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Case Report

A sustainable way to prevent oral diseases caused by heavy metals with phytoremediation

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ABSTRACT

Sustainability, food security, and human health. This study builds on previous research [1] and explores the role of phytoremediation, a plant-based, eco-friendly strategy in mitigating heavy metal pollution to achieve Sustainable Development Goal 3 (Good Health and Well-being) while addressing its lesser-known implications for oral and dental health. Through an analysis of seven key metals (copper, lead, zinc, iron, cadmium, arsenic, and mercury), the study identifies 99 plant species classified by their lifespan, light, and water needs, emphasizing perennials for large-scale remediation. Additionally, it highlights the impact of these metals on dental conditions such as caries and enamel hypoplasia. By supporting the establishment of green belts around industrial zones, this research integrates soil restoration with public health improvements, paving the way for future studies to deepen the connections between environmental contamination, phytoremediation, and oral health.

1. Introduction

Heavy metal contamination represents a significant global environmental and public health challenge, with severe implications for soil quality and human well-being, including oral health [2]. Mining and industrial activities are major contributors to this issue, releasing heavy metals into the environment and leading to their progressive accumulation in soils [3]. Mining operations generate large volumes of waste that accumulate in dumping sites, often transforming fertile agricultural regions into barren landscapes [4]. Additionally, water used in mining processes often contains heavy metal pollutants, which contaminate surrounding soils and water bodies [5]. Airborne particles laden with metals, released during mining or transportation activities, settle on nearby soils, further exacerbating the contamination [6]. These processes are influenced by climatic conditions and unpredictable environmental events [7], which can result in sudden spikes in pollution levels in affected areas [8].

Soil contamination by heavy metals poses a variety of risks, including the inhibition of crop growth, reduction of agricultural yields, and, most critically, the introduction of toxic metals into the food chain [9]. Fig. 1 illustrates the primary impacts of heavy metal soil pollution on achieving SDGs.

As illustrated in Fig. 1, soil contamination with heavy metals directly impacts Sustainable Development Goal 3 (SDG 3), which prioritizes human health [10–12]. Oral and dental health is one of the parameters associated with SDG 3. Therefore, achieving this goal requires communities to implement strategies for preventing and reducing soil pollution caused by heavy metals.

Heavy metal contamination significantly affects human health, including oral and dental health, as metals such as lead, cadmium, mercury, and arsenic accumulate in the body through dietary and environmental exposure [13]. Research has established links between these metals and dental diseases, including enamel hypoplasia, increased risk of caries, and systemic health conditions that indirectly influence dental health [14]. Consequently, monitoring soil contamination is essential not only for preserving ecosystems but also for protecting public health, particularly oral and dental health outcomes [15].

Heavy metal pollution from mining activities poses significant ecological challenges by degrading soil quality and threatening the health of local communities. Soil enzymes, which are vital proteins that regulate soil ecology and fertility, are particularly vulnerable to heavy metal contamination [16]. These enzymes facilitate essential biochemical reactions, contribute to the breakdown of organic pollutants, and sustain soil health. However, their functionality is disrupted in the

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presence of heavy metals, emphasizing the importance of regular soil sampling, laboratory testing, and enzyme activity monitoring to effectively assess and manage contamination [9].

The sources of heavy metal pollution are diverse, originating from both natural and anthropogenic processes [16]. While natural sources include erosion, weathering, and geological activity, human activities such as mining, industrial operations, traffic emissions, and agricultural practices are the dominant contributors [17]. Mining and traffic emissions are significant sources of soil pollution, releasing heavy metals such as lead and cadmium into the environment. Traffic-related sources include gasoline fumes, brake wear, and tire degradation [18]. Industrial processes also contribute by utilizing heavy metals as catalysts, which directly introduce contaminants into the environment [19]. In agricultural areas near roads or industrial sites, heavy metals can accumulate in crops, subsequently entering the human food chain [20]. These exposures have been directly linked to an increased risk of oral diseases, as heavy metals interact with biological tissues, potentially compromising oral hygiene and promoting conditions such as caries and enamel defects [21].

In a previous study of Pouresmaieli et al. (2022) [1], the primary focus was on identifying plant species capable of removing heavy metals from soil. While that research provided a comprehensive analysis of the characteristics and capabilities of various plants [1], it did not address the impact of heavy metal contamination on oral health. This article builds upon that foundation by exploring the relationship between heavy metal contamination, oral health, and the potential of phytoremediation to mitigate these effects. Notably, this study updates the tables of plant species with new data and introduces additional plant species not covered in the earlier research. Section 2 examines in detail the connection between heavy metals and oral and dental diseases, highlighting treatment and prevention strategies for these conditions, with a particular focus on environmental control. Effective management of soil contamination, a critical pathway for heavy metal absorption into the human body, is identified as a key element of these strategies. Section 3 discusses methods to reduce heavy metal concentrations in soil, emphasizing phytoremediation as one of the most effective and cost-efficient approaches. This method is emphasized as a cornerstone of the article's preventive strategies. In Section 4, seven heavy metals, copper, lead, zinc, iron, cadmium, arsenic, and mercury are analyzed, detailing their direct and indirect contributions to oral and dental diseases. The section also identifies plant species capable of absorbing these metals from the soil, offering a preventive solution that addresses the root cause of many such diseases. Sections 5 and 6 provide a discussion and conclusion, respectively, summarizing the findings and presenting insights into the implications of mitigating heavy metal contamination for oral and dental health.

2. Relation between heavy metals and oral diseases

Heavy metals, naturally occurring elements with high atomic weight and density, have garnered significant attention due to their potential impact on human health, including oral and dental health. Metals such as lead, mercury, cadmium, and arsenic are introduced into the environment through industrial processes and are present in contaminated water, food, and air [1]. Even at low concentrations, their accumulation in the human body can lead to toxic effects, many of which manifest in the oral cavity. The relationship between heavy metal exposure and dental diseases is multifaceted, involving both direct and indirect mechanisms [22,23].

Heavy metals can directly affect dental structures, including enamel, dentin, and periodontal tissues. For instance, lead exposure is associated with enamel hypoplasia, a developmental condition resulting in defective enamel that increases susceptibility to cavities. Mercury, widely used in dental amalgams, has been linked to oral lichenoid reactions and hypersensitivity in certain individuals. In addition to structural damage, heavy metals can disrupt the oral microbiome, fostering the proliferation of pathogenic bacteria and exacerbating periodontal diseases such as gingivitis and periodontitis [24,25].

Indirectly, heavy metals contribute to systemic conditions such as oxidative stress and inflammation, which can exacerbate oral health problems. For example, cadmium disrupts the cellular redox balance, impairing the healing of periodontal tissues [26,27]. Similarly, arsenic exposure has been implicated in the development of oral cancers, highlighting the broader health consequences of heavy metal toxicity [28,29].

The vulnerability to dental issues caused by heavy metals is influenced by factors such as age, genetic predisposition, and overall health status. Children, whose bodies are still developing and who engage in frequent hand-to-mouth behaviors, are particularly susceptible to lead-induced dental complications [30,31]. Adults, especially those with occupational exposure to heavy metals, also face heightened risks to their dental health. This intersection of environmental exposure, systemic health, and oral disease emphasizes the importance of comprehensive strategies to mitigate heavy metal toxicity [32,33]. Understanding these interactions is crucial for developing preventive measures, enhancing dental treatments, and supporting for policies aimed at reducing environmental exposure to heavy metals. Such efforts are essential to safeguard both oral and overall health. Table 1 summarizes the diseases caused by heavy metals that directly and indirectly threaten oral health.

Based on the findings presented in Table 1, heavy metals have been shown to influence oral and dental health both directly and indirectly. The data indicate that the diseases listed in Table 1 account for over 50 % of all oral and dental health conditions [34–74]. With over 90 % of the

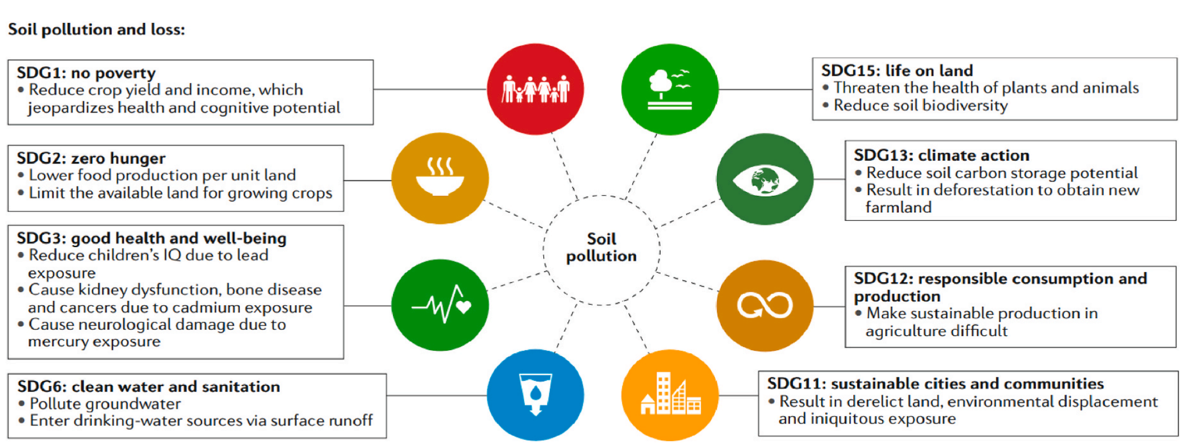

Fig. 1. Impact of soil contamination on SDGs [1].

Table 1
Some diseases that directly or indirectly affect oral health are caused by heavy metals.

Effect type	Diseases	Reference
Direct	Enamel Hypoplasia, Dental Caries, Oral Lichenoid Reactions, Hypersensitivity Reactions, Ulceration of Oral Mucosa, Contact Stomatitis, White Patches (Leukoplakia), Pigmentation Changes in Gums, Burning Mouth Syndrome, Dry Mouth (Xerostomia), Erosion of Oral Mucosa, Delayed Wound Healing in Oral Surgeries, and Contact Dermatitis (Localized to Oral Tissues)	[34–45]
Indirect	Periodontitis, Gingivitis, Oral Squamous Cell Carcinoma, Alveolar Bone Loss, Impaired Periodontal Healing, Oral Candidiasis, Oral Submucous Fibrosis, Chronic Oral Inflammation, Immune-Mediated Oral Ulcers, Pulpal Necrosis, Increased Tooth Mobility, Halitosis (Bad Breath), Oral Melanosis, Angular Cheilitis, Reduced Salivary Flow (Hyposalivation), Oral Lichen Planus, Soft Tissue Fibrosis, Temporomandibular Joint Dysfunction, Oral Papilloma, Paresthesia in Oral Tissues, Delayed Eruption of Teeth, Oral Kaposi Sarcoma, Chronic Dryness (Sjögren-Like Syndrome), Tissue Atrophy, Oral Hyperkeratosis, Erythema Multiforme, Impaired Oral Wound Healing, Oral Dysesthesia (Burning Sensation), Impaired Tooth Development, and Palatal Erosion	[46–74]

global population exposed to industrial, mining, traffic, and pollution-related activities as primary sources of heavy metal contamination, the role of these metals in the development and progression of oral and dental diseases is substantial [75–79] Statistically, heavy metals contribute to more than 45 % of these conditions, highlighting their significant impact. Thus, preventing the accumulation of heavy metals in the human body is essential for mitigating these health risks. Table 2 outlines various therapeutic and preventive strategies aimed at minimizing the effects of heavy metals on oral and dental health.

As shown in Table 2, one of the primary preventive measures to safeguard oral and dental health is environmental control, which seeks to reduce excessive exposure to and absorption of heavy metals. While numerous therapeutic and preventive approaches exist to address the adverse effects of heavy metals, this study emphasizes prevention through environmental management [1]. Environmental control involves the development and implementation of strategies to minimize human contact with heavy metals by regulating key environmental components, including the lithosphere, atmosphere, biosphere, and hydrosphere. Among these, soil management plays a pivotal role in mitigating heavy metal contamination. Heavy metals present in soil can infiltrate groundwater systems, leading to the contamination of water sources and aquatic ecosystems [1]. Additionally, heavy metal accumulation in soil can result in elevated concentrations in agricultural products and animal fodder, which are directly and indirectly linked to the human food chain [1]. When these metals enter the food chain, they accumulate in the human body, causing a wide array of health issues, including cancer and oral and dental diseases. Therefore, controlling soil contamination by heavy metals is of paramount importance and can significantly reduce the incidence of oral and dental diseases associated with heavy metal exposure.

Table 2
Therapeutic and preventive approaches aimed at minimizing the impact of heavy metals on oral and dental diseases.

Approach	Manners
Prevention of heavy metal exposure	• ***Environmental measures*** • Dietary practices • Workplace safety • Dental materials
Detoxification	• Chelation therapy • Natural detoxifying agents
Oral hygiene and local care	• Regular dental check-ups • Oral hygiene practices • Desensitizing agents
Management of specific oral diseases	• Treatment of periodontitis and gingivitis • Treatment of oral lichenoid reactions • Treatment of oral ulcers or irritation • Management of oral cancer risks
Lifestyle and systemic support	• Antioxidant therapy • Immune support
Public awareness and advocacy	• Education campaigns • Policy advocacy

3. Soil contamination treatment methods by phytoremediation

Soil pollution management primarily involves two remediation strategies: clean-up and containment. The clean-up approach, introduced in the early 2000s, focuses on the complete removal of contaminants to meet safe environmental standards. In contrast, the containment strategy aims to reduce the mobility and bioavailability of contaminants, mitigating their harmful effects without requiring complete removal [80]. Both strategies can be executed through in-situ or ex-situ methods. In-situ remediation treats soil directly on-site, eliminating the need for relocation and generally minimizing environmental and health costs. Ex-situ remediation, typically employed when on-site treatment is infeasible, involves transporting contaminated soil to a different location for decontamination [80].

Selecting the most effective method for reducing heavy metal contamination requires careful consideration of several factors: the type and toxicity of contamination, pollution sources, contamination risks, soil properties (both chemical and physical), local climate, land use, time constraints, community acceptance, and financial viability. These factors vary significantly across methods. Due to economic constraints, there is increasing interest in low-cost remediation techniques that do not rely on advanced technology. Such methods are especially advantageous for both developing and developed countries. Fig. 2 provides an overview of the costs associated with each method [9].

Growing concerns over soil pollution have spurred a demand for advanced and efficient remediation techniques. Advances in molecular biology emphasize the potential of utilizing living organisms, such as microorganisms and plants, for soil remediation. These approaches are cost-effective, simple, and accessible. This review focuses on plant-based strategies for mitigating heavy metal contamination in soils affected by activities such as mining and industrial operations [80]. Consequently, this paper emphasizes phytoremediation as a key remediation approach.

Bioremediation encompasses the use of microorganisms (e.g., fungi, bacteria, archaea) and phytoremediation, a plant-based method [81]. Phytoremediation uses plants to absorb and transfer heavy metals to their above-ground parts. Its primary mechanisms include (Fig. 3) [82].

- **Phytostabilization:** Reduces heavy metal mobility by encouraging root secretions that lower metal bioavailability in the rhizosphere.
- **Phytovolatilization:** Releases certain contaminants from the soil into the atmosphere.
- **Phytoextraction:** The primary process in phytoremediation, where plant roots absorb metals that accumulate in above-ground tissues, allowing for later removal through harvesting.

4. Control of heavy metals pollution effect on oral diseases by phytoremediation

The following sections provide an in-depth discussion of the impacts of soil contamination by heavy metals specifically copper, lead, zinc, iron, cadmium, arsenic, and mercury on oral and dental health. Additionally, plants known to mitigate these contaminants in soil are introduced, with particular emphasis on species that demonstrate high efficacy in enhancing soil remediation. Sections 4.1 to 4.7 focus on the primary characteristics of these plants. Factors such as light irradiation, electrolytic treatment, intercropping, CO_2 fumigation, and other

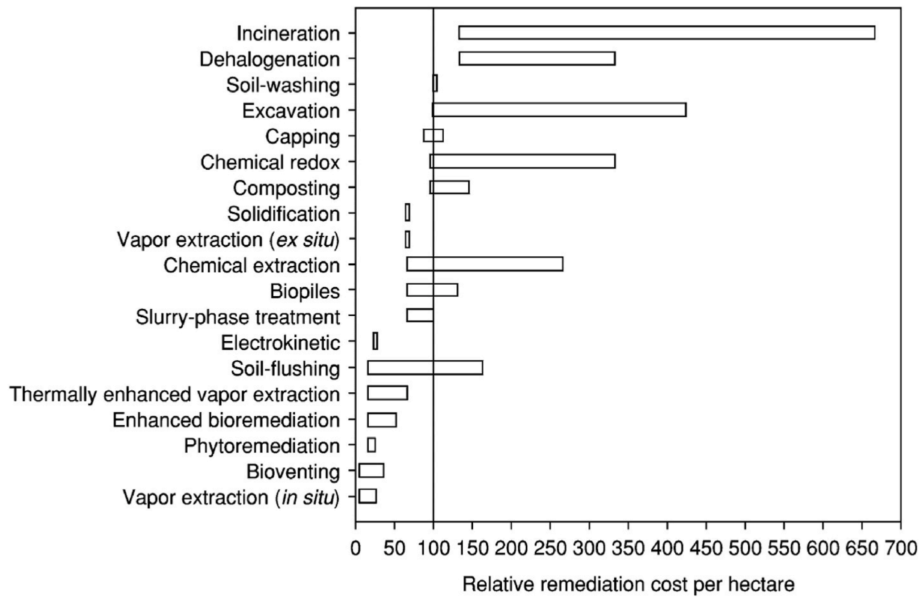

Fig. 2. Relative range of costs for different methods. The range is estimated for a one-hectare contaminated land with a specific weight of 1.2 g/cm^3 at a depth of 0.25 m [1].

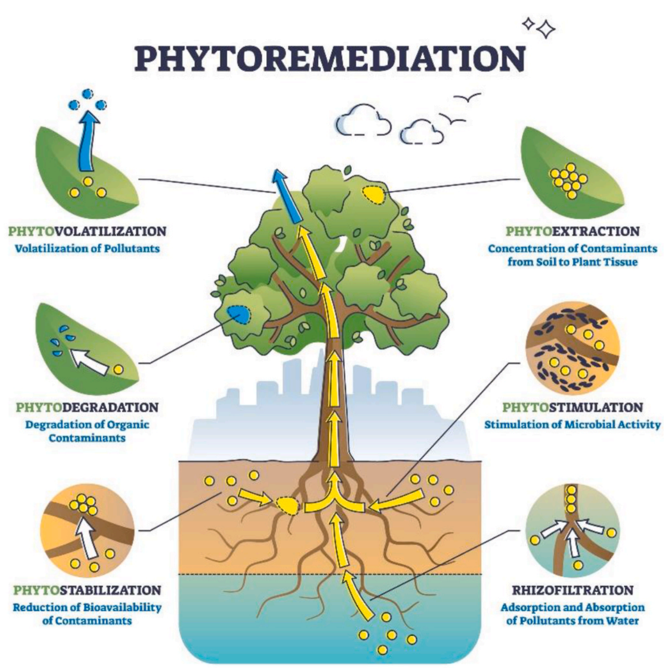

Fig. 3. Phytoremediation processes in various components of plants.

conditions are excluded from this review due to insufficient data regarding their relevance and applicability.

The tables presented in this section complement those from previous research [1] by incorporating additional plant species identified through recent investigations and analyses conducted as part of the current study. Given the extensive list of plants covered in the previously published article, they are not reiterated here. Instead, this section highlights only the newly identified species discovered through this study. Information from the previous article has been integrated into the results section, where findings from both studies are combined to provide a comprehensive overview of the subject.

4.1. Copper

Copper plays a crucial role in metabolism due to its involvement in the functioning of several essential enzymes [83,84]. However, elevated copper levels have been linked to an increased risk of dental caries, with higher concentrations of copper found in decayed teeth compared to healthy ones [30]. Studies suggest a correlation between elevated copper levels in water, food, soil, and vegetables and a greater prevalence of cavities. Furthermore, research has shown that serum copper levels are significantly higher in individuals with oral conditions such as leukoplakia, oral submucous fibrosis, and malignant tumors, including squamous cell carcinoma [85].

In assessing the impact of trace elements on dental health, it has been observed that copper concentrations are generally higher in the enamel of healthy and primary teeth compared to decayed teeth [86]. The recommended daily copper intake varies by age group: 340 mcg/day for children aged 1–3, 440 mcg/day for ages 4–8, 700 mcg/day for ages 9–13, 890 mcg/day for ages 14–18, and 900 mcg/day for adults over 18. Pregnant women are advised to consume 1000 mcg/day while lactating women require 1300 mcg/day. Copper is naturally abundant in foods such as oysters, shellfish, whole grains, hazelnuts, potatoes, dark leafy greens, dried fruits, and organ meats, including kidneys and liver [87].

Copper contamination in soil is predominantly caused by human activities [88]. Major contributors include mining, smelting, and refining operations, as well as the irrigation of agricultural land with copper-contaminated water and the application of copper-based fertilizers and fungicides [89]. Table 3 identifies the plants that are most effective in reducing copper levels in contaminated soils.

4.2. Lead

Exposure to lead commonly occurs through contaminated food and beverages, often as a consequence of industrial and mining activities [31]. Vegetables grown in lead-contaminated soil serve as a significant source of exposure, enabling lead to enter the food chain. Additionally, lead can be absorbed by plants and grasses growing in polluted soils, which subsequently accumulate in grazing animals, particularly cattle. This accumulation results in toxic effects on livestock and poses health risks to humans consuming lead-contaminated meat and dairy products [101].

Table 3
Newly identified plant species for copper remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Aeollanthus subacaulis	Lamiaceae	plant	[90]
Ipomea alpina	Convolvulaceae	Perennial	[91]
Medicago sativa	Fabaceae		[92]
Nicotiana tabacum	Solanaceae		[93]
Brassica juncea	Brassicaceae	Flower	[94]
Elsholtzia splendens	Lamiaceae	Annual	[95]
Trifolium alexandrinum	Fabaceae	Legume Annual	[96]
Helianthus annuus	Asteraceae	Plant Annual	[97]
Pteris vittata	Pteridaceae	Herbaceous	[98]
Alyssum murale	brassicaceae	Perennial	[99]
Silene vulgaris	Caryophyllaceae	Flower Perennial	[100]

Lead is especially detrimental to human health, as it can replace calcium (Ca^{2+}) in hydroxyapatite (HAP) within teeth, reducing the size of HAP crystals and compromising dental integrity [102,103]. Environmental and dietary lead exposure allows the metal to reach body tissues, including teeth, where it has been shown to contribute to dental caries. Studies indicate that lead exposure increases the prevalence of enamel hypoplasia, with a positive correlation observed between lead levels in saliva and the development of early childhood tooth decay. Thus, lead exposure is a critical factor in the formation of new dental caries [30,102,104]. Given lead toxicity and its ability to enter the human body through contaminated soil and food, it is imperative to monitor lead levels in soil, especially in areas near lead-containing mines and industrial zones. One way to reduce soil lead contamination is through plants. Table 4 highlights several plants that have proven effective in reducing lead concentrations in soil.

4.3. Zinc

The human body contains between 2 and 4 g of zinc, distributed across various organs, including the prostate, eyes, brain, muscles, bones, kidneys, and liver. Zinc is the second most abundant transition metal in living organisms after iron and is unique in being present in all classes of enzymes. In blood plasma, approximately 60 % of zinc is bound to albumin and 10 % to transferrin, with its concentration remaining stable regardless of dietary zinc intake [115–117].

The average daily zinc requirement ranges from 15 to 20 mg, with 2–5 mg excreted through the pancreas and intestines. Plasma zinc levels may decline during pregnancy, fluid loss, use of oral contraceptives, blood loss, acute myocardial infarction, infections, and malignancies [118]. Zinc is essential for cell reproduction, differentiation, and metabolic functions, supporting healthy growth during pregnancy, childhood, and adolescence [84,119,120]. It is most concentrated in animal-based foods such as meat, milk, and fish, while its bioavailability is lower in plant-based foods [85].

Table 4
Newly identified plant species for lead remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Ricinus communis	Euphorbiaceae	Tree	[105]
Taraxacum officinale	Asteraceae	Flower	[106]
Pelargonium hortorum	Geraniaceae	Perennial	[107]
Lantana camara	Verbenaceae	Plant Perennial	[108]
Cucumis sativus	Cucurbitaceae	Vegetable Annual	[109]
Cannabis sativa	Cannabaceae	Plant	[110]
Brassica rapa	Brassicaceae	Annual	[111]
Festuca arundinacea	Poaceae	Grass	[112]
Chrysopogon zizanioides	Poaceae	Perennial	[113]
Allium cepa	Amaryllidaceae	Vegetables Biennial	[114]

The role of zinc in dental caries development remains a subject of debate. Some studies have reported elevated zinc levels in children with higher rates of dental caries and higher zinc concentrations in the carious enamel of primary teeth. Conversely, other research suggests that zinc in saliva may reduce the incidence of dental caries [121,122].

Despite conflicting evidence, zinc is frequently incorporated into oral health products to manage plaque, combat halitosis, and reduce tartar formation. Zinc released from mouthwashes and toothpaste can persist in plaque and saliva for extended periods. Additionally, low levels of zinc may mitigate enamel demineralization, though its anti-cariogenic effects remain contested [123]. Zinc deficiency has been identified as a potential risk factor for oral and periodontal diseases, often manifesting as parakeratotic changes in the cheeks, tongue, and esophagus. Lower serum zinc levels have also been associated with potentially premalignant conditions such as oral leukoplakia [119].

In soil, zinc accumulation can be absorbed by plants through their roots. Due to their inability to effectively filter or eliminate excess zinc, plants may become contaminated. Zinc disrupts soil functions by adversely affecting microorganisms and earthworms, which slows the decomposition of organic matter. Monitoring and regulating zinc levels in soil is therefore critical for preserving farmland fertility [124]. Table 5 outlines plants effective in reducing zinc concentrations in contaminated soils.

4.4. Iron

Iron (Fe) is one of the most abundant elements in nature and a vital component of all living organisms. Despite its geological abundance, iron often forms poorly soluble oxides upon exposure to oxygen, reducing its bioavailability [134]. Iron is primarily obtained from dietary sources such as liver, meat, poultry, fish, cereals, green leafy vegetables, legumes, nuts, oilseeds, and dried fruits [85]. While green vegetables are a significant source of dietary iron, enamel in human teeth generally contains low concentrations of this element [103]. In healthy individuals, the total iron content in the body ranges between 4 and 5 g. As a trace metal, iron is indispensable for the survival of nearly all organisms. It plays a critical role in numerous biological functions, including oxygen transport, DNA synthesis, metabolic energy production, and cellular respiration, due to its involvement in heme and iron-sulfur cluster-containing proteins [135]. Iron has been suggested to have cariostatic properties that may help prevent dental caries. For instance, one study found that adding 2 mmol/L of $FeSO4{\cdot}7H2O$ to acidic beverages reduced mineral loss and preserved the surface microhardness of human enamel [136,137]. Moreover, certain iron supplementation products developed to address iron deficiency anemia have been reported to delay the onset of dental caries in human teeth. However, iron deficiency can lead to several oral health issues, including angular cheilitis, atrophic glossitis, diffuse oral mucosal atrophy,

Table 5
Newly identified plant species for zinc remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Pennisetum purpureum	Poaceae	Grass	[125]
Lolium perenne	Poaceae	Perennial	[126]
Festuca arundinacea	Poaceae		[127]
Taraxacum officinale	Asteraceae	Flower Perennial	[128]
Ricinus communis	Euphorbiaceae	Tree	[129]
Brassica napus	Brassicaceae	Plant	[130]
Chenopodium album	Amaranthaceae	Annual	[131]
Rumex acetosa	Polygonaceae	Plant	[132]
Nicotiana tabacum	Solanaceae	Perennial	[133]

candidal infections, oral premalignant lesions, and stomatitis [85].

While appropriate iron levels can positively impact oral health, excessive iron concentrations in the human body have been linked to cancers, including liver, breast, and lung cancers [138]. The proliferation of iron ore mines worldwide and the use of nearby land for agriculture have significantly increased iron pollution, particularly in urban areas. Controlling and reducing soil iron concentrations is essential, and plants capable of absorbing iron offer a viable solution. Table 6 lists effective plant species for this purpose.

4.5. Cadmium

Cadmium is found in certain vegetables, including leafy greens, potatoes, grains, and seeds, as well as in animal-based foods such as liver and kidney [26]. Once absorbed into the body, cadmium tends to accumulate in the liver and bones and is excreted at an extremely slow rate. Cadmium is highly mobile in soil and readily absorbed by plants, making it a significant environmental concern due to its entry into the food chain and potential to contaminate water sources through soil runoff [147]. The movement of cadmium in soil can be exacerbated by the use of chelating agents, which accelerate its leaching into groundwater, posing risks to both drinking water supplies and agricultural irrigation systems [27,148].

Exposure to cadmium is associated with a wide range of health problems, including kidney damage, bone disorders, and cardiovascular diseases [149]. In dental contexts, cadmium can be released from certain dental alloys used in intraoral applications. It subsequently accumulates in teeth and oral tissues, where it binds strongly to metallothioneins [150]. Research indicates a link between cadmium exposure and higher rates of dental decay. Although cadmium deposition in teeth after their formation does not directly contribute to caries, studies in animal models suggest a strong association between cadmium exposure during tooth development and the onset of dental caries [151]. Given the widespread dispersal of this toxic element, its impact on both systemic and oral health is a growing concern, particularly for vulnerable populations such as children [150].

Due to the severe health risks posed by cadmium, reducing its concentration in soil is critical. One effective method with low cost for mitigating cadmium contamination involves the use of specific plants capable of absorbing and sequestering cadmium from the soil, as listed in Table 7.

4.6. Arsenic

Arsenic, a toxic metalloid, is frequently found in contaminated soil, water, and air due to industrial activities, mining operations [160]. Human exposure to arsenic primarily occurs through drinking contaminated water, consuming foods cultivated in polluted soil, and, to a lesser extent, inhaling air in regions with high industrial emissions [161].

Arsenic exposure is linked to numerous systemic and oral health issues. Regarding oral health, arsenic is associated with an increased risk of dental fluorosis, a condition characterized by the discoloration and weakening of tooth enamel, often resulting from the coexistence of fluoride and arsenic in contaminated environments. Chronic arsenic exposure has also been implicated in gum disease, delayed wound healing in the oral cavity, and a heightened risk of oral cancers [28,29]. The toxic effects of arsenic arise partly from its ability to disrupt cell division, impair DNA repair, and dysregulate oxidative stress, adversely affecting various tissues, including oral tissues. Arsenic can also accumulate in bones and teeth, replacing essential minerals like calcium. This substitution compromises the structural integrity of teeth, increasing their susceptibility to decay and erosion. Furthermore, arsenic exposure has been shown to suppress immune responses, exacerbating oral infections and inflammatory conditions [162–164].

Given the significant health risks posed by arsenic, monitoring and mitigating its presence in contaminated soil are of paramount importance. Phytoremediation, the use of specific plants to absorb and sequester arsenic, has shown promise as an effective strategy to reduce arsenic levels in soil. These plants, listed in remediation guides, can help lower arsenic contamination in agricultural fields, thereby reducing its entry into the food chain and mitigating associated health risks, including those affecting dental health. Plants that are effective in absorbing arsenic are listed in Table 8.

4.7. Mercury

Mercury is a toxic heavy metal that happens naturally in the environment, but its levels are significantly amplified by human activities such as mining, coal combustion, waste incineration, and various industrial processes [171]. Common sources of mercury exposure include contaminated fish and shellfish, dental amalgam fillings, industrial emissions, and, in some cases, polluted drinking water. Mercury exists in three primary forms elemental, inorganic, and organic (methylmercury) each with distinct toxicity levels and exposure risks [172].

In the context of dental health, mercury exposure is particularly

Table 6
Newly identified plant species for iron remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Helianthus annuus	Asteraceae	Plant	[139]
Brassica napus	Brassicaceae	Annuals	[140]
Corn (zea mays)	Poaceae		[141]
Medicago sativa	Fabaceae	Flower	[142]
Pelargonium hortorum	Geraniaceae	Perennial	[143]
Pteris vittata	Pteridaceae	Herbaceous Perennial	[144]
Typha latifolia	Typhaceae	Plant Perennial	[145]
Lolium perenne	Poaceae	Grass Perennial	[146]

Table 7
Newly identified plant species for cadmium remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Phyllanthus amarus	Phyllanthaceae	Plant	[152]
Datura innoxia	Solanaceae	Annual	[153]
Lolium perenne	Poaceae	Grass	[154]
Typha latifolia	Typhaceae	Perennial	[155]
Atriplex halimus	Amaranthaceae		[156]
Festuca arundinacea	Poaceae		[157]
Vicia faba	Fabaceae	Vegetable	[158]
Cucumis sativus	Cucurbitaceae	Annual	[109]
Avena sativa	Poaceae	Grass Annual	[159]

Table 8
Newly identified plant species for arsenic remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Typha latifolia	Typhaceae	Plant	[165]
Eichhornia crassipes	Pontederiaceae	Perennial	[166]
Lemna minor	Araceae		[167]
Brassica napus	Brassicaceae	Plant	[168]
Brassica rapa	Brassicaceae	Annual	[168]
Cucumis sativus	Cucurbitaceae	Vegetable Annual	[169]
Juncus effusus	Juncaceae	Grass Perennial	[170]
Medicago sativa	Fabaceae	Flower Perennial	[92]

noteworthy due to the historical use of dental amalgam fillings, which contain approximately 50 % mercury. Although deemed safe by regulatory agencies, small amounts of mercury vapor can be released from amalgam fillings over time, especially during chewing or grinding. This vapor may be inhaled and absorbed into the bloodstream, raising concerns about its potential long-term health effects, particularly for individuals with multiple fillings or those who are pregnant or more sensitive to mercury exposure [24,25]. Mercury exposure can adversely affect oral tissues and overall dental health. Studies suggest that elevated mercury levels may contribute to oral inflammation, metallic taste, and allergic reactions in sensitive individuals. Chronic mercury exposure has also been linked to neurological symptoms, which could indirectly impact oral hygiene practices and increase vulnerability to gum disease. Additionally, in regions with high mercury pollution, such as those near mining sites, mercury can contaminate soil, infiltrate food chains, and ultimately accumulate in human tissues, including teeth. Once deposited in teeth and bones, mercury is challenging to excrete and may weaken dental structures over time [173–175].

To address the harmful impacts of mercury, it is essential to monitor contamination levels in affected regions and implement strategies to minimize exposure, such as adopting dietary precautions and enhancing occupational safety protocols. Research is exploring phytoremediation and other soil remediation methods as potential approaches to lower environmental mercury concentrations, thereby mitigating its effects on public health and dental care. Table 9 provides a list of plant species capable of absorbing mercury.

5. Finding: phytoremediation as a solution for oral and environmental health

This review examined the use of various plants to reduce heavy metal contamination in soils affected by mining activities, focusing on seven specific heavy metals and identifying their primary sources of soil contamination. It also addressed the transfer of these metals to humans, the dental health issues they can cause, and the challenges they pose to soil health. Additionally, the study presented plants capable of reducing contamination by each metal. Key findings from this study and the results of the previous study [1] are summarized below:

Effect of studied heavy metals on oral health: This study highlights the adverse effects of heavy metal contamination in soil on both oral and general health, emphasizing the potential of phytoremediation to mitigate these risks. Table 10 outlines dental diseases linked to the studied metals discussed in Sections 4.1 to 4.7. For example, copper causes gum and tooth discoloration; lead is associated with tooth decay and gum color changes; zinc contributes to xerostomia and bad breath; iron may lead to blackened teeth and cancer; cadmium causes alveolar bone resorption and tooth loss; arsenic leads to gum discoloration and cancer; and mercury exacerbates gum sensitivity and bad breath. Fig. 4 shows which part of the tooth is directly affected by heavy metals as part of the mouth. By reducing heavy metal concentrations in soil, phytoremediation can significantly improve oral health and align with sustainable development goals.

Table 9
Newly identified plant species for mercury remediation: findings from the current study complementing previous research by Pouresmaieli et al. (2022) [1].

Plant name	Family	Plant type	References
Helianthus annuus	Asteraceae	Plant Annual	[176]
Vetiveria zizanioides	Poaceae	Grass	[177]
Spartina alterniflora	Poaceae	Perennial	[178]
Tagetes patula	Asteraceae	Flower Annual	[179]
Triticum aestivum	Poaceae	Grass Annual	[180]
Eichhornia crassipes	Pontederiaceae	Plant	[181]
Scirpus acutus	Cyperaceae	Perennial	[182]
Solanum melongena	Solanaceae	Vegetable Perennial	[183]

Table 10
Oral diseases caused by studied heavy metals.

Heavy metal name	Diseases
Copper	Xerostomia, periodontitis, Ulcer, Bad breath, Discoloration of the teeth and gums, which appears in the gums with gray or blue -green colors, and in the teeth with yellow and brown colors.
Lead	Periodontitis and tooth decay cause a change in the color of the gums, which appears with blue or gray colors on the edge of the gums.
Zinc	Xerostomia, gingivitis, mild periodontal issues, bad breath
Iron	Cancer, Ulcer, gingivitis, Bad breath, Blackening of teeth
Cadmium	Gingivitis, periodontitis, Ulcer, Cancer, alveolar bone resorption, decreased calcium absorption, Tooth loss.
Arsenic	Cancer, Ulcer, bad breath, discoloration of the teeth and gums appear with the formation of white, gray, or black spots, gingivitis, alveolar bone resorption.
Mercury	Gingivitis, bad breath, Gum sensitivity, Minamata

- Knowledge Gaps in Metal Uptake by Plants: A major challenge in reducing soil pollution using plants is the lack of comprehensive data on the uptake rates for each plant-metal combination. Limited information on the absorption capacities of various plants makes it difficult to identify the most effective species for practical applications. Future research should focus on studying metal absorption by individual plants to support evidence-based decision-making in real-world remediation projects.
- Diversity of Plants Used: The study introduced 99 plant species capable of reducing heavy-metal contamination, categorized as follows: 20 tree species, 34 plant species, 21 flower species, 14 grass species, 7 vegetable species, 2 legume species, and 1 fern species. These details are summarized in Tables 3–9 and in the previous study [1].
- Plant Lifespan Classification: The 99 plant species were categorized based on their biological lifespans. Of these, as identified in this and a prior study [1], 27 were annuals with a lifespan of one year, 3 were biennials with a two-year lifespan, and 69 were perennials with lifespans exceeding two years.

Light and water are essential factors for plant growth. The plants examined in this study were assessed for their light and moisture needs, with the findings summarized as follows.

- **Light Requirements:** Of the 99 species, 47 require full sunlight (no shade), while 39 thrive with partial sunlight (6–8 hours of direct light with some shade). The light requirements for 8 species remain unspecified (Fig. 5).
  - **Water Requirements:** Regarding moisture, 48 species grow well in moist soil, while 19 are suited to relatively dry or semi-dry conditions. Irrigation needs for 13 species lack clear scientific documentation (Fig. 6).

The study also explored the plants' abilities to absorb heavy metals from contaminated soil.

- **Metal Absorption Capabilities:** Among the 99 plants, 60 were found to absorb only one heavy metal. The remaining 39, referred to as Valuable Phytoremediation Plants (VPP), demonstrated the ability to reduce multiple heavy-metal concentrations in soil (Figs. 7 and 8). Overall, 178 phytoremediation plants were identified across Tables 3–9 and previous study [1].

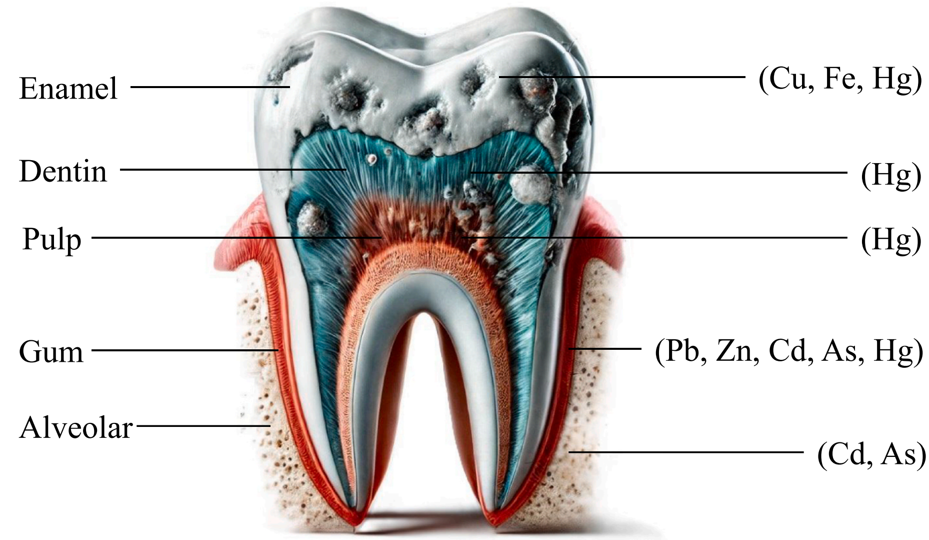

Fig. 4. Effect of studied heavy metals on tooth.

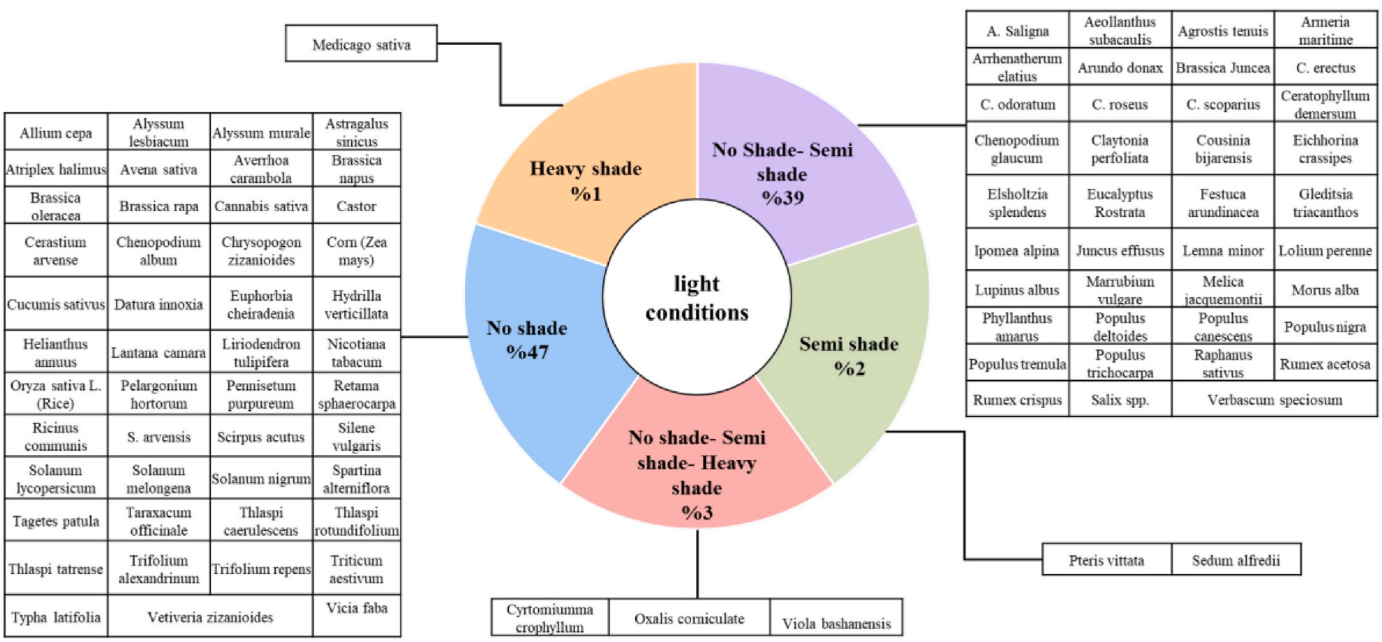

Fig. 5. Plant names and percentage distribution based on their light requirements (8 % have unknown light conditions).

6. Broader implications of phytoremediation: governance, socioeconomic, and environmental perspectives

This section examines the findings from a broader and visionary perspective, focusing on their implications for governance, policy-making, and social, economic, and environmental dimensions. Key considerations include the following.

F0B7 Health Risks from Soil Contamination: Soil pollution caused by mining operations poses direct and indirect risks to human health. Regular monitoring of soil contamination levels in farmlands and gardens near mines, factories, industrial hubs, and major roads is essential to mitigate these risks and prevent diseases, including cancers.

F0B7 Phytoremediation as a Temporary Solution: When heavy-metal contamination in soil is identified, the plants highlighted in this study can serve as an effective temporary measure to reduce contamination to acceptable levels. However, addressing the root causes of soil pollution by identifying and mitigating the primary sources is a critical prerequisite for sustainable remediation efforts.

F0B7 Creating Green Belts Around Mines: Governments and mining regulators should mandate the creation of green belts around mining sites. These green spaces not only improve the aesthetics of mining areas and contribute to the well-being of engineers and workers but also represent a significant step toward sustainable development. Green belts help contain contaminated soil, preventing its spread to farmlands and gardens and thereby reducing heavy-metal pollution in adjacent areas.

F0B7 Preference for Perennials in Green Belts: Given the extensive areas typically occupied by mines, the use of perennial species or trees in green belts is recommended. Unlike annuals, which

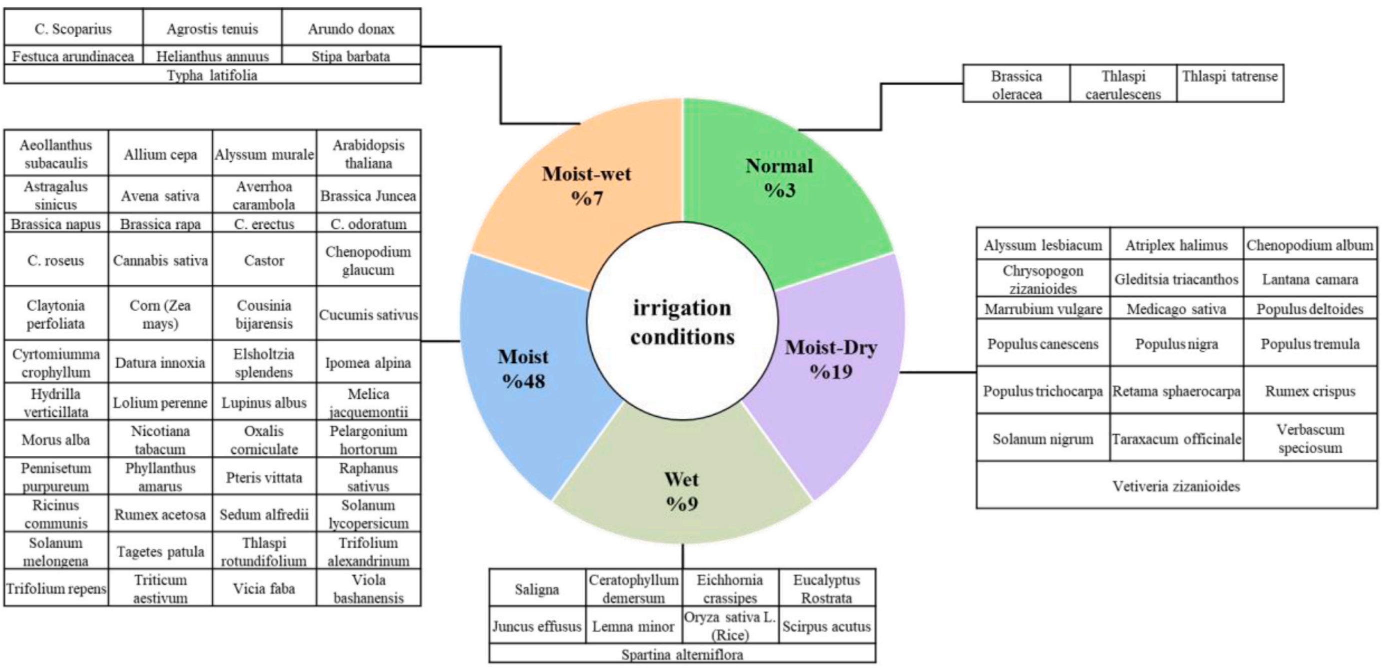

Fig. 6. Plant names and percentage distribution based on their irrigation needs (13 % have unknown irrigation conditions).

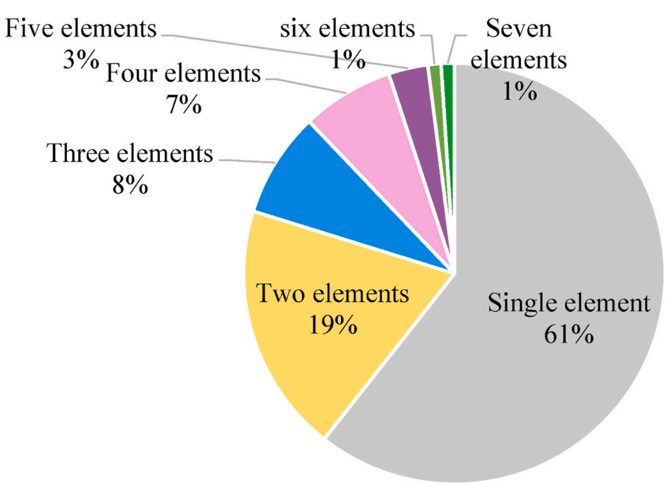

Fig. 7. Percentage distribution of plants in terms of the number of heavy metals they take up from soil.

require yearly replanting and entail higher maintenance costs, perennials and trees offer a more cost-effective and practical solution for large-scale planting. The selection of plants for green belts should be tailored to the specific minerals extracted at the site and the prevailing climatic conditions.

F0B7 Regulating Crop Choices Near Mines: Since heavy-metal-contaminated soil poses significant risks to human and environmental health, legislative bodies should implement regulations to prevent farmers and gardeners from planting species that readily absorb metals excavated nearby. These measures would limit the transfer of heavy metals from soil to crops, thereby safeguarding the health of local populations and communities.

F0B7 Promoting Horticulture Around Mines: Encouraging farmers to practice horticulture near mines and industrial areas can help reduce heavy-metal contamination in agricultural products. Trees, with their deeper root systems, can coexist with plants that absorb high levels of heavy metals. This practice minimizes metal uptake by tree roots, reduces contamination of crops, and enhances food quality and public health.

F0B7 Handling Contaminated Plants: Fully grown annual plants used for heavy-metal soil remediation should be uprooted, collected in specialized containers, and safely incinerated. Importantly, fruits from these plants and trees should not be consumed, as they often contain the highest concentrations of heavy metals.

F0B7 Soil Function and Fertility: Even when heavy-metal contamination does not pose direct health risks, it can degrade soil function and fertility, adversely affecting farmers' economic stability. Reducing soil contamination is critical to restoring fertility, enhancing agricultural productivity, and indirectly improving public health outcomes.

F0B7 Preventing Groundwater Contamination: Heavy metals can percolate into deeper soil layers via rainwater and runoff, ultimately contaminating groundwater reserves. Given the high costs and technical challenges of purifying groundwater, it is essential to address metal concentrations in surface water before they infiltrate aquifers.

F0B7 Regulating Irrigation Practices: Polluted irrigation water is a major contributor to heavy-metal contamination in soil. Governments should enforce regulations requiring farmers to obtain permits for using water that meets maximum permissible heavy-metal concentrations. This would protect both soil health and public health in mining and industrial regions.

F0B7 Innovative Mining Strategies: Emerging methods such as biomining utilize living microorganisms and plants to extract metals from the environment. As mineral grades decline and demand increases, biomining is expected to become more cost-effective. This approach involves selecting plants capable of absorbing high concentrations of metals while adapting to local climates. The current study identifies suitable plant species and their optimal growing conditions for reducing the contamination of various heavy metals.

F0B7 Targeting Multi-Metal Contamination: While certain plants specialize in absorbing specific metals, soils near metal mines often exceed permissible limits for multiple heavy metals. Identifying the primary contaminants from mining activities and

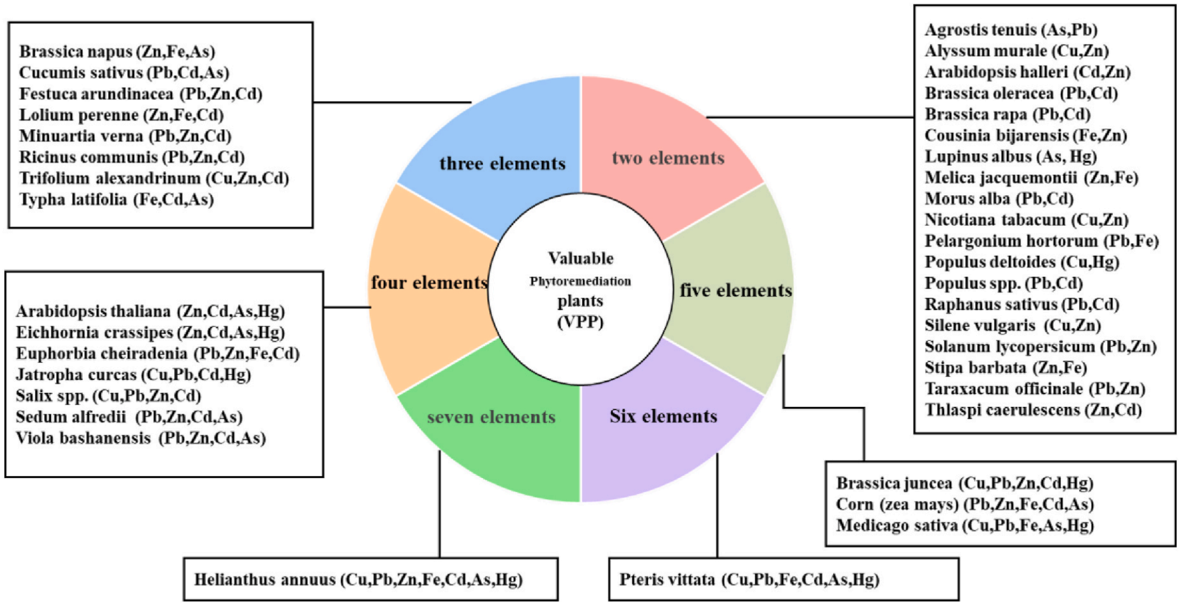

Fig. 8. Valuable phytoremediation plants (VPP).

selecting plants capable of absorbing multiple metals is essential for cost-effective and efficient soil remediation.

7. Conclusion

This study builds upon previous research by Pouresmaieli et al. (2022) [1], which primarily focused on sustainable phytoremediation techniques for mitigating heavy metal contamination in soil, providing a comprehensive review of various plant species for their remediation potential. While the prior work concentrated on the environmental and technical aspects of phytoremediation, the present study extends the scope to explore the impact of heavy metal contamination on oral and dental health, offering an interdisciplinary perspective. Additionally, the plant tables in this study have been updated to include newly identified species from recent investigations, complementing the findings of the earlier research. The results section integrates the outcomes of both studies, presenting a cohesive framework that emphasizes the broader health implications of heavy metal pollution while advancing practical plant-based solutions for sustainable remediation and public health enhancement.

Heavy metal contamination of soil is a pervasive global issue with extensive environmental, health, and socio-economic repercussions. This study investigates phytoremediation a sustainable, cost-effective, and eco-friendly approach to mitigate heavy metal pollution in soils, particularly in regions impacted by mining and industrial activities. By analyzing 99 plant species capable of remediating contaminated soils, this research establishes a robust foundation for implementing plant-based strategies to address soil and environmental health challenges effectively.

The findings indicate that these plants vary in their uptake capacity, light and water requirements, and lifespans, all of which are critical for optimizing their application in practical scenarios. The study categorizes the plants into trees, grasses, flowers, vegetables, legumes, and ferns, each group offering distinct advantages for specific contamination scenarios. Moreover, the plants are classified by lifespan, with annual, biennial, and perennial species identified. Perennials, in particular, emerge as cost-effective solutions for large-scale remediation due to their longevity and reduced maintenance requirements.

A significant challenge highlighted in this study is the lack of comprehensive data on metal uptake rates and absorption ranges for specific plants. This knowledge gap limits the precision of phytoremediation strategies, emphasizing the need for targeted research to better understand plant-metal interactions. Expanding this knowledge base will enable stakeholders to make evidence-based decisions, ensuring the selection of optimal plant species tailored to specific contaminants, soil types, and climatic conditions.

The study highlights the significant role of phytoremediation in addressing public health concerns, particularly the impact of heavy metal contamination on human and dental health. Heavy metals such as lead, cadmium, mercury, and arsenic, which often leach into agricultural soils, enter the food chain and pose risks ranging from systemic toxicity to dental disorders, including caries and enamel hypoplasia. By reducing metal concentrations in soil, phytoremediation directly contributes to improving food safety and public health while aligning with global SDGs, particularly Goal 3, which focuses on health and well-being.

Beyond its health benefits, the implementation of green belts around mining and industrial sites was emphasized as a practical measure to reduce soil contamination. These green belts, composed of carefully selected perennial plants and trees, not only enhance the aesthetic landscape but also act as natural barriers against the spread of pollutants, preventing their dispersal into agricultural lands and water sources. Additionally, the establishment of such vegetation supports sustainable development by improving soil fertility, enhancing ecosystem services, and bolstering community resilience. However, while phytoremediation holds considerable promise, its successful application requires an interdisciplinary approach. Policymakers must enact and enforce regulations to limit harmful irrigation practices and discourage the cultivation of crops that exacerbate contamination in polluted areas. Collaborations among environmental scientists, agricultural experts, and local communities are critical to ensure the effective implementation and maintenance of phytoremediation projects.

This research emphasizes the potential of phytoremediation as a viable strategy for restoring soil health, safeguarding public health, and advancing sustainable development. Future efforts should focus on closing knowledge gaps, fostering innovation in plant selection and cultivation techniques, and integrating phytoremediation into comprehensive environmental management policies. By leveraging nature-based solutions, society can tackle the dual challenges of soil contamination and public health, paving the way for a greener, healthier future.

CRediT authorship contribution statement

Sana Salehi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Mahdi Pouresmaieli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Ali Nouri Qarahasanlou:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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