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Review

Phytoremediation of Heavy Metals in Tropical Soils an Overview

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Abstract: The geomorphological characteristics of the materials inherent in tropical soils, in addition to the excessive use of fertilizers and pesticides, industrial waste and residues, and novel pollutants derived from emerging new technologies such as nanomaterials, affect the functionality and resilience of the soil-microorganism-plant ecosystem; impacting phytoremediation processes and increasing the risk of heavy metal transfer into the food chain. The aim of this review is to provide a general overview of phytoremediation in tropical soils, placing special emphasis on the factors that affect this process, such as nanoagrochemicals, and highlighting the value of biodiversity among plant species that have the potential to grow and develop in soils impacted by heavy metals, as a useful resource upon which to base further research.

Keywords: emerging contaminants; heavy metals; nanoagrochemicals; plants to phytoremediation; tropical soil

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1. Introduction

Soil is a complex and dynamic system with a direct influence on food production and, consequently, on human survival. It supports and regulates nutrients, and, therefore, is essential for the structure and life of ecosystems [1,2]. A healthy soil increases an area's attractiveness for the development of human settlements and for activities such as agriculture [3]. The health and productivity of soils are determining factors for all animal and vegetal life on Earth.

Unfortunately, a lack of control and unbridled exploitation of the world's soil has seriously modified its properties. Contamination contributes to desertification, limiting the soil's functionality as a natural resource [4,5]. Mines, foundries, factories, oil refineries, and heavy industries produce contaminants such as metals, ash and slag, and petroleum byproducts that are too often released into the environment where they break down into largely unknown compounds. These toxic products are also worsened with regular additions of pesticides and fertilizers, themselves sources of traces of heavy metals—especially from phosphoric chemicals. The accumulation of these heavy metals, such as cadmium (Cd), lead (Pb), chromium (Cr), mercury (Hg), and nickel (Ni), among others [6], in plant tissues is toxic [7]. Their presence strongly affects plant productivity, as well as the soil's ecology and biodiversity—both pillars of a healthy soil [8–10]. These effects lead to serious consequences for the environment, agriculture, and human health.

Along with the development of novel sciences, the growing industrialization of new technologies and new chemicals results in the release into the environment of various organic and inorganic compounds referred to as "contaminants of emerging concern". These include plastics, pharmaceuticals for veterinary or human use, hormones, personal care products, and nanoparticles, to name a few [11]. In all cases of soil contamination, plants generally absorb heavy metals and accumulate them. This sequestration represents

the first step of bioaccumulation in the food chain, with various contaminants being more or less available to the plant [12–14]. This absorption and subsequent bioaccumulation will depend primarily upon the metal's mobility from a state of solution in the soil to the roots of plants, where the process known as "phytoremediation" is initiated; this process being understood as the ability to incorporate, immobilize, or transform contaminants into harmless compounds [15,16].

Studies also suggest that plants benefit from heavy metal tolerant soil microorganisms, as growth-promoting bacteria [17] or arbuscular mycorrhizal fungi (AMF), which can enhance phytoremediation of contaminated soils. The interaction of soil microorganisms with contaminants to decrease their bioavailability in the soil, with plants to promote the host's growth, and with soil to improve its quality [18], are ecological and potentially profitable techniques.

This review aims to present the characteristics of tropical soils, and their advantages and disadvantages for heavy metal phytoremediation. It includes the emerging pollutants of nanoagrochemicals, and considers their deleterious effects on plants and microorganisms, which could affect phytoremediation processes in the long term. The review also emphasizes the diversity of tropical plants and of the species that develop in the presence of heavy metals. The authors suggest that further studies should be carried out with native tropical plants to select those species that are most promising for heavy metal phytoremediation processes, especially in Latin America, where the greatest biodiversity of plant species is concentrated, with at least one third of the world's biodiversity [19].

2. Tropical Soils and Heavy Metals

The tropics host one third of the world's soils, which in turn support more than three quarters of the world's population. Unfortunately, less is known about soils in the tropics as compared to those in temperate regions [20,21].

Located between the 30° N and 30° S parallels, these soils exhibit particular chemical and physical properties different from those in temperate climes. They are typically constituted of a thin altered layer that covers the bedrock [22,23], and exhibit mineralogy characteristics due to either the stages of their formation or to physical and chemical weathering [24,25].

In tropical soils, characterized by variable temperatures with a predominance of high temperatures and abundant rainfall, the effects of material weathering are very significant. There is rapid decomposition of feldspars and ferromagnesian minerals, while the concentration of iron and aluminum oxides remains stable, and silica and Na_2O bases -K_2O- CaO and MgO disappear [26]. For example, Cuba tends to contain extensively weathered tropical soils (ferralsols, nitisols, oxisols, lixisols, acrisols, and alisols), with 69.6% of soils exhibiting low organic matter (OM) and 43.3% with heavy erosion. [27]. As the latter is very considerable in the tropics, the deficiencies produced in soil quality put the food supply at risk [20,28]. Those nutrients that are available in tropical soils are concentrated in its higher and wetter layers. They are rapidly incorporated back into the vegetation to promote growth and development and are quickly recycled. Nutrients are, thus, a limiting factor in these soils. The geotechnical behavior of these soils is known to be influenced by various factors such as: degree of saturation, genesis, alteration, structure, and chemical and mineralogical properties, to name a few [22,29,30].

Tropical soils are also associated with atypical behaviors, for example, expansion and collapse. Misuse and by anthropogenic activities affect the quality of various types of these soils. Due to changes in land use, tropical ecosystems are being altered and will face even greater pressures as the human population increases, driving significant expansion and intensification of tropical agriculture especially in sub-Saharan Africa and South America [31]. Anthropogenic activities such as deforestation and fragmentation affect the quality of various types of tropical soil, with the biodiversity of tropical forests being especially impacted [32].

The large-scale use of pesticides may have direct or indirect effects on soil biodiversity, and intensified land use can potentially reduce soil fertility. Increased livestock density, as well, can lead to negative soil and environmental impacts. Other anthropogenic sources of heavy metal pollution include mining, smelting, fossil fuel combustion, waste disposal, and corrosion [27].

The most common soils in the tropical regions are classified into the following orders: oxisols, ultisols, alfisols, aridisols, inceptisols, and entisols [33]. Their specific differences compared to temperate soils could be summarized as follows: (i) kaolinite-dominated clay fractions, relative to 2:1 clay; (ii) low organic matter (OM) content; (iii) high levels of Fe oxides. To maintain soil quality, the suggested organic carbon threshold is approximately 2% [34], below which deterioration may occur; in tropical soils this value may be lower, for example, the carbon content in soils of various uses in the Colombian Caribbean region is between 0.5–1% [35]. Iron concentrations in soils worldwide range from 20 to 550 g/kg [36]. Brazilian soils contain iron oxides (from a few grams to about 800 g/kg^{-1}) [37].

