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Article

Risk-Informed Screening of Locally Occurring Plants for Nature-Based Restoration of Heavy-Metal-Contaminated Soils in Central Kazakhstan

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Abstract

Industrial emissions and legacy contamination from metallurgical activities can constrain sustainable land use by degrading soil quality and limiting vegetation establishment. This study combines a site-based contamination assessment with an early-stage plant tolerance screening to inform nature-based restoration planning in Central Kazakhstan. Soils were collected around three metallurgical complexes and analysed for heavy metals; exceedance relative to maximum permissible concentrations (MPC) was used to prioritise contaminants of concern. Seven locally occurring plant species were then screened in controlled Petri-dish assays using metal salt solutions (Pb, Zn, Cu, Cr, Cd and Ni), and germination percentage, germination dynamics, seedling shoot length and a growth inhibition index were quantified. Soil results showed elevated metal loads with frequent MPC exceedance, supporting the selection of these metals for biological screening. Plant responses were strongly species-specific: *Brassica juncea* and *Medicago sativa* maintained comparatively higher germination and early growth across treatments, whereas *Suaeda salsa*, *Artemisia absinthium* and *Trifolium repens* exhibited very low germination. These findings provide an evidence-based shortlist of candidate species for subsequent soil-based trials (including uptake and stabilisation assessment) and support risk-informed revegetation strategies for contaminated industrial landscapes.

Keywords: sustainable land management; ecological restoration; nature-based solutions; contaminated soils; heavy metals; revegetation; seed germination; central Kazakhstan

1. Introduction

Heavy metals are pollutants that have been widely studied, primarily due to their long-term harmful effects [1]. The main cause of soil and water pollution with heavy metals is anthropogenic activity [2]. As industrialization develops, heavy metals are released into the environment, causing great harm and disrupting the ecological balance [3]. Industrial activities significantly contribute to environmental pollution caused by heavy metals [4]. The intake of heavy metals into the human body in doses exceeding the limits recommended by the World Health Organization (WHO) can cause various carcinogenic and non-carcinogenic disorders [5]. Due to the widespread metal production in Kazakhstan, harmful heavy metals are widely distributed in the environment. The most common toxic heavy metals are lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), cadmium (Cd) and nickel

(Ni). Kazakhstan has a developed mining and processing industry, rich in natural resources, such as oil, gas, uranium, lead, zinc, chromium, manganese and copper [6,7]. Emissions from the Balkhash Metallurgical Plant pose a serious environmental concern due to their negative impact on the surrounding ecosystem [8]. The Balkhash Concentration Plant, located in close proximity to the lake, contributes to environmental pollution with heavy metals, including cadmium and lead, which have already reached hazardous levels. Elevated background concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), cobalt (Co), and nickel (Ni) have been recorded in the Pribalkhash region, indicating widespread soil contamination [9]. The Zhezkazgan Copper Smelting Plant named after K. Satpayev is one of the largest sources of industrial emissions, adversely affecting public health and the regional environment. During copper production, solid particles, sulfur oxides, and carcinogenic compounds are released into the atmosphere, leading to air and soil pollution. Studies conducted in nearby settlements have revealed increased rates of cardiovascular, respiratory, and endocrine diseases, highlighting the harmful effects of industrial emissions on human health [10]. The Qarmet Joint Stock Company complex in Temirtau is a major steel-producing metallurgical enterprise. Localized areas of soil contamination with heavy metals have been identified near the Qarmet complex [11]. The rise in atmospheric emissions from these facilities has intensified pollution in the delta, as harmful substances released into the air can travel long distances [12].

Problems of heavy metal pollution similar to those in Central Kazakhstan are found in China [13–15], India [16,17] and South Africa [18,19]. Heavy metals, namely cadmium (Cd), zinc (Zn), chromium (Cr), nickel (Ni) and lead (Pb), which are known for their high atomic numbers and density, demonstrate remarkable stability in the soil, not subject to decomposition [20].

Lead (Pb) is one of the most dangerous heavy metals due to its non-biodegradability and can persist in soil for long periods of time [21]. High concentrations of Pb can disrupt hemoglobin biosynthesis, affect the central nervous system, and cause kidney damage, miscarriage, learning disabilities, high blood pressure, Alzheimer's disease, lung and kidney cancer, and behavioral disorders in children [22]. Zinc (Zn) is non-biodegradable and can persist in the soil environment for a long time, potentially damaging ecosystems and human health [23]. In addition, zinc pollution disrupts the balance of soil microorganisms, affecting nutrient cycling and overall soil fertility [24]. Zn is mainly introduced into soil by metallurgy (mining, smelting, tillage), agriculture (fertilizers, pesticides, manure), energy use (electricity generation, gasoline), wastewater, surface water, etc. through, thereby causing contamination of agricultural soils [25].

