to Brazil, with potential for rehabilitating degraded soils. Species in the family Fabaceae demonstrated high efficiency in copper accumulation within plant tissues, while Poaceae, Asteraceae, and Brassicaceae also exhibited strong phytoremediation potential. The key factors contributing to successful phytoremediation included the ability of plants to establish and grow in contaminated soils, resistance to salinity, and effective translocation of copper from roots to shoots, concentrating the metal in aerial tissues.

Keywords: Environmental degradation; Environmental impacts; Environment

RESUMO

Este trabalho teve como objetivo destacar plantas e suas propriedades fisiológicas utilizadas em uma técnica milenar para tratamento de solos contaminados com cobre, a fitorremediação. Para isso, foi realizada uma seleção de publicações de 2000 a 2025 de trabalhos elegíveis pela presença dos termos em inglês e português: "copper", "phytoremediation", "copper phytoremediation" ou "fitorremediação de cobre", "contaminação por cobre". A busca ocorreu em bases de dados científicos como Portal de

Periódicos da CAPES, SCOPUS e Google Acadêmico. Os trabalhos foram filtrados buscando técnicas e espécies utilizadas na fitorremediação de áreas contaminadas com cobre entre 2000 e 2025. A pesquisa levantou 51 espécies de 22 famílias, das quais 14 são nativas do Brasil, que podem ser utilizadas para recuperação de áreas degradadas. A família vegetal Fabaceae foi eficiente em acumular cobre nos tecidos. As famílias Poaceae, Asteraceae e Brassicaceae também se destacaram na fitorremediação de solos. Os principais fatores para o sucesso dos processos de fitorremediação foram a capacidade da planta de se desenvolver sem maiores problemas em solos contaminados, a resistência à salinidade, bem como sua capacidade de concentrar cobre na parte aérea da planta por meio da translocação do contaminante das raízes para os brotos.

Palavras-chave: Degradação ambiental; Impactos ambientais; Meio ambiente

1 INTRODUCTION

The processes of urbanization—including the creation, expansion, and development of cities—have driven increasing demand for natural resources, particularly metals and petroleum derivatives. Among these, the use of metals for technological purposes has significantly impacted resource extraction, recycling, transportation, and waste disposal (Vyalov et al., 2022). As nations transition their energy matrices toward clean energy sources, the demand for metals such as copper (Cu)—used in transmission lines, batteries, and other technological devices—continues to rise (Zhang et al., 2022).

Copper is extensively exploited and utilized across diverse economic sectors, elevating the risk of environmental contamination through extraction and improper disposal. Agricultural practices, such as applying copper-based fungicides and fertilizing with animal manure, as well as industrial waste disposal and mining activities, all contribute to Cu accumulation in soils (Glibota et al., 2019).

Under natural conditions, copper serves as a critical cofactor in essential metabolic pathways. In soils, it typically occurs at background levels ranging from 2 to 119 mg Cu kg^{-1} across nine soil classes (Fadigas et al., 2006). As an essential micronutrient, copper is indispensable to plants, animals, fungi, bacteria, protozoa, and other organisms, playing vital roles in growth, oxidative metabolism, and numerous biochemical reactions. Its unique physicochemical properties, including high electrical conductivity, render it a strategic material in contemporary society, especially given the demand for clean energy systems. Consequently, copper prospecting and recycling have intensified as global energy strategies shift toward sustainability.

The search for effective, efficient, and low-cost solutions to remediate contaminated sites has likewise intensified, particularly for ubiquitous contaminants such as copper. Among the available alternatives, phytoremediation—a bioremediation technique that employs plants, often in association with microorganisms—stands out for its efficiency, simplicity, low implementation costs, and broad public acceptance (Pires et al., 2003; Santana, Morales & Jacques, 2020).

Phytoremediation involves the use of plants, their rhizospheric microbiota, and soil amendments (e.g., fertilizers, organic matter) combined with agronomic practices to remove, immobilize, or neutralize contaminants in the environment (Accioly & Siqueira, 2000). Compared to conventional remediation techniques, phytoremediation offers notable advantages, including cost-effectiveness and decontamination efficacy (Cunningham et al., 1996; Perkovic et al., 1996). This technique can be applied to soils contaminated by a variety of organic and inorganic pollutants, including heavy metals, petroleum hydrocarbons, pesticides, explosives, chlorinated solvents, and industrial toxic by-products (Cunningham et al., 1996). Heavy metals, in particular, lend themselves to phytoremediation, as they do not readily form intermediate metabolites during biodegradation and can be more easily quantified in soils (Cunningham et al., 1996). The effectiveness of phytoremediation in remediating heavy-metal-contaminated soils has been demonstrated in several studies (Accioly & Siqueira, 2000).

Given these challenges and opportunities, identifying plant species that effectively mitigate copper contamination is crucial for protecting soils, subsoils, surface waters, and groundwater, while reducing risks to human and animal health. Immobilizing reactive copper species to reduce contamination impacts represents a viable remediation strategy.

This study therefore reviewed the literature from 2000 to 2025 to identify efficient plant species for the phytoremediation of copper-contaminated soils. The timeframe reflects sustained scientific interest in this area and underscores the continued relevance of this ancient yet powerful technique for rehabilitating degraded landscapes. The review highlights plant species and their physiological traits that contribute to successful phytoremediation outcomes.

2 MATERIAL AND METHODS

This study was a systematic review and analysis of scientific literature, conducted in structured stages to extract data on the frequency of studies identifying the most efficient plant species for the phytoremediation of copper-contaminated soils. It constitutes meta-research, producing secondary data (Wottrich & Rosário, 2022). The originality of this research lies in its analysis of parameters that can guide the selection of plant species for future qualitative assessments, investigations of biochemical mechanisms, and the design of projects for managing contaminated areas. According to Jacks (2022), meta-research is characterized by:

> In researchers' investigative trajectories, meta-research can be conducted at various levels, with emphasis on theoretical-methodological inquiry. Equally important, however, are studies based on accumulated empirical results in a given field or on secondary data produced by official sources or market research institutes. Such data are crucial for constructing research objects that are informed by and articulated with the diverse fields surrounding them (Jacks, 2022, p.337).

The meta-research was conducted in several stages. First, the research problem was defined as identifying the most efficient plant species for phytoremediation. Selection criteria included efficiency indicators reported in the literature, as well as the number of relevant articles, book chapters, and reviews. Data were collected from online scientific publication databases, including the CAPES Journal Portal, SCOPUS, and Google Scholar, by searching for techniques and species used in the phytoremediation of copper-contaminated areas in Brazil between 2000 and 2025. The search employed the English and Portuguese terms 'copper,' 'phytoremediation,' 'copper phytoremediation,' 'copper contamination', 'fitorremediação de cobre,' and 'contaminação por cobre'. In addition to journal databases, information was gathered from the websites of federal and state agencies, universities, and academic project directories. From the selected publications, information was filtered by identifying terms related to species used, efficiency data, and other parameters supporting this study's conclusions. Eligibility criteria for selecting papers are presented in Table 1.

Table 1 – Criteria used to determine article eligibility

Eligibility	**Criterion**
Eligible papers	Reporting plant species with demonstrated potential for copper phytoremediation in soils.
Ineligible papers	Reporting plant species with low potential for phytoremediation; Presenting alternative remediation methods in association with plants; Highlighting other goals unrelated to testing plant species' phytoremediation potential; Showing tests for contaminants or metals other than copper; Consisting of literature reviews; Drawing conclusions not supporting the use of phytoremediation; Duplicating previously published work.

Source: Authors, 2025

Based on a preliminary survey of academic papers, an exploratory reading of the selected articles was conducted. The analysis focused on cases of phytoremediation in copper-contaminated soils, considering plant species only, excluding engineered microorganisms and mycorrhizal fungi. Studies reporting low phytoremediation potential were disregarded, as the review targeted efficient plant species. The endemic ranges or successfully introduced regions of each highlighted species were identified, and their frequencies were incorporated into a global distribution map. The Pl@ntNet platform was consulted to supplement information from the articles and verify the geographic occurrences of the species.

Using the collected and processed data, a public database was compiled, containing relevant information on each species and their potential applications.

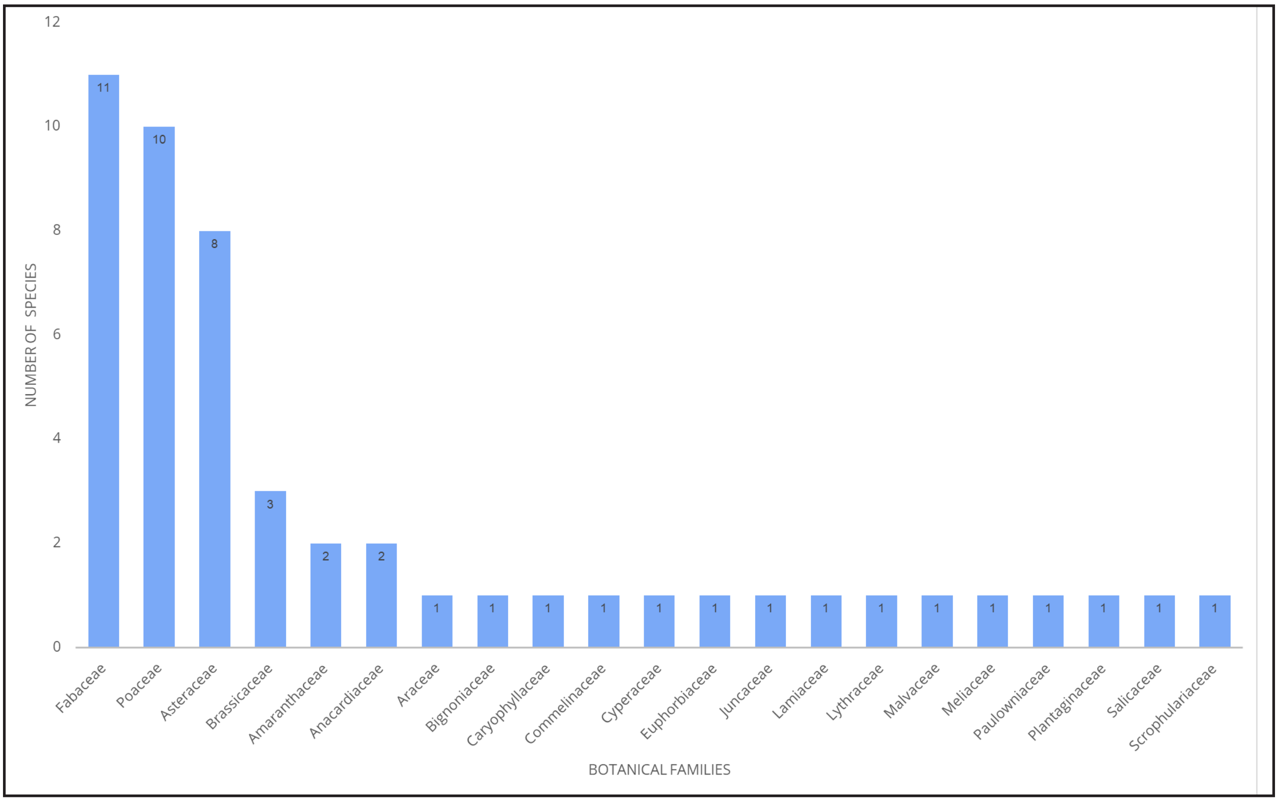
3 RESULTS AND DISCUSSION

Phytoremediation can occur through various mechanisms, in which specific plant tissues absorb contaminants for decomposition, mobilization, and/or volatilization (Anselmo & Jones, 2005). Through data analysis and qualitative review, plant species with potential for phytoremediation in copper-contaminated areas were identified.

The use of the search terms "copper, phytoremediation," "copper phytoremediation," and "copper contamination" yielded 90 academic papers, of which 28 met the eligibility criteria. Analysis of these selected studies identified 51 species, belonging to 21 botanical families, with traits indicative of copper phytoremediation potential. Notably, certain families were more frequently represented: Fabaceae, with 11 species; Poaceae, with 10 species; Asteraceae, with 8 species; and Brassicaceae, with 3 species (Figure 1).

The Fabaceae family, which accounted for the largest number of species, demonstrates considerable potential for phytoremediation of copper-contaminated soils, with traits that support both revegetation and phytoextraction. Some species in this family can accumulate up to 2.5 kg ha^{-1} of copper, primarily stored in the roots, where concentrations as high as 115.5 mg kg^{-1} have been reported (Widmer & Norgrove, 2022). These plants exhibit high bioconcentration factors, with some classified as copper hyperaccumulators, and show strong tolerance to soil contamination. Although translocation of copper to aboveground biomass is generally limited, certain species demonstrate enhanced transport and accumulation in shoots, further supporting their use in diverse remediation strategies (Silva et al., 2011, 2016). Moreover, species in this family are well suited for field cultivation, enhancing their practical applicability in restoring degraded areas (Martins et al., 2022). Together, these characteristics position Fabaceae as a valuable resource for mitigating the environmental impacts of copper contamination.

Figure 1 – Number of species identified as efficient for phytoremediation of copper-contaminated soils, grouped by botanical family



Source: Authors, 2025

The Poaceae family, the second most represented, also exhibits remarkable phytoremediation potential, particularly in phytoextraction, phytomining, and phytostabilization. Some species, such as *Avena sativa* L. (oat), are recognized as hyperaccumulators, accumulating over 1,000 mg kg^{-1} of copper in tissues, particularly in roots, where concentrations between 198.6 and 289.1 mg kg^{-1} have been observed (Widmer & Norgrove, 2022). These grasses combine high resistance to metal exposure with strong establishment in contaminated areas, making them effective in remediating soils such as those in vineyards, which often have elevated copper levels. Their substantial biomass production, both above and below ground, contributes to efficient absorption and translocation of heavy metals, including copper and zinc (Tavares et al., 2013). Although copper accumulation is typically greater in roots, some species efficiently translocate copper to shoots as well (Tavares et al., 2013; Zand & Mühling, 2022). With demonstrated performance in both hydroponic systems and soil, and the ability to extract additional heavy metals such as chromium, lead, and mercury, Poaceae is emerging as a promising group for mitigating metal contamination in degraded environments (Singh & Pani, 2022).

Similarly, the Asteraceae family shows strong potential, with species exhibiting hyperaccumulation and tolerance to heavy metals. Reported copper concentrations in these species range from 34.0 to 440 mg kg^{-1} of dry matter, with predominant storage in roots (103.3–319.1 mg kg^{-1}) (Afonso et al., 2020; Malayeri et al., 2008). These plants are well adapted to adverse conditions, such as nutrient-poor soils and high copper levels, although excessive copper can negatively impact growth and flowering (Menegaes et al., 2019, 2020). Some Asteraceae species are classified as high copper accumulators, with phytoextraction capacities up to 3.5 kg ha^{-1}, combining robust biomass production with efficient metal uptake (Afonso et al., 2019; Andreazza et al., 2015; Widmer & Norgrove, 2022). These attributes make Asteraceae valuable not only for reducing copper concentrations in soils but also for additional applications, such as biofuel production, reinforcing their strategic role in remediating contaminated areas.

Finally, Brassicaceae, the fourth most represented family, includes species recognized as hyperaccumulators of copper (Apori et al., 2018). Under experimental conditions, concentrations of up to 879 mg kg^{-1} of copper in dry matter were reported at soil contamination levels of 150 mg kg^{-1}, demonstrating exceptional uptake and accumulation capacity (Apori et al., 2018). When cultivated in combination with other species, such as *Salix nigra*, Brassicaceae species produced greater overall biomass and achieved effective copper stabilization and extraction, with most of the metal retained in the roots (Massenet et al., 2021). These characteristics highlight Brassicaceae as a promising group for mitigating copper contamination, particularly due to their ability to support both phytoextraction and phytostabilization strategies.

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
1	*Acacia mangium* Willd.	Mangium	Fabaceae	northwestern Australia (Queensland), Papua New Guinea and eastern Indonesia (Moluccas, Sula, and Aru Islands)	Shows potential for revegetating contaminated areas	Anselmo & Jones (2005)
2	*Arachis pintoi* Krapov. & W.C.Greg.	Pinto peanut	Fabaceae	South and Central America, Asia, Oceania	Demonstrates strong phytoextraction potential, up to 2.5 kg ha^{-1} of copper	Widmer & Norgrove (2022)
3	*Arundo donax* (Giant Reed)	Giant reed	Poaceae	temperate regions, as well as Europe, North Africa, and the Mediterranean	Accumulates copper and chromium in its tissues	Prelac et al. (2016)
4	*Arundo donax* L.	Giant reed	Poaceae	North America, Europe, southern Asia, and the subtropical regions of South America	Accumulates copper and chromium, exhibiting phytoextraction capabilities in hydroponic systems	Prelac et al. (2016)
5	*Avena sativa* L.	Oat	Poaceae	South America, the United States, Europe, Asia, and Oceania	Considered a copper hyperaccumulator, with tissue concentrations exceeding 1,000 mg kg^{-1} and high phytoextraction potential	Widmer & Norgrove (2022)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
6	*Avena strigosa* Schreb.	Black oat	Poaceae	São Paulo and Rio Grande do Sul States (Brazil), France	Demonstrated phytoextraction potential under the soil and contamination conditions tested	Panziera et al. (2018)
7	*Baccharis trimera* (Less.) DC.	Carqueja	Asteraceae	southern and southeastern Brazil (including Pará State), northwestern Argentina, Uruguay, Spain, and France	Adapted to low-nutrient soils, tolerant to heavy metals, with copper concentrations up to 440 mg kg^{-1}	Afonso et al. (2019)
8	*Bidens pilosa* L.	Spanish needle	Asteraceae	South, Central, and North Americas; Africa; Europe; Asia; and Oceania	Exhibits characteristics of a high copper hyperaccumulator, with phytoextraction potential up to 3.5 kg ha^{-1}	Andreazza et al. (2015), Widmer & Norgrove (2022), Afonso et al. (2019)
9	*Brachiaria decumbens* Stapf	Signal grass	Poaceae	native to Africa and dispersed throughout tropical regions	Effective in copper phytoextraction in vineyard soils, with capacity for phytomining and phytostabilization through biomass production in shoots and roots, including root bioaccumulation	Apori et al. (2018), Andreazza et al. (2013), Afonso et al. (2019)
10	*Brassica juncea* (L.) Czern.	Brown mustard or Indian mustard	Brassicaceae	Europe, the United States, southern Africa and South America, and India	Reached copper concentrations of 879 mg kg^{-1} dry mass in soils treated with 150 mg kg^{-1} copper, confirming hyperaccumulator status	Apori et al. (2018)

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(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
11	*Brassica napus* L.	Rapeseed or Canola	Brassicaceae	South, Central, and North Americas; Africa; Europe; Asia; and Oceania	When co-planted with Salix nigra, achieved greater biomass, with most copper stabilized and extracted in the roots	Massenet et al. (2021)
12	*Canavalia ensiformis* (L.) DC.	Jack bean	Fabaceae	Brazil, India	Exhibited increased copper concentration, accumulation, and transport to shoots	Zancheta et al. (2011)
13	*Cecropia* sp.	Trumpet tree	Urticaceae	northern Brazil, Guyana	Presented high bioconcentration in roots, qualifying as a copper hyperaccumulator	Asensio et al. (2018)
14	*Cedrela fissilis* Vell.	Argentine cedar	Meliaceae	northeastern Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, French Guiana, Panama, Paraguay, Peru, Trinidad-Tobago, Uruguay, and Venezuela	Maintained dry matter gains up to 100 mg kg^{-1} copper and showed bioconcentration in roots, with phytoremediation potential	Caires et al. (2011), Asensio et al. (2018)
15	*Chenopodium album* L.	Lamb's quarters	Amaranthaceae	South and North America, Africa, Europe, Asia, and Oceania	Displayed an exceptional translocation factor, making it a strong candidate for copper phytoremediation	Widmer & Norgrove (2022)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
16	*Chenopodium botrys* L.	Jerusalem oak or Feather geranium	Amaranthaceae	North America and Europe	Classified as a high copper accumulator, with concentrations up to 56.0 mg kg^{-1} dry weight (DW)	Malayeri et al. (2008)
17	*Chrysanthemum leucanthemum* L.	Oxeye daisy	Asteraceae	South and North America, Europe, Asia, Oceania	Accumulated copper mainly in the root system, ranging from 103.3 to 319.1 mg kg^{-1}	Widmer & Norgrove (2022)
18	*Dendranthema grandiflora* Tzevelev cv. Dark Fiji	Chrysanthemum	Asteraceae	temperate regions of Asia, South America, Central America, and Europe	Tolerated excess copper in soil, though higher levels negatively impacted development, including flowering	Menegaes et al. (2020)
19	*Chrysopogon zizanioides* (L.) Roberty	Vetiver grass	Poaceae	Europe, India, and Saint-Denis	Showed high resistance to copper exposure and viability in contaminated soils, with phytoremediation potential	Mendonça et al. (2021)
20	*Cirsium comgestum*	Not identified	Asteraceae	Not identified	Classified as a high copper accumulator, with tissue concentrations around 57.0 mg kg^{-1} DW	Malayeri et al. (2008)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
21	*Copaifera langsdorffii* Desf.	Copaiba or Diesel tree	Fabaceae	Brazil and India	Exhibited bioconcentration in roots, confirming hyperaccumulator characteristics	Asensio et al. (2018)
22	*Corchorus capsularis* L.	White jute	Malvaceae	tropical and subtropical regions, India, Bangladesh, China, Thailand, Nepal, Nigeria, and Vietnam	Corchorus species showed phytoremediation potential for heavy metals due to their physiological and morphological traits	Saleem et al. (2020)
23	*Cousina* sp.	Not identified	Asteraceae	Not identified	Classified as a high copper accumulator, with tissue concentrations of 34.0 mg kg^{-1} DW	Malayeri et al. (2008)
24	*Cymbopogon citratus* (DC.) Stapf	Lemongrass	Poaceae	South, Central, and North Americas; Europe; Africa; southern Asia; Australia; and New Zealand	Identified as a potential phytoextractor of multiple metals, including mercury, lead, copper, chromium, nickel, cadmium, and arsenic, due to high biomass and absorption capacity	Singh & Pani (2022)
25	*Cyperus rotundus* L.	Purple nutsedge	Cyperaceae	South, Central, and North Americas; Africa; Europe; Asia; and Oceania	Proved more efficient in removing copper from soil despite being more susceptible to contamination, supporting its use in phytoremediation	Widmer & Norgrove (2022), Mendonça et al. (2021)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
26	*Dianthus chinensis* L.	China pink	Caryophyllaceae	native to China and invasive in Europe, the Americas, Africa, Asia, and Oceania	Tolerated excess copper without showing phytotoxicity, maintained ornamental value, and was recommended as a cover crop	Menegaes et al. (2019, 2020)
27	*Elsholtzia splendens*	Copper plant or Shiny mint	Lamiaceae	China and Korea	Grew normally with 80 mg kg^{-1} copper in soil, exhibiting hyperaccumulator and copper-tolerant behavior	Jiang et al. (2004), Xiao-e (2005)
28	*Enterolobium contortisiliquum* (Vell.) Morong	Ear tree or Pacara earpod tree	Fabaceae	native to Brazil, Uruguay, Argentina, the United States, Africa, Europe, and Israel	Tended to store copper in roots with low translocation to shoots, demonstrating tolerance to soil contamination	Silva et al. (2011, 2016)
29	*Handroanthus serratifolius* (Vahl) S.O.Grose	Yellow trumpet tree	Bignoniaceae	Brazil, Guyana	Exhibited root bioconcentration, indicating phytoremediation potential	Asensio et al. (2018)
30	*Helianthus annuus* L.	Sunflower	Asteraceae	The Americas, Europe, and Asia	Combined high biomass production and copper phytoaccumulation with biofuel potential, effectively reducing soil copper levels	Tavares et al. (2013), Andreazza et al. (2014)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
31	*Hymenaea courbaril* L.	Jatobá or Brazilian cherry	Fabaceae	South and Central Americas, Africa, and France	Exhibited a bioconcentration factor in the roots, indicating potential for use in phytoremediation	Asensio et al. (2018)
32	*Juncus effusus* L.	Common rush or Soft rush	Juncaceae	Southern South America, the United States, Europe, and Oceania	Accumulated heavy metals in shoots, particularly cadmium, copper, and nickel; considered a hyperaccumulator, concentrating high levels of metals in the root system	Afonso et al. (2019)
33	*Lafoensia pacari* A.St.-Hil.	Dedaleiro or Pacari	Lythraceae	Paraná and São Paulo States, and Brasília (Brazil)	Seedlings showed higher tolerance to soil contamination and better quality at elevated copper doses	Silva et al. (2012)
34	*Lolium multiflorum* Lam	Annual ryegrass	Poaceae	South America, the United States, Europe	Accumulated copper mainly in roots, ranging from 198.6 to 289.1 mg kg^{-1}	Widmer & Norgrove (2022)
35	*Mimosa caesalpiniifolia* Benth.	Sabiá or Thorn mimosa	Fabaceae	Brazil, Colombia	Demonstrated root bioconcentration and hyperaccumulator characteristics	Asensio et al. (2018)
36	*Myracrodruon urundeuva* Allemão	Aroeira or Brazilian pepper tree	Anacardiaceae	São Paulo, Minas Gerais, Mato Grosso, and Pernambuco States in Brazil	Demonstrated root bioconcentration and copper hyperaccumulator characteristics	Asensio et al. (2018)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
37	*Parapiptadenia rigida* (Benth.) Brenan	Angico or Rigida	Fabaceae	Minas Gerais, São Paulo, and Rio Grande do Sul States in Brazil	Showed increased tolerance to copper-contaminated soils	Silva et al. (2011)
38	*Paulownia tomentosa* (Thunb.) Steud.	Princess tree or Empress tree	Paulowniaceae	The Americas, Europe, Asia, and Oceania	Accumulated copper mainly in roots, ranging from 126.2 to 175.6 mg kg^{-1}	Widmer & Norgrove (2022)
39	*Peltophorum dubium* (Spreng.) Taub.	Golden trumpet tree or Yellow poinciana	Fabaceae	Brazil, Uruguay, Argentina, India, and Israel	Tended to store copper in roots with limited translocation to shoots	Silva et al. (2011)
40	*Plantago lanceolata* L.	Narrowleaf plantain or Ribwort plantain	Plantaginaceae	Southern South America, Mexico, the United States, Canada, Europe, Asia, Australia, and New Zealand	Exhibited the highest copper concentrations in shoots (142 mg kg^{-1}), roots (964 mg kg^{-1}), and whole plants (1,106 mg kg^{-1}), displaying traits of a high copper hyperaccumulator	Andreazza et al. (2015), Widmer & Norgrove (2022)
41	*Ricinus communis* L.	Castor bean or Castor oil plant	Euphorbiaceae	The Americas, Europe, Asia, Africa, and Oceania	Classified as a copper hyperaccumulator, with tissue concentrations exceeding 1,000 mg kg^{-1} and strong phytoextraction potential; also demonstrated high biomass production and tolerance to elevated heavy metal levels	Widmer & Norgrove (2022)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(To be continued...)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
42	*Salix nigra* Marshall	Black willow	Salicaceae	The United States and Europe	When co-planted with Brassica napus L., most copper accumulated in the roots, with increased overall biomass and maximum copper stabilization and extraction	Massenet et al. (2021)
43	*Scariola orrientalis* (Boiss.) Soják	Not identified	Asteraceae	Asia	Identified as a high copper accumulator, with tissue concentrations of 87.0 mg kg^{-1} dry weight (DW)	Malayeri et al. (2008)
44	*Schinus terebinthifolia* Raddi	Brazilian pepper tree	Anacardiaceae	Brazil, Paraguay, Uruguay, Argentina, Peru, Dominican Republic, Mexico, the United States, Europe, Africa, Asia, and Oceania	Demonstrated tolerance to high copper doses	Silva et al. (2011)
45	*Schizolobium amazonicum* Huber ex Ducke	Paricá or Yellow guapuruvu	Fabaceae	Brazil, Colombia, and Costa Rica	Suitable for field cultivation	Martins et al. (2022)
46	*Sorghum hirsutum* L.	Sorghum	Poaceae	Africa; midwestern India and Burma; Australia; the Americas; and southeastern Europe	Effective in phytoextracting both copper and zinc	Tavares et al. (2013)
47	*Verbascum speciosum* Schrad.	Showy mullein	Scrophulariaceae	The United States and Europe	Identified as a high copper accumulator, with tissue concentrations of 40.0 mg kg^{-1} DW	Malayeri et al. (2008)

Table 2 – Plant species identified as efficient for copper phytoremediation: their distribution and potential

(Conclusion)

N°	SPECIES	COMMON NAME	FAMILY	CURRENT OBSERVED DISTRIBUTION	POTENCIAL	REFERENCE
48	*Vicia sativa* L.	Common vetch	Fabaceae	South and North America, Europe, Asia, and Oceania	Accumulated copper predominantly in the root system, reaching 115.5 mg kg^{-1}	Widmer & Norgrove (2022)
49	*Zantedeschia* spp.	Calla lily or Arum	Araceae	native to Egypt and considered exotic in Colombia, the Americas, Europe, Africa, Asia, and Oceania	Tolerated cultivation in copper-contaminated soil; however, excessive copper negatively affected development, including flowering	Menegaes et al. (2020)
50	*Zea mays* L.	Maize or Corn	Poaceae	The Americas, Europe, Asia, and Oceania	Roots accumulated significantly higher copper levels than shoots, while producing greater dry biomass and demonstrating higher efficiency in translocating copper and zinc to the aerial parts	Tavares et al. (2013), Zand & Mühling (2022)
51	*Brassica juncea* L.	Brown mustard or Indian mustard	Brassicaceae	Europe, the United States, and southern Africa	Confirmed as a copper hyperaccumulator	Apori et al. (2018)

Source: Authors, 2025

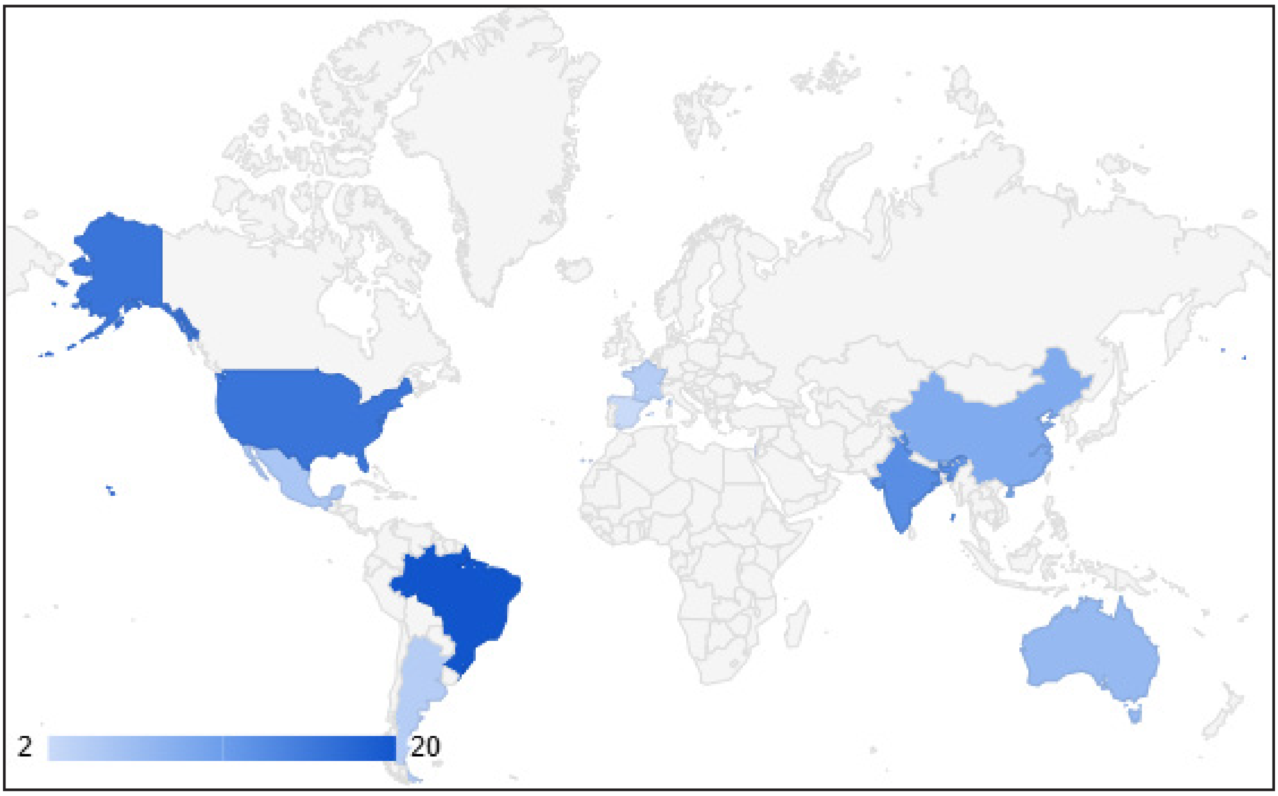
The species *Helianthus annuus* L. (sunflower) exhibits key traits for phytoremediation, including high phytomass production, copper phytoaccumulation, and potential as a biofuel crop, effectively reducing soil copper concentrations

(Andreazza et al., 2014; Tavares et al., 2013). Among the species that accumulate copper in their tissues, *Arundo donax* (giant reed) and *Elsholzia splendens* (copper plant) have also demonstrated strong potential (Jiang et al., 2004; Prelac et al., 2016; Xiao-E, 2005). According to Saleem et al. (2020), *Corchorus capsularis* (white jute) possesses desirable characteristics for phytoremediation, being valued in herbal medicine as a source of potassium, calcium, phosphorus, iron, vitamins A, C, and E, and leaf protein. It has a deep taproot system, is tolerant to salinity stress, and can remediate metals such as copper (Cu), cadmium (Cd), zinc (Zn), mercury (Hg), and lead (Pb). Another species with notable phytoremediation potential is *Brachiaria decumbens* (signal grass), which has been used for copper phytoextraction in vineyard soils, demonstrating phytomining and phytostabilization capabilities through biomass production in both shoots and roots (Apori et al., 2018). *Zea mays* (corn), widely cultivated for food in the Americas, Europe, and Asia, produces substantial dry biomass and efficiently translocates copper and zinc to shoots, further supporting its potential in remediation strategies (Tavares et al., 2013). Native Brazilian species such as *Baccharis trimera* (carqueja) and *Schizolobium amazonicum* (paricá) have shown high copper tolerance and suitability for field cultivation, respectively (Martins et al., 2022).

3.1 Species distribution around the world

The copper-phytoremediating species identified in this meta-research are distributed globally, with the highest frequencies observed in South America, followed by Europe, Asia, North America, Africa, and Oceania, in that order, with ten countries being particularly prominent in the data (Figure 2). These findings reflect regions characterized by significant agricultural production, intensive mining, and other activities with high potential for soil contamination. Such countries demonstrate greater interest in research and implementation of projects aimed at mitigating the environmental impacts of agriculture, mining, and improper waste disposal.

Figure 2 – Worldwide distribution of plant species efficient in copper phytoremediation



Source: Authors, 2025

Among the 10 countries with the highest occurrences, Brazil stands out for its remarkable diversity of observed species, particularly native species. The United States ranks second, characterized by a high occurrence of invasive and cultivated species, reflecting its climatic diversity. India ranks third, with numerous tropical and subtropical species, including key agricultural crops. China follows in fourth place, notable for its high concentration of native and cultivated species, especially in temperate regions. Australia ranks fifth, distinguished by its unique flora as well as many exotic and invasive species.

In Brazil, 14 native species with potential for phytoremediation were identified, distributed widely across the country. This broad distribution facilitates their application and management, as these are species already well studied (Table 6). Among them, nine belong to the Fabaceae family, represented by legumes.

Table 3 – Native plant species of Brazil and their distribution

Species	Common name	Distribution
Schizolobium amazonicum Huber ex Ducke	Paricá or Yellow guapuruvu	mainly in the Amazon
Baccharis trimera (Less.) DC.	Carqueja	southern and southeastern Brazil, Pará, northwestern Argentina, and Uruguay
Lafoensia pacari A.St.-Hil.	Dedaleiro or Pacari	Paraná and São Paulo State, and Brasília (Brazil)
Parapiptadenia rigida (Benth.) Brenan	Angico or Rigida	Minas Gerais, São Paulo, and Rio Grande do Sul States in Brazil
Peltophorum dubium (Spreng.) Taub.	Golden trumpet tree or Yellow poinciana	Brazil, Uruguay, and Argentina
Enterolobium contortisiliquum (Vell.) Morong	Ear tree or Pacara earpod tree	native to Brazil, Uruguay, and Argentina
Cedrela fissilis Vell.	Argentine cedar	Brazil, Northeastern Argentina, Bolivia, Colombia, Costa Rica, Ecuador, French Guiana, Panama, Paraguay, Peru, Trinidad-Tobago, Uruguay, Venezuela
Copaifera langsdorffii Desf.	Copaiba or Diesel tree	Brazil and India
Hymenaea courbaril L.	Jatobá or Brazilian cherry	South and Central Americas, Africa, and France
Mimosa caesalpiniifolia Benth.	Sabiá or Thorn mimosa	Brazil and Colombia
Myracrodruon urundeuva Allemão	Aroeira or Brazilian pepper tree	São Paulo, Minas Gerais, Mato Grosso, and Pernambuco State in Brazil
Arachis pintoi Krapov. & W.C.Greg.	Pinto peanut	South and Central Americas, Asia, and Oceania
Handroanthus serratifolius (Vahl) S.O.Grose	Yellow trumpet tree	Brazil and Guyana
Cecropia spp.	Trumpet tree	northern Brazil and Guyana

Source: Authors, 2025

The results demonstrated that the studied species possess traits relevant to the phytoremediation of copper-contaminated soils. Notably, *Cedrela fissilis* Vell. (pink cedar) exhibited significant dry matter gain at a copper dose of 100 mg kg^{-1}, indicating tolerance to contamination and satisfactory growth at moderate metal concentrations (Asensio et al., 2018; Caires et al., 2011).

The species also exhibited high bioconcentration factors in the roots with limited translocation to shoots, reinforcing their ability to sequester copper in the root system and minimize its impact on aerial tissues. This trait was observed in several tree species, including *Copaifera langsdorffii* Desf. (copaiba or diesel tree), *Enterolobium contortisiliquum* (Vell.) Morong (ear tree or Pacara earpod tree), *Handroanthus serratifolius* (Vahl) S.O. Grose (yellow trumpet tree), *Hymenaea courbaril* L. (jatobá or Brazilian cherry), *Mimosa caesalpiniifolia* (sabiá or thorn mimosa), *Myracrodruon urundeuva Allemão* (aroeira or Brazilian pepper tree), and *Peltophorum dubium* (Spreng.) Taub. (golden trumpet tree or yellow poinciana), all of which demonstrated greater tolerance to soil contamination, particularly at higher copper levels (Asensio et al., 2018).

In addition, *Schizolobium amazonicum* (paricá or yellow guapuruvu) seedlings showed suitability for field cultivation, supporting their use in revegetation and recovery of areas degraded by heavy metals (Martins et al., 2022). Collectively, these findings underscore the potential of these native Brazilian species for phytoremediation, highlighting their practical and environmental significance.

4 CONCLUSIONS

Phytoremediation is emerging as a promising *in situ* environmental decontamination technique, offering an alternative for mitigating the impacts of heavy metal contamination. Compared with other remediation methods, phytoremediation is socially acceptable, economically viable, and environmentally sustainable. Its key advantages include accessibility, low cost, and ease of implementation and control. Moreover, the diversity of plant species developed and studied over the past 25 years has facilitated seedling production and the application of various techniques across different climates, enabling its deployment at diverse scales and locations.

The results of this study demonstrated that the evaluated species possess physiological traits adapted to the phytoremediation of copper-contaminated soils. Notable findings included dry matter accumulation at copper doses up to 100 mg kg^{-1}, tolerance to contamination, and satisfactory growth at moderate metal concentrations. The results also highlighted the use of forage and invasive species, which behave similarly to salt-stress-tolerant organisms, maintaining productivity with minimal cultural inputs (Hasanuzzaman & Fujita, 2023). These traits have motivated the design of phytoremediation studies, given their maintenance without major demands on cultural practices.

A critical factor for successful phytoremediation was the accessibility of both aboveground and root biomass, which facilitates harvesting and metal removal. Regarding metal uptake, the biochemical mechanisms involve the kinetics of heavy metal salt absorption and the induction of transporter activation in root cells, which are effective even at elevated soil metal levels (Silva et al., 2022). These findings support the use of herbaceous plants with relatively short life cycles, as reflected in studies of *Corchorus capsularis* L. (white jute) in India (Saleem et al., 2020), *Sorghum hirsutum* L. (sorghum) in Croatia and Ukraine (Prelac et al., 2016), and *Cymbopogon citratus* (DC.) Stapf (lemongrass) in India (Singh & Pani, 2022).

Among the 10 countries with the highest occurrence of copper-phytoremediating species, Brazil exhibited the greatest diversity, particularly of native species, followed by the United States, which is dominated by invasive and cultivated species reflecting its climatic diversity. India ranked third, characterized by tropical and subtropical species, including major agricultural crops. China ranked fourth, notable for its concentration of native and cultivated species, especially in temperate zones, while Australia ranked fifth, distinguished by its unique flora of exotic and invasive species.

In Brazil, 14 native species with potential for phytoremediation were identified, widely distributed across the country. Of these, nine belong to the Fabaceae family, which appears particularly effective at accumulating copper in plant tissues. Species from the Poaceae, Asteraceae, and Brassicaceae families were also associated with phytoremediation in copper-contaminated soils. The success of phytoremediation processes depends largely on a plant's ability to grow in contaminated soils and its capacity to concentrate copper either in shoots or roots, depending on the biotransformation mechanism involved.

Among the plant families identified, Fabaceae stands out as the most effective in accumulating copper in plant tissues. Species from Poaceae, Asteraceae, and Brassicaceae also demonstrate potential for phytoremediation of copper-contaminated soils. Further research is recommended to evaluate additional species across different climates and soil conditions. The main factors determining successful phytoremediation include the plant's ability to grow without significant stress in contaminated soils and its capacity to translocate copper from roots to shoots, enabling biomass production and metal removal throughout development.

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Authorship contributions

1 – Marcela Pinto Barbosa Vassar

Master’s degree in Sustainable Development Practices from the Federal Rural University of Rio de Janeiro
https://orcid.org/0009-0005-6994-1882 • mavassar16@gmail.com
Contribution: Data, Curation, Formal analysis, Investigation, Methodology, Software, Writing - orginal draft

2 – Fabiola de Sampaio Rodrigues Grazinoli Garrido

PhD in Agronomy from the Federal Rural University of Rio de Janeiro
https://orcid.org/0000-0001-5177-1241 • fabiola_srg@yahoo.com.br
Contribution: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervison, Validation, Visualization, Writing - original draft, Writing - review & editing

3 – Fábio Souto Almeida

PhD in Environmental and Forestry Sciences from the Federal Rural University of Rio de Janeiro
https://orcid.org/0000-0001-6214-397X • fbio_almeida@yahoo.com.br
Contribution: Conceptualization, Data, Curation, Formal Analysis, Supervision, Validation, Visualization, Writing – review & editing

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