These characteristics are the result of intense and long-term weathering, leaching, and faster decomposition [38]. The main types of tropical soils, particularly oxisols and ultisols, differ from most temperate soils in terms of exhibiting clays with low activity, low organic matter content, low pH values, and high levels of Fe oxides. Details of each one of the tropical soils are summarized in Table 1. These soils are found in most of the tropical areas of Africa, Asia, and Central and South America and have some properties in common, for example, that most are very fragile, and that they do not retain water for a long period when saturated [22].

Table 1. Tropical soils and their general descriptions.

Classification	Description
Oxisols	Highly degraded tropical soils. These are located in hot and humid areas, have undergone major weathering processes, and accumulate kaolinite and sesquioxides necessary for the formation of the characteristic oxic horizon of this order. All Oxisols have relatively low cation exchange values and some have a net positive charge in the subsoil. Natural limitations due to acidity and low nutrient content have been overcome economically with lime and fertilizer applications.
Ultisols	These form in humid areas. Commonly known as red clay soils, they are extremely eroded and exhibit low fertility. Kaolin, gibbsite, and aluminum-interlayered clays are common in the clay fraction. These soils can become productive with the addition of fertilizers and lime.
Alfisols	Soils located in arid climates. Dry soils have low organic content and are sparsely vegetated by drought- or salt-tolerant plants. They accumulate salt, gypsum, calcium carbonate, and other materials that are easily leached.
Inceptisols	These are found in a wide range of environments and include a variety of soils in semi-arid and humid areas. They are considered moderately eroded and their mineralogy generally reflects their relative immaturity. They are present in a wide variety of climates.
Entisols	Easily erodible soils lacking developed horizons. They are most extensive in floodplains and valleys or on steep slopes where erosion is rapid. Found in dunes, steep slopes, and flood plains.

Depending on the characteristics of each soil and region, pollutants such as heavy metals (HMs) can interact within its matrix. A study carried out in Brazilian soils found that the adsorption of heavy metals is greater in young soils (alfisols and ultisols) compared to older soils (oxisols) [39]. HMs affect crop yields due to toxicity, and present the risk of biomagnification and bioaccumulation in the food chain. Certain chemical elements which may be present in harmful xenobiotic concentrations. Such as nitrogenous compounds: nitrate, nitrite, or N_2O. These chemical elements represent a special type of contamination and soil degradation [40].

Ion exchange, specific adsorption, organic matter complexation, precipitation and dissolution, and redox reactions define the content of bioavailable elements in the soil solution [41]. Among these processes, adsorption is the most important [42]. In general, heavy metals (HMs) have been defined as high molecular weight metals (density > 5 g/cm^3).

However, this definition is considered imprecise, as it is based on a categorization by density, which is rarely a biologically significant property. Understanding bioavailability is the key to assessing the potential toxicity of metallic elements and their compounds, [43]. They can accumulate in soils and in living tissues; from a practical standpoint, HMs can be classified as contaminants according to their toxic effects and persistence in the environment. Among these are included lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium Cd), copper (Cu), mercury (Hg), and nickel (Ni) [44]. In minimal concentrations, some heavy metals are essential micronutrients, while others are not essential for life (Table 2). In excess, HMs can cause phyto toxicological reactions that modify normal biological processes by blocking functional groups, by displacing or replacing essential elements, or by affecting cell integrity [45].

HMs are, in general, present as trace elements in low concentrations in the earth's crust and, as mentioned above, they are essential for the development of life; however, they can also be toxic depending on concentration and molecular compound, with the soluble ones being those most easily bioassimilated [46,47].

Table 2. Essential micronutrients and nonessential heavy metals for living organisms.

Category	Metals
Metals that are essential micronutrients	Cu, Zn, Mn, Fe
Nonessential heavy metals	As, Cd, Cr, Co Pb, Hg, Ni, V

Source: Aprile et al. [48].

The sources of contamination by heavy metals are numerous and varied. In modern agriculture, the intensive use of pesticides, some containing copper sulphate and copper oxychloride, leave pollutants and heavy metals in tropical soils. Large quantities of synthesized fertilizers provide the N, P, and K ions indispensable for crops, but also contain traces of heavy metals such as Cd, Pb, and As [49,50] continuous use of these fertilizers significantly increases the accumulation of these impurities in the soil. Certain phosphoric fertilizers contain Cd and other potentially toxic elements including Fe, Hg, and Pb, and are unfit for agriculture. Most low-quality fertilizers with low Zn content have a relatively high Cd content, making these equally inappropriate for agriculture [51]. Another often unsuspected source of contamination are biofertilizers. These biosolids, mostly pig and poultry manures, are seen as valuable but lead to the accumulation of HMs in soils, including: As, Cd, Cr, Cu, Pb, Hg, Ni, Se, Mo, Zn, Tl, and Sb [52,53]. To the sources above, of course, must be added the host of industrial activities, which can deposit large amounts of HMs directly or indirectly into the soil (Table 3).

It is recognized that the deposition of HMs into the soil of the entire ecosystem, water and food, causes toxicity. In soils, this deposition depends on their specific characteristics such as movement depends on the specific characteristics of each soil, such as physical granulation, acidity, content and type of clay, minerals, organic matter, cation exchange capacity [55], chemical specificity, persistence, and trend tendency of accumulation or bioaccumulation [56], which immediately affects the normal growth of plants and disturbs their development [57,58]. Harmful levels of HMs (Table 4) affect the functions of the soil microbe populations and cause their long-term decline [59,60].

Many countries may not even regulate heavy metals for agricultural use, however, a study found regulatory standards of heavy metals in agricultural soil (mg/kg) for nine countries, including the permissible or regulatory levels of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn. According to the data obtained, there is a wide variation of the allowed values of HMs in each country. For example, the permitted values of As for Australia, Canada, and China are 20 mg/kg, but only 1 mg/kg for Tanzania, and 0.11 mg/kg in the EU. The permitted value of Hg in New Zealand is 200 mg/kg, while for China the permissible values range from 0.3–1.0 mg/kg [61]. It would be advisable to carry out more research to establish these regulatory values in soils for each country.

Table 3. Common sources of heavy metals and their associated processes and pollutants.

Industrial Activity	Metals	Associated Processes and Pollutants
Agriculture and ranching	As, Cd, Cr, Cu, Mn, Mo, Pb, U, V, Zn	Pollution from runoff leads to contamination of surface and ground water. The industry also produces agricultural chemi-cals, which can bioaccumulate in plants and animals
Batteries	Cd, Hg, Ni, Pb, Sb, Zn	Residual battery fluids cause contamination of groundwater and soil.
Electronic waste	As, Au, Cd, Cr, Hg, Mn, Ni, Pb, Pt	Aqueous and solid metallic waste from the manufacturing and recycling processes results in air and water pollution
Electroplating	Cu, Cr, Ni, Zn	Liquid effluents from coating processes pollute water and soil.
Ferrous metal mining	Cd, Co, Cu, Cr, Ni, Zn	Leakage of acids from mining. Generation of tailings and sludge.
Hydrocarbons	Ag, As, Cu, Cr, Fe, Hg, Ni, Pb, Mn	Exploration, extraction, and refining processes generate pollution of surface water, groundwater, and soil
Metallurgy	Cu, Cr, Mn, Zn, Pb, Sb	Thermal treatment of metals. Atmospheric pollution.
Paints and pigments	As, Ba, Cr, Pb, Ti, Zn	Aqueous residues from the manufacture of new paint, and the deterioration of old.
Steel and alloys	As, Cd, Cu, Mo, Ni, Pb, Te, U, Zn	Manufacture, disposal, and recycling of metals. Includes tailings and cinders. Contaminates water and soils
Smelting	As, Cd, Pb, Ti	Processing of ores to extract metals. Atmospheric pollution and solid waste.
Waste management	Cd, Cu, Cr, Hg, Ni, Pb, Mn, Zn	Incineration of waste or leaching from landfills can cause atmospheric pollution, as well as contamination of soils, surface water, and groundwater

Source: Caviedes Rubio et al. [54]

Environmental conditions, soil utilization, and the criteria followed by an array of authors give variable values for toxic concentrations (Table 4). HMs toxicity increases with accumulation in water and soil. This accumulation is promoted by adsorption processes where heavy metals are transferred from a mobile liquid phase to the surface of a solid phase. This process is influenced by a variety of parameters such as: soil pH, composition and age of soil, type, and metal ion speciation involved, metal concentration, solid–solution mass ratio, and contact time [62]. The most important parameter that influences the chemistry of the soil surface and metal solution is pH [63]. HMs are less available when soil pH is about 6.5 to 7.0 [64], whereas higher retention of metals and lower solubility in soil occurs at high pH values. For example, Cd adsorption by plants increases as pH decreases [65]. The highest levels of Pb and Cd adsorption in oxisols and ultisols depend more on the soil mineralogy than on organic matter. In general, tropical soils tend to exhibit high acidity, a factor that can drive increased adsorption of heavy metals.

Table 4. Values of heavy metals in soils (mg/kg).

Parameters	Limit Values	Higher Reference Value Ecological Risk
Cadmium (Cd)	1–3	20
Copper (Cu)	50–140	200
Nickel (Ni)	30–75	150
Lead (Pb	50–300	750
Mercury (Hg)	1–1.5	5

Adapted from Adnan Tutic et al.and Tóth et al. [66,67].

3. Emerging Contaminants and New Nanoagrochemicals as Potential Factors Altering Phytoremediation Processes

Emerging contaminants are synthetic or naturally occurring chemicals, or any microorganisms that are not commonly monitored in the environment but have the potential to enter the environment and cause known or suspected adverse ecological and/or human health effects [68].

Emerging contaminants of concern include veterinary or human pharmaceuticals, plastics, hormones, personal care byproducts, and nanomaterials [11]. All contain traces of heavy elements that can be released into the environment.

"Emerging" is related to the time of application of a substance and the moment at which it appears as a possible contaminant. Evidence for its toxicity is observed over time and is submitted to rigorous analysis before the substance is considered to be a contaminant. The classic example of an emerging contaminant is the insecticide dichlorodiphenyltrichloroethane (DDT) and dichlorodiphenyltrichloroethylene (DDE), its main metabolite. DDT was introduced in the 1950s to control the mosquito vector of malaria. It was used during the 1980s on a large scale for pest control, and permeated the environment, appearing in all life forms, humans, plants, animals, water, and air [69]. It was reported as the first organochlorine compound with a high biological accumulation [70], and due to its negative environmental impact, it was almost universally banned.

The glyphosate-based [*N*-(phosphonomethyl) glycine] broad-spectrum herbicide family is another example of emerging contaminants. These were first commercialized in 1974 and quickly became the most widely used herbicides worldwide [71]. They suppress the ability of plants to generate aromatic amino acids [72], and are known to be easily leached from cultivated areas into the subterrestrial zone and ground water during the rainy season. They have been found at concentrations of up to 1.42 μg/L in groundwater and 0.47 μg/L in human urine in the Yucatan Peninsula, Mexico [73]. Glyphosate causes damaging changes to soil function and in earthworm populations [74] and symbiotic microorganisms, for example arbuscular mycorrhizal colonization is decreased in glyphosate-treated plants [75]. Glyphosate has a negative effect on nontarget organisms in agricultural environments. DDT and glyphosate illustrate the concept of contaminants of emerging concern, among a wide range of products having deleterious effects on the environment and agricultural soil.

Today, interest in nanomaterials (NMs) continues to grow. These comprise a diverse class of small-scale substances that have structural components of less than 1 micron (1000 nanometers) in at least one dimension. Nanoparticles (NP) are a subtype of nanomaterial with at least two dimensions between approximately 1 and 100 nm [76]. These materials are widely used in various industries, and their intensive production can lead to the release of nanoparticles derived from manufacturing. Paint, semiconductors, automobiles, packaging, medicines, electronic devices, bioproducts, energy, and cosmetics are among the diverse sources of nanoparticles.

In the agricultural field, interest in nanomaterials (NMs) has grown in recent years, leading to the emission of nanoparticles derived from so-called nanopesticides or nanofertilizers; generally known as "nanoagrochemicals" [77]. This new progress, however, is not free of risks related to phytotoxicity, beneficial soil microorganism, and the environment.

NMs can change the metabolism of plants and interfere with the electron transport chain in mitochondria and chloroplasts. This, in turn, may result in an increase of reactive oxygen species (ROS) concentration, causing an oxidative burst [78,79].

Cerium oxide nanoparticles interfere with the absorption of nutrients in *Pisum sativum* by significantly reducing Cu, Mn, Zn, and Fe concentrations in the roots and aerial parts of the plant, thus, any highly beneficial effect of cerium oxide nanoparticles upon the plant growth was not supported by this study [80]. Metal and metal oxide nanoparticles exhibit the negative effects of their toxicity on plants of agriculture interest, p.e *Pisum sativum* seedlings treated with Ag nanoparticles showed an enhanced Ag level followed

by oxidative stress, which adversely affected the plants' pigments, as well as decreasing growth and photosynthesis [81].

The toxicity of three types of AgNP (using an array of different surface coatings) synthesized in the laboratory was trialed on the roots of *Allium cepa*. All three AgNPs tested caused oxidative stress and exhibited toxicity at higher concentrations. AgNP toxicity was directly correlated with its size, total surface charge, and/or surface coating [82]. AgNP has shown significant efficacy in controlling and eliminating some pathogenic fungi, however, its use in agriculture remains questionable [83]. TiO_2 and similar nanoparticles, commonly found in cosmetic products, induce toxicity for plants at high soil concentrations [84]. Lead, Mercury, and Tin NPs are not easily degraded, resulting in a potentially toxic effect on the environment [85].

Arbuscular mycorrhizal fungi are associated with most plants that produce flowers and fruits, and increase their area available for nutrient absorption through the hyphal network, while also promoting plant growth through phytohormones. Among the diversity of microorganisms in the rhizosphere, microorganisms called PGPR can directly stimulate the proliferation of roots and, therefore, promote plant growth and increase tolerance to heavy metals [86], making them excellent resources for phytoremediation processes.

Although these plant-related microorganisms stimulate and promote heavy metal phytoremediation processes, they can also be affected by products derived from NMs. Certain examples cited in the literature demonstrate the deleterious effect that nanoparticles exert on beneficial soil microorganisms. The application of ZnO nanoparticles reduced litter-derived organic carbon decomposition efficiency by up to 130% due to decreased microbial activity [87]. TiO_2, ZnO, and Fe_2O_3 nanoparticles reduce the carbon of microbial biomass [88]. The toxicity of NMs on the beneficial communities within agricultural soils has also been researched, with different studies showing that inorganic nanoparticles (metal and metal oxide) have a toxic effect and act as antimicrobial agents [89,90].

Another study evaluated the responses of mycorrhizal clover (*Trifolium repens*) to silver nanoparticles (AgNP) and iron oxide nanoparticles (Fe_2O_3NP) along a concentration gradient of each. Fe_2O_3NPs at 3.2 mg/kg significantly reduced the biomass of mycorrhizal clover 34% by reducing glomalin content and nutrient acquisition from arbuscular mycorrhiza fungi roots [91].

Nanomaterial technology is an emerging field with many applications. Plant studies using various NPs exhibiting different phytotoxicity profiles are much less common in the literature. More research is needed into the possible interactions of nanomaterials or nanoagrochemicals with different species of tropical plants; their interactions with heavy metals in soils and the impacts that NP emissions may have on the environment and on plant health. Few studies [92] have been carried out to evaluate the effects of NMs on agrochemicals applied to plant species (both food crops and those of economic interest) in tropical soils—especially in the early stages of growth for food crops and the possible biomagnification of NMs in the food chain remains unknown.

Full knowledge of the physical and chemical characteristics of these nanoparticles, as well as their distribution and/or accumulation in plant tissues, the effect that their distribution and accumulation in soils and water sources could have, are essential to understand their phytotoxic effects and the possible impact on the food chain.

4. Plant Defense Mechanisms against Heavy Metals

Although many heavy metals fulfill important biological functions in plants and animals, they can become harmful and affect various functions of metabolic cells through redox processes when they are present in excess [93]. This process is known as oxidative stress. HMs produce alterations in the processes of cellular transport and homeostasis cause oxidative damage. Oxidative stress is caused by free radicals and molecules containing activated oxygen atoms known as reactive oxygen species (ROS) [94]. It is associated with a shortage of electrons, which damages cellular compounds and causes cellular apoptosis [95,96].

Against these effects, plants employ various antioxidant defense mechanisms. These take place primarily in the chloroplasts, mitochondria, and peroxisomes; and secondly in the endoplasmic reticulum, cell membrane, cell wall, and apoplast [97]. To maintain cell homeostasis and reduce oxidizing effects while under attack by ROS, plants have developed anatomical and physical adaptations. They may reorganize or suppress the photosynthetic process. The effect of heavy metals upon plants in general is their attack on the photosynthetic apparatus [98]. Cadmium is one of the most toxic heavy metals in terms of its reduction of chlorophyll biosynthesis [99], which reduces the activity of several enzymes, consequently affecting the Calvin cycle and diminishing photosynthesis [100], electrons travelling through the respiration transport chains and using them to reduce O_2 to H_2O; thereby preventing the formation of superoxide radicals O_2^-. These reactions are governed by a group of enzymes known as the alternate oxidases [101]. To prevent the formation of hydroxyl radicals (-OH), plants remove superoxide and hydrogen peroxide radicals (O_2^- and H_2O_2) by sequestering the Fe ions that catalyze the Haber–Weiss reaction to ferritins or metallothioneins [102].

Plants have an efficacious tool to eliminate ROS, the agent of oxidative stress, in the form of enzymatic and non-enzymatic antioxidant compounds, such as the superoxide dismutase (SOD), an enzyme with significant antioxidant potency that is commonly used as a marker of oxidative stress in plants [103]. Other examples of enzymes that are expressed under stress conditions are peroxidase (POD), which can, together with catalase (CAT), catabolize H_2O_2; and Glutathione-S-transferase (GST), which efficiently converts the superoxide radicals into hydrogen peroxide, and subsequently into water and oxygen. This might protect the plants from certain abiotic stresses including HMs and UV radiation [103–106]. This Glutathione-S-transferase (GST) has been extensively studied for its ability to detoxify herbicide [107]. Other low molecular weight non-enzymatic antioxidants consisting of proline, ascorbic acid, and glutathione may directly detoxify reactive oxygen species (ROS).

5. Mobility of Metal and Metalloid Elements

The mobility of metals and metalloids in soils is the determining factor for their availability and leaching potential through various soil profiles. HMs acting as pollutants can leave the soil by volatilization, dissolution, leaching, or erosion [108,109]. They generally pass into organisms when they are in a fairly soluble form. The possibility that an element—pollutant or not—is free to solubilize in a soil is called availability. This factor is defined to be a dynamic process, where three fundamental steps take place: (1) a physicochemically controlled desorption process, referred to as environmental availability; (2) a physiologically controlled uptake process, referred to as environmental bioavailability; (3) a physiologically induced effect or accumulation within an organism, referred to as toxicological bioavailability [110,111]. In this dynamic process, the type of organism affected by the contaminants, the length of exposure, and the nature of the heavy metal are crucial. This dynamic principle of bioavailability has been widely accepted by the US National Research Council [112] and by the International Standards Organization (ISO 17402). With respect to heavy metals, the most important factors affecting mobility are the soil's sorbent nature, pH, and presence and concentration of organic and inorganic ligands, including humic and fulvic acids, nutrient root exudates, and redox reactions, both biotic and abiotic [113].

Environmental risk studies generally evaluate only the pseudo-total concentration of metals in soils and do not provide information related to bioavailable metal fractions [114]. For the assessment of bioavailable fractions of metals in soil, the diffusive gradients in thin-films (DGT) technique has gained great importance in the last decade, and its use has been extended to soils and sediments where it has provided unique information related to the dynamics of the system [115]. The strategy has been used for the general evaluation of the risks associated with soil contamination with Cu, Zn, and Cd under field conditions [116].

DGT is an effective technique for the prediction and evaluation of the bioavailability of As in soils and the viability of DGT on-site application [117].

6. Mechanisms Involved in Phytoremediation

Phytoremediation occurs as a series of plant biochemical processes that reduce in situ or ex situ the concentration of various polluting compounds. Phytoremediation depends on the ability of plants to absorb, accumulate, metabolize, volatilize, or stabilize soil contaminants. It is considered to be a type of "green" technology that utilizes plant species tolerant to toxic organic compounds and heavy metals found in contaminated surface water and soils [16,118]. This technology has been found to represent a realistic biotechnological strategy to address environmental management problems in natural resources, specifically water and soils. Phytoremediation, or the potential for decontamination, stems from the ability of plants to absorb contaminants from soil particles or liquids, to bind those contaminants in their root tissue either physically or chemically, to transport the contaminant from the roots to the foliage, and to metabolize the contaminants and eventually to volatilize the subproducts derived from this process [16,119]. This biotechnological strategy has frequently been used to decontaminate slightly HMs polluted soils and to identify promising plant species [120,121]. One strategy to effectively address contaminated soils is to involve energy crops to meet the demand for biofuels without affecting food security or the environment. Various species of plants can be established to both phytoremediate contaminated soils and produce bioenergy, e.g., Ricinus (Euphorbiaceae) has been used for the phytoremediation of Cd while producing biodiesel from seed oil [122]; and Eucalyptus (Myrtaceae) for phytoremediation of As -contaminated soil [123] with bioenergy production from biomass [124]. Through the use of energy crops, it is possible to carry out phytoremediation processes in municipal sludge. One study showed that giant Miscanthus (*Miscanthus* × *giganteus*) had higher yields, higher bioaccumulation, and higher absorption of heavy metals [125].

The steps involved within the phytoremediation process are: phytoextraction, phytovolatilization, phytostabilization, and rhizodegradation, which vary in nature according to the plant specimen or species and the heavy metal concerned. In phytostabilization, plants immobilize heavy metals and reduce their bioavailability by combining them into chemically interactive complexes [126]. In the rhizosphere, plant roots and symbiotic organisms such as arbuscular mycorrhiza fungi have the ability to release organic acids that promote the sequestration and sorption of heavy metals [127].

Phytostabilization is one of the preferred techniques for the remediation of contaminated soils, and is especially applicable in the case of metallic pollutants in landfills, to stabilize them and reduce the risk to human health and the environment.

Rhyzodegradation involves the decomposition of organic pollutants in the rhizosphere of plants as a result of the activity of microorganisms. This process represents the primary mechanism contributing to removal of petroleum hydrocarbons (PHCs) when performed by plant roots and associated bacteria [128].

Phytoextraction is the process by which heavy metals captured by roots are translocated to stems and leaves. Some plants can absorb heavy metals such as Se, Hg, and As from the soil and release them into the atmosphere as volatile compounds in a process called phytovolatilization [129]. Nevertheless, a disadvantage of this process is that once the metal has been volatilized, its final destination in the atmosphere can no longer be controlled. Phytoextraction and phytostabilization are primarily techniques selected for metals and metalloids. [130].

7. Plant Strategies for Growing in Contaminated Soils

Plants can be grouped into three groups according to their strategies for growing in soils contaminated with metals: (a) accumulators: metals are concentrated in aboveground plant parts from both low or high metal concentrations in the soil; (b) excluders: metal concentrations in the roots are maintained constant and low over a wide range of

soil concentrations; and (c) indicators: uptake and transport of metal to the shoots are regulated, with internal concentration reflecting external levels [131].

Heavy metals can affect the metabolism and the translocation of molecules at the cellular level of "non-tolerant" plant species [132] (while other plants are tolerant and can become hyperaccumulators) [133]. Heavy metal accumulation varies considerably depending on the plant species in question. Accumulation variations have also been seen among the different tissues of the same plant [134]. The response of plant species to heavy metals also varies along with their taxonomic category, with the Trachaeophyta (vascular plants) being slightly more tolerant [135]. Some plant species have developed morphological adaptations to tolerate heavy metals, for example, cadmium stress results in a larger root diameter due to the increased size of parenchymal cells and enlarged cortical tissues, which play a role in increasing the resistance of plants to fluxes and solutes [136].

Other species are able to accumulate and tolerate more than one metal in elevated concentrations, i.e., *Thlaspi caerulescens* is a hyperaccumulator for Zn, Cd, and Ni [137]. *Sedum alfredii* can hyperaccumulate Zn, Pb, and Cd [138], and *Trifolium alexandrinum* can be used for the phytoextraction of Cd, Pb, Cu, and Zn [139].

Hyperaccumulator species are distributed over a wide range of distantly related taxonomic families, a fact which suggests that the hyperaccumulation trait might have evolved independently more than once under the pressure of selective ecological factors [109,140]. These species can accumulate very high levels of heavy metals in roots and aerial organs, well above the levels found in most species, without symptoms of phytotoxicity [141,142]. (Plants that can grow and develop in soils with high concentrations of heavy metals belong to a specialized type of flora [143,144].) Well-adapted to soils rich in heavy metals, they are called "metalophytes" and are considered to be botanical curiosities [144,145]. Various species of hyperaccumulating plants have been recognized for their ability to store high concentrations of heavy metals in their shoots, for example a plant species is said to be hyperaccumulating As or Pb when it accumulates $\geq$1000 mg/kg in its aerial organs and Cd when it accumulates $\geq$100 mg/kg (on a dry weight basis) [129].

Several hypotheses have been proposed to explain why certain plants became heavy metal hyperaccumulators, including:

Metal tolerance and availability. The possible responses include large alterations of gene expression, particularly of membrane transporters responsible for uptake, translocation, and sequestration of essential and nonessential mineral nutrients. Genes involved in transport, synthesis of metal chelators, and responses to oxidative stress are constitutively and highly expressed in hypertolerant and hyperaccumulative metal species [146].

Drought resistance. This hypothesis suggests that to overcome the effects of drought, metals could be preferentially stored (localized) within the epidermis of the leaf tissues to reduce cuticular perspiration or improve osmolality within the cell. However, in another study using two plant species in the presence of Ni and polyethylene glycol, it was concluded that hyperaccumulated metals did not contribute significantly to osmotic adjustment in either of the species [147].

Interaction with other neighboring plants species could be used to "protect" conventional plants by depleting potentially toxic metals within shared rhizospheres in a process known as "phytoprotection" [148].

Defense against natural enemies. Through the acute toxicity of metal-containing plant tissue in which the ingestion of plant material causes mortality. Based on this hypothesis, a study was carried out using *Pieris brassicae* larvae [149].

Hyperaccumulation of heavy metals in tropical and subtropical plants may have developed as a defense mechanism against phytopathogenic insects. This interesting hypothesis is driving studies into this physiological phenomenon [150,151]. Little is known about the role of vegetation in the processes of phytoremediation, especially in tropical latitudes. More studies might help to optimize these processes [16,152]. Geographically, metal hyperaccumulators are widely distributed around the planet. They are found in soils rich in metals, in both tropical and temperate zones [132], and exist as both native and non-

native vegetation in South Africa, North and South America, and Europe [153,154]. A list of some species of tropical and subtropical plants, from herbaceous to shrubby varieties, which exhibit heavy metal protective phytoremediation characteristics, is presented in Table A1 in Appendix A.

These cultivars are used as models to test the phytoextraction or immobilization of HMs in soil, or to assess their tolerance to stress. These species, despite sharing a potential for heavy metal phytoextraction, are not necessarily phylogenetically related. However, the degree of efficacy in the process depends on the plant species, the characteristics and content of the heavy metals involved [155,156] and the type of phytoremediation strategy used [16,157].

8. Phytoremediation in Tropical Soils—Advantages and Limitations

Tropical soils exhibit a high diversity of plant species that have not yet been sufficiently explored for phytoremediation studies, especially in Latin America where the greatest biodiversity of plant species is concentrated—the region being home to at least a third of global biodiversity [19]. Taking advantage of this great diversity of species, the screening of plants from soils contaminated with heavy metals in tropical areas would be a useful tool.

At one of the most important artisanal and small-scale gold mining sites in Colombia, research was carried out to identify native plant species that grow in agricultural soils contaminated with Hg and to evaluate their potential as phytoremediators. Twenty-four species of native plants, both grasses and shrubs, were identified, which, despite their low biomass production, were found suitable for phytoremediation in the field due to their rapid growth and high values of Hg-accumulation factors in large and easily harvestable parts. Of the species identified, eleven were found to be herbaceous [158]. These wild plants are normally abundant and rapidly colonize their ecosystems. Assessing these plants is important, as several of them are native and grow normally in this type of soil and environment.

Different studies using tropical and subtropical plants have demonstrated their ability to phytoremediate heavy metals (Table A1). Among the plant families that have the ability to hyperaccumulate heavy metals are members of Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, Cunouniaceae, Fabaceae, Flacourtiaceae, Lamiaceae, Poaceae, Violaceae, and Euphobiaceae [159].

The Amaranthaceae, comprise 165 genera and 2040 plant species [160]. The genus Amaranthus comprises about 70 species, of which approximately 40 are native in America. *Amaranthus hybridus* L., originating in tropical and subtropical America, it is currently spread throughout the temperate regions around the world, grows in different places, including mining wastelands, tailings, barrens, and other disturbed habitats as soils contaminated with Cd and Pb [161]. *A. hibridus* in symbiosis with arbuscular mycorrhizal fungi improves the phyto-extracting capacity of lead [162].

The Araceae, comprises 114 genera and approximately 3750 species [160]; recent studies of the Xanthosoma genera for western South America reported a total of 124 species, including 92 new species, for the Guianas a total of 22 species, including 10 new species [163], demonstrating the potential of biodiversity for targeted phytoremediation studies. *Xanthosoma undipes* is a good candidate for Cd phytoremediation and suitable for ex situ phytoextraction studies [164]. The Asteraceae or Sunflower family consists of 24,000–30,000 species and 1600–1770 genera. The members of the family are distributed in every continent but Antarctica [165]. Species of the Asteraceae family, especially herbaceous and subshrub species, possess characteristics related to water stress that provide resistance to extreme climatic variations [166], different species of plants belonging to the Asteraceae family have been used to phytoremediate heavy metals [55,167–169], for its ability to hyperaccumulate metals (Table A1).

The Brassicaceae includes 340 genera and over 3700 species distributed worldwide [170], but mainly confined to the Mediterranean region and north temperature regions. Some species of this family are known because they play an important role in the accumula-

tion of heavy metals in their tissues and have potential genes to which tolerance/resistance against the harmful effects of these HMs are attributed. *Brassica juncea*, *Brassica oleracea*, *Brassica napus*, *Brassica carinata* are known for their phytoremediation property [171]. Indian mustard (*Brassica juncea* L. Czern.) is a promising species for the purpose of phytoextraction of cadmium [120]. The Cyperaceae has around 5400 species described in 106 genera [172]. Forty-three genera and approximately 1000 species are found in the Neotropics, Brazil has 622 species in 43 genera [173]. Representative species of Cyperus genus have been used successfully for their ability to hyperaccumulate and phytostabilize heavy metals [174,175]. The Cyperaceae family has a high diversity of species in the Neotropics, constituting an opportunity for studies aimed at bioprospecting in phytoremediation studies of soils impacted by heavy metals and oil. The Euphorbiaceae s.s. has pantropical distribution, with higher occurrence in tropical regions, and is composed of 334 genera [176] and over 8000 species [177]. *Jatropha curcas* L. is a species representative of this family. It can be found in tropical and subtropical regions, it is considered native to Mexico and other Central American countries [178], and it has been proposed for phytoremediation of HMs contaminated areas (Table A1) for its ability to tolerate and accumulate Hg from polluted soils and for its ability to hyperaccumulate As and Fe [158,179]. The Leguminosae (Fabaceae) is the third largest family of flowering plants, comprising 751 genera and 19,500 species [159]. Genus Sesbania, comprises approximately 85 species of trees, shrubs, and perennial or annual herbs, which are widely distributed in tropical and subtropical regions of the world [180]. *Sesbania drummondii* and *S. rostrate* are species that are used to remediate soils contaminated with Pb and Cd respectively [181,182].

Heliconiaceae is a tropical family with a genus (Heliconia). Heliconias are a group of distinctive plants of the biodiversity characteristic of tropical America. Heliconiaceae, includes many ornamental species in the neotropics and are generally known as "platanillos" [183]. Heliconias reach their beauty only in the tropics, where these ornamental plants get enough water and suitable temperature that determine its freshness and durability and the showiness of its color [184]. Heliconias genus comprises neotropical species, 98% of which are distributed in South and Central America and the Caribbean, with the remainder being located on certain South Pacific islands such as Samoa and the Indonesian island of Sulawesi [185]. Colombia ranks first in diversity of heliconia in the world, followed by Brazil [186].

Heliconia psittacorum has been used for the remediation of water and cocoa soils contaminated with cadmium in Colombia [14,187], for its ability to accumulate Cd in the roots. Cocoa (*Theobroma cacao* L.) is a crop, important to the economic development of many equatorial countries. Its production in the 2016–2017 harvest was of 4.7 million tons globally [188]. Compared to other cocoa-producing regions such as those in Africa and Asia-Pacific, some countries in Latin America and the Caribbean (LAC) are particularly affected by worrying cadmium levels in cocoa beans that are a concern for manufacturers of products with a high cocoa content. In this context, there is a pressing need for solutions to reduce cadmium levels in cocoa beans and provide mitigation solutions at key processing stages in the value chain [189]. The Poaceae includes mainly grasses, with around 780 genera and 12,000 species [160], and they are of great interest due to their rapid growth and high rooting capacity in soils under unfavorable conditions. South American soils polluted with heavy metals by the oil industry are a good example of colonization by these plants [190]. *Gynerium sagittatum* (caña fleche), *Chrysopogon zizanioides* (vetiver grass), and *Pennisetum purpureum* (Napier grass) are representatives' species of this family with capacity for hyperaccumulate high concentrations of HMs [191–193], as shown in Table A1.

The Urticaceae includes about 2625 species, grouped into 53 genera [160], and are distinctive in being usually monoecious or dioecious herbs, shrubs, trees, or lianas. Cecropia spp. are ecologically important pioneer trees in the nootropic. *Cecropia peltata*, the "guarumo", a tree representative of the American intertropical zone, has the ability to accumulate a considerable quantity of Hg in its tissues—especially in the roots—and can remove 15.7% to 33.7% of Hg from the soil [194]. The Verbenaceae is in the major

group Angiosperms. They are distinctive in being trees, shrubs, and lianas. Members of the Verbenaceae are distributed in mostly tropical regions; especially South America [195]. Verbenaceae includes 34 genera of plants and 2712 species [196].

P. nodiflora is considered an efficient plant species in the accumulation of Cu and Zn [154].

The enormous number of plant species in Latin American tropical soils represent the highest levels of biodiversity worldwide and form a valuable natural resource for heavy metal phytoremediation processes. However, tropical soils also experience serious environmental impacts attributed to mining, intensive use of pesticides, industrial activities, and emerging pollutants. Most of this mining occurs in the Andean countries, leading to high metal concentrations in soil and metal contamination problems [197]. Phytorremediation of toxic mine sites is a long-term process. After the invasion of successional plants, the growth of potentially useful toxic metal remediating plants is inhibited. Thus, this restoration process is time consuming and will require monitoring and human assistance over time, as invasive plant species that develop rapidly in tropical soils can have catastrophic impacts on ecosystem services such as reduced habitat quality and decreased vegetation cover and diversity [198]. Most of the available metal hyperaccumulator species have limitations in commercial phytoremediation due to their slow growth rate and low biomass production [199]. A good strategy would use energy crop species, as these can provide high biomass yields in a short period of time, are resistant to abiotic stress conditions, and have the ability to accumulate toxic substances [200]. Therefore, the diversity of plant species in tropical soils should be taken advantage of to carry out studies that lead to the selection of hyper-accumulators that grow rapidly and produce large biomass.

In accordance with the great diversity of plant species in tropical soils, studies aimed at the phytoremediation of HMs are still scarce. It would be advisable to test at least some of the candidates in situ and in controlled experimental plots. The tropical climate is not an obstacle to this type of research, in fact, quite the contrary. Various species across an array of different families and environments should be tested, as they are well adapted to their individual media. For example, halophytic plants that tolerate salts use the same mechanisms to incorporate HMs [201] and, thus, may be good candidates for phytoremediation work. More studies should also be undertaken with respect to plant species that grow naturally in tropical soils contaminated by heavy metals and their potential for phytoremediation.

Phytoremediation is a strong, environmentally friendly option for various types of heavy metal-contaminated soils in agriculture, mining, and industry. Several species have already been evaluated for their potential in tropical and subtropical areas (Table A1). Other plant species that have a strong ability to grow and survive in mine waste include a wide diversity of species. A few tropical soil examples are: *Ricinus communis*, *Solanum nitidum*, *Brassica rapa*, *Fuertesimalva echinata*, *Urtica urens*, and *Lupinus ballianus*.

Identifying species tolerant to HMs is actually, not particularly difficult. Once a contaminated area has been identified, it is relatively simple to identify those plants that are growing normally—indicating that these may be potential phytoremediators. Indeed, if these plants are well established on a heavily polluted soil, they are certainly adapted [202] and should, thus, have the physiological and germplasm potential for phytoremediation [203]. Another technique is the possible combination of phytoremediation with a second method. In some cases, the biological uptake of a metal can be improved by forming soluble complexes using chelating agents or extractors [109,204]. Even genetic engineering could be of use in making changes to the physiological aspects of tropical plants for the benefit of phytoremediation [172].

Another possibility is to emphasize the use of plant-microbe associations to increase and improve phytoremediation processes. Mycorrhizal symbiosis and rhizospheric microorganisms that promote plant growth are green technologies that can be employed alongside the great diversity of tropical plants to reduce the HMs stress they suffer; as various rhizospheric microorganisms can accumulate, transform, or detoxify HMs.

Nevertheless, there are advantages and limitations in phytoremediation processes to remove heavy metals from tropical soils, and Figure 1 represents those to be considered.

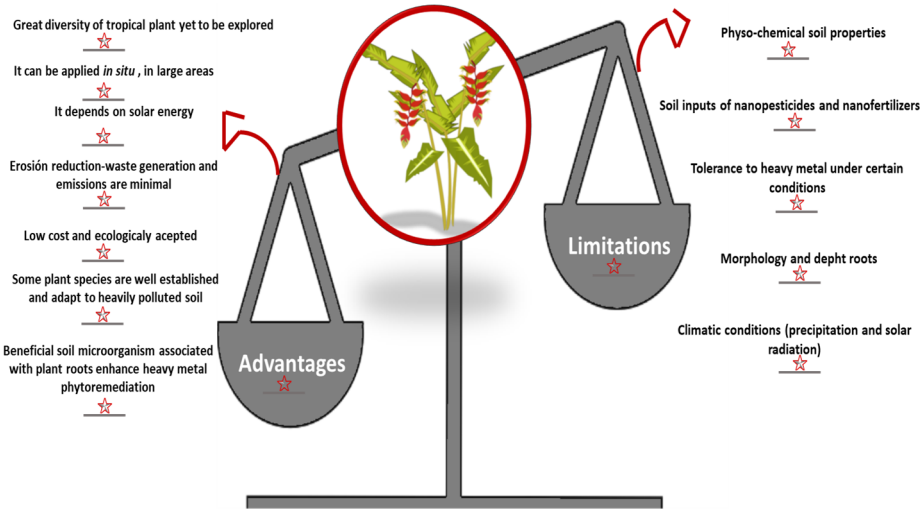

Figure 1. Advantages and limitations in phytoremediation processes to remove heavy metals from tropical soils.

9. Conclusions

Anthropogenic activities are largely responsible for soil and plant contamination with heavy metals. As we have seen, the latter can accumulate in the soil at concentrations that may be very high. They increase oxidative stress in plants and inhibit their normal growth and development. Fortunately, some plants can successfully utilize enzymatic and non-enzymatic antioxidants to counteract these effects. This metabolic arsenal has evolved in soils naturally rich in salts.

Far from being a disadvantage, the presence of heavy metals in tropical soils represents an opportunity for the survival of plant metallophyte species and for the selection of species for phytoremediation studies in cultivable tropical soils impacted by heavy metals. This very special biocenosis is assisted by microorganisms that have also become specialized to survive and counteract the toxic effects of heavy metals and constitutes a sustainable and environmentally friendly ecological tool. The adaptation systems that the plants have developed to grow in this type of soil and the great diversity of plant species that host the tropical soils, are sufficient reasons to continue and increase phytoremediation studies.

The successful phytoremediation of HMs in tropical soils is achieved through human intervention, including good soil-management practices and the planting of a mixture of native or adapted species to the area of concern. It is suggested that a successful strategy will involve a mixture of grasses for their rapid growth, along with legumes, shrubs, and trees that have been previously validated as useful in phytoremediation processes. In addition, it is suggested to include energy crops in mining soils, as well as in municipal and industrial sludge. It is important to continue studying more species of the great diversity of plants that grow in tropical soils to select those that are most promising for each particular zone, considering their adaptation and growth according to the physical chemical characteristics of the soils in question. Moreover, important will be the incorporation of other strategies used to improve heavy metal phytoremediation, including chelate and microbe-assisted phytoremediation.

However, the constant addition into the soil of fertilizers, new emerging pollutants, and nanoagrochemicals that contain traces of heavy metals could interfere with the phytoremediation process in tropical soils, a possibility that requires further research to properly understand.

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Species of tropical and subtropical plants used in phytoremediation processes.

Family/Specie	Description	Reference
Amaranthaceae *Amaranthus hybridus* L.	The capacity of *A. hybridus* for the extraction of heavy metals Lead (Pb) and Cadmium (Cd) was evaluated, in symbiosis with arbuscular mycorrhiza. The results showed that the addition of mycorrhizae significantly increased the concentration of Pb and Cd in the roots, stems, and leaves. The concentrations of Pb and Cd increased significantly as the age of the plant increased.	[162]
Araceae *Xanthosoma undipes*	*X. undipes* was used to evaluate its extraction capacity in soils contaminated with Cadmium (Cd) in areas of oil exploitation in Ecuador. The results showed a Cd removal of up to 79.67% and no sign of oxidative stress. These results make the species a good candidate for phytoremediation of Cd and appropriate for ex situ phytoextraction studies.	[164]
Asteraceae *Berkheya coddii*	*B. coddii*, a species native to the subtropics of South Africa, has an extraction affinity for metals such as nickel (Ni) and palladium (Pd), making it a candidate for phytoremediation in mining soils affected by high concentrations of these metals. *B. coddii* in symbiosis with arbuscular mycorrhizae (*Glomus intraradices*), increases its ability to hyperaccumulate Nickel (Ni).	[167,168]
Asteraceae *Baccharis trimera*	Plant found in areas of southern Brazil. Exhibits spontaneous growth in areas contaminated with various heavy metals, showing greater capacity to accumulate copper (Cu) in its roots.	[56]
Asteraceae and Euphorbiaceae *Helianthus annuus* and *Ricinus communis*	The tolerance capacity of these two species was evaluated in soils artificially contaminated with Lead (Pb) in a greenhouse. It was found that these species are tolerant to Pb and accumulate it in their roots with little translocation to the shoots, showing evidence of immobilization in the underground parts of these plants.	[169].
Brassicaceae *Brassica juncea*	Indian mustard (*Brassica juncea* L. Czern.) tolerates high concentrations of heavy metals and is a promising species for the purpose of phytoextraction of cadmium (Cd) from metal-contaminated soils.	[121]

Table A1. *Cont.*

Family/Specie	Description	Reference
Cyperaceae *Cyperus involucratus* *Cyperus rotundus*	This species has demonstrated the ability to hyperaccumulate Cu, Zn, Cd, Ni, Cr, and Pb in various parts of the plant. *Cyperus rotundus*, may successfully be used as a phytostabiliser for the metals; Zn, Pb, Ni. The grass may also serve as a metal indicator for the Cd.	[174,175]
Euphorbiaceae *Jatropha curcas*	The phytoremediation capability of *J. curcas* was tested using soils from gold mining areas. This plant species has a good ability to tolerate and accumulate Hg from polluted soils in Colombia. Due to the high translocation and bioaccumulation factors obtained in this study, *J. curcas* L. can be considered a hyperaccumulating plant of As and Fe.	[158,179]
Fabaceae *Sesbania drummondii* *Sesbania rostrata*	A shrubby plant 1 to 3 m tall. It is one of the potential tropical plants to remedy soils contaminated with Pb, since it grows naturally in places with this type of contamination and seems to tolerate considerable concentrations. An annual tropical legume, it is a promising candidate species for revegetation at mine tailings. Efficient for hyperaccumulation of cadmium and copper in contaminated soils.	[181,182]
Heliconiaceae *Heliconia psittacorum*	This species was tested in wastewater with leachate from sanitary landfills to phytoremediate heavy metals, finding great potential for phytoextraction of metals such as cadmium (Cd) and lead (Pb).	[14]
Poaceae *Gynerium sagittatum* (caña fleche)	The mercury (Hg) accumulation capacity of the plant com-monly called “caña fleche” (Gynerium sagittatum) was evalu-ated in vitro. It was found that this plant is hyperaccumulative of mercury metal, with metal concentrations increasing in its roots and stems over time.	[191]
Chrysopogon zizanioides (Vetiver Grass)	Commonly found on flood plains and stream banks, but also appears throughout the tropical and subtropical regions of Africa, Asia, America, Australasia, and Mediterranean Europe. Highly tolerate extreme climatic variation such as prolonged drought, flood, submergence and temperatures, soils high in acidity and alkalinity. Accumulates high concentrations of heavy metals (lead, zinc, arsenic, cadmium, zinc, chromiun, and copper) in its roots and shoots	[192]
Pennisetum purpureum (Napier grass)	Commonly known as Napier grass, due to its rapid growth rate and ability to survive in highly contaminated soils, is a candidate plant for phytoremediation processes. In this study, a phytobacterial system was used that uses *Pennisetum purpureum* together with a lead-resistant bacterium (LRB) for lead uptake.	[193]
Urticaceae *Cecropia peltata*	This species, commonly called “guarumo”, was used as a phytoextractor of mercury (Hg) present in contaminated soils in the south of Bolívar (Colombia). An elevated concentration of mercury was found in its roots and leaves.	[194]

Table A1. *Cont.*

Family/Specie	Description	Reference
Verbenaceae *Phyla nodiflora*	Species selected among 17 germinated in sites in North Florida contaminated with metals: lead (Pb), copper (Cu) and zinc (Zn). *P. nodiflora* was the most efficient at accumulating Cu and Zn in its stems and is a native species of the area considered to exhibit phytoremediation potential.	[155]

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