Copper (Cu), a non-degradable toxic heavy metal, has inhibitory and toxic effects on cells when its concentration exceeds certain limits [26]. Sources of copper pollution include the proximity of copper mines and smelters, the combustion of fossil fuels, especially coal, industrial incinerators, sludge from municipal sewage treatment plants, and the frequent discharge of wastewater, pesticides, and fungicides into the environment [27]. Chromium (Cr), one of the most widespread heavy metal pollutants, is released into the environment mainly through industrial activities such as galvanization and oxidation, and through improper disposal of chromium-containing wastes [28]. Chromium Cr (VI) can have adverse health effects, including skin irritation, respiratory problems, and an increased risk of lung cancer, as well as damage to the liver, kidneys, and immune system [29].

Cadmium (Cd) is released into the atmosphere by natural and anthropogenic activities, and can have various effects on animals and humans. Cadmium pollution of the aquatic environment occurs through absorption, industrial wastes, and surface runoff into soil and sediments. People can be poisoned by cadmium when they eat food rich in this metal, breathe air, or drink water. Cadmium has no beneficial properties for plant growth and metabolic processes [30]. Cadmium has two target tissues in humans: the renal cortex and the liver [31]. Cadmium is a toxic and carcinogenic metal. In addition to its carcinogenic properties, cadmium causes kidney, bone, and cardiovascular diseases [32].

Nickel (Ni) is a naturally occurring element and has wide industrial uses. It is released into the atmosphere from natural and anthropogenic sources [33]. Nickel has many adverse effects on the

human body, causing allergies, nasal and lung tumors, and kidney and cardiovascular diseases when inhaled in polluted air [34].

Soils provide the fundamental medium for plant growth, and their physical and chemical characteristics largely determine the success of plant development [35]. Among the various pollutants that destabilize soil ecosystems, heavy metals attract particular attention because they are persistent, toxic, and prone to bioaccumulation [36]. Contamination of soils with heavy metals has been shown to impair plant vitality and productivity [37]. The ability of plants to accumulate metals is of special relevance, since certain species are recognized as hyperaccumulators and, together with genetically engineered variants, can be applied in phytoremediation strategies [38]. Conventional remediation approaches, such as chemical or physical treatments, are often costly, may alter soil properties, and risk secondary contamination [39]. In contrast, phytoremediation offers a sustainable and relatively inexpensive alternative. Within this framework, plants that restrict the upward translocation of metals and retain them in the root zone act as phytostabilizers or bioindicators [40]. Nevertheless, practical application of hyperaccumulators faces several challenges: (i) possible entry of metals into the food chain when edible species are used, (ii) long growth cycles, (iii) shallow rooting that limits access to deeper contaminated horizons, and (iv) susceptibility to pathogens [41]. Moreover, candidate species frequently struggle to adapt to nutrient-poor or otherwise unfavorable soils [42]. The effectiveness of phytoremediation is therefore closely linked to the careful selection of plant species. Native taxa are often preferred, as they are adapted to local climates and require minimal maintenance. Metallophytes represent a distinct group of plants capable of thriving in soils enriched with heavy metals. They can be categorized as: excluders, which confine metals mainly to roots; indicators, which reflect soil contamination by accumulating metals in shoots and leaves; and accumulators, which store high concentrations of metals in above-ground tissues [43]. Environmental stresses such as drought or temperature extremes can further slow remediation, underscoring the need to select species suited to local conditions. Germination, as the earliest stage of plant development, provides a sensitive measure of seed tolerance to adverse chemical and physical properties of the rhizosphere [44].

The purpose of our study is to analyze the effect of heavy metals on the germination of seeds of local wild plants of Central Kazakhstan. We aim to answer the following research questions: Are heavy metals present in the soil of industrialized regions? Do heavy metals in the soil affect plants? This is important for understanding plant responses to anthropogenic pollution and conducting a preliminary screening of their suitability for remediating contaminated soils. The problem of soil contamination with heavy metals is one of the most acute environmental threats in Central Kazakhstan. Intensive industrial activities, including metallurgy, lead to the accumulation of toxic elements that negatively affect the ecosystem. Local wild plants play a special role in ecological restoration, as they are adapted to the extreme conditions of the region and can demonstrate mechanisms of resistance to pollution. Furthermore, the results of this study may be useful for developing sustainable land use and environmental management strategies in the region, as well as for establishing experimental phytoremediation approaches in other contaminated areas.

Despite extensive evidence on heavy-metal phytotoxicity, Central Kazakhstan lacks a comparative baseline screening across multiple locally occurring species under exceedance-level exposure. We hypothesize species-specific tolerance patterns reflected in germination percentage and early seedling growth metrics. Therefore, we (i) quantify soil metal loads near three metallurgical complexes and (ii) screen seven species using controlled metal salt solutions to identify candidates for subsequent soil-based trials.

2. Materials and Methods

Central Kazakhstan was selected due to its industrial load from mining and metallurgical activities. Figure 1 shows the block diagram of the study.

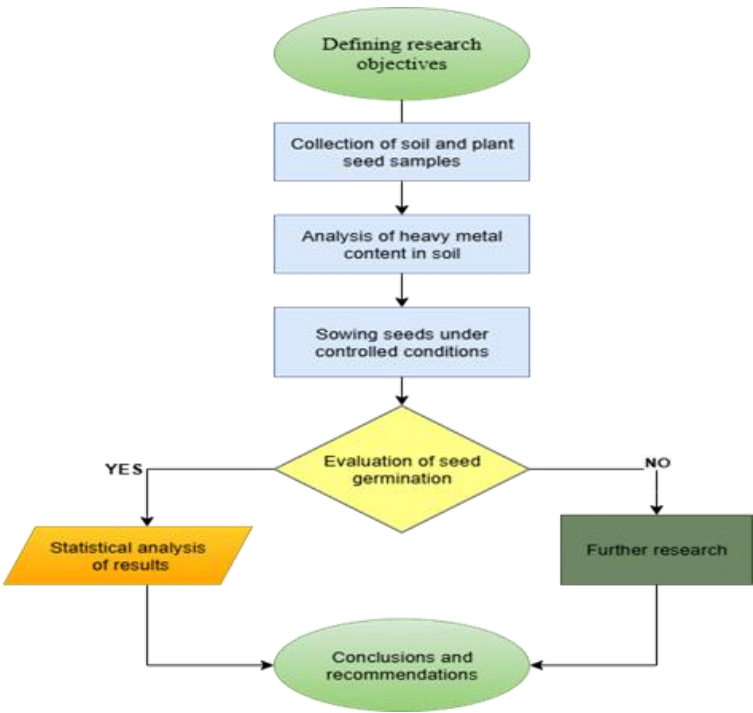


Figure 1. Flow chart of the research methodology.

The study workflow comprised: (i) soil sampling around three metallurgical complexes, (ii) laboratory quantification of metal concentrations, and (iii) Petri-dish germination assays using metal salt solutions, followed by statistical analysis.

2.1. Research Area

Our research covers three large mining and metallurgical plants in Central Kazakh-stan. The complexes of the Kazakhmys Production Association: Balkhash Mining and Metallurgical Plant located in Balkhash, Karaganda region, Zhezkazgan Mining and Metallurgical Plant named after K. Satpayev located in Zhezkazgan, Ulytau region, and the complex of Qarmet JSC “Karaganda Metallurgical Plant” located in Temirtau, Karaganda region. Table 1 lists the coordinates of soil sampling sites near metallurgical plants in Central Kazakhstan.

Table 1. Coordinates of soil sampling points in the study area.

Enterprise	Coordinates (DMS)	Coordinates (Decimal, DD)
Balkhash Mining and Metallurgical Combine (BMMC, Balkhash city)	46°20'31" N; 74°46'26" E	46.3419° N; 74.7739° E
Zhezkazgan Mining and Metallurgical Combine named after K. Satpayev (ZMMC, Zhezkazgan city)	47°20'31" N; 67°46'26" E	47.3419° N; 67.7739° E
Karaganda Metallurgical Plant (KMP, Temirtau city)	50°47'09" N; 73°13'53" E	50.7858° N; 73.2314° E

The presented maps were created using ArcGIS 10.8. Soil samples were collected from industrial areas of Central Kazakhstan in September and October 2023 using the “envelope method”. The map in the upper part of Figure 2 shows the territory of the Republic of Kazakhstan within the state borders, administrative divisions. The lower part shows the geographical location of the studied mining and metallurgical enterprises in Central Kazakhstan and the sampling sites.

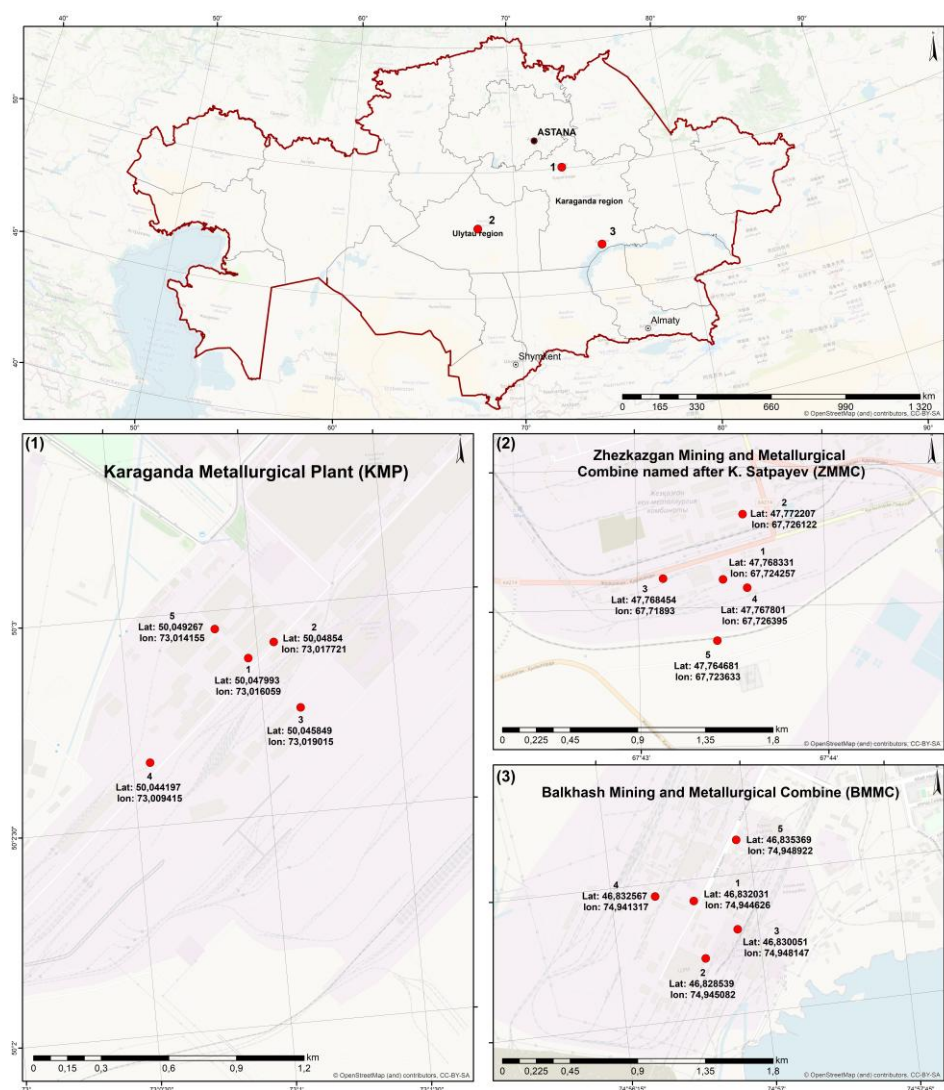


Figure 2. Geographical location of the studied industrial facilities and sampling points on the territory of the Republic of Kazakhstan.

Soil sampling was carried out in accordance with the requirements of GOST 17.4.4.02–2017 [45]. Three horizons of the plant root zone were identified for analysis: 0–10, 10–20 and 20–30 cm. This depth range reflects the initial contact of the root system with pollutants and allows us to assess their vertical distribution. Samples weighing approximately 500 g were collected from the middle of each horizon and placed in pre-prepared polyethylene containers. All samples were labeled and stored at a temperature not exceeding +4 °C until laboratory analysis. Soil samples were taken from five points located at different distances from each of these production areas. The first sample was taken from the middle point of the first sample on the territory of the Balkhash Mining and Metallurgical Combine and from this first point, the second sample was taken at a distance of ± 866 m, the third sample was taken at a distance of ± 784 m, the fourth sample was taken at a distance of ± 546 m, and the fifth sample was taken at a distance of ± 1160 m (five samples in total). Four points were marked in the corners of the test sites on the territory of the Zhezkazgan Mining and Metallurgical Combine named after K. Satpayev, one in the middle. The first sample was taken from the middle point of the first sample and from this first point, the second sample was taken at a distance of ± 535.82 m, the third sample was taken at a distance of ± 273.87 m, the fourth sample was taken at a distance of ± 161.63 m, and the fifth sample was taken at a distance of ± 618.56 m (five samples in total). Soil samples were taken from five points on the territory of the Karaganda Metallurgical Plant at different distances. Four points were marked in the corners of the test sites and one in the middle. The first sample was taken from the center point and from this first point, the second sample was taken ± 158.58 m, the third

sample was taken $\pm 488.88\text{m}$, the fourth sample was taken $\pm 696.55\text{m}$, and the fifth sample was taken $\pm 255.18\text{m}$ (five samples in total). A sixth soil sample was taken from the clean area of each area for control purposes. Soil samples from the control area were taken from a chestnut soil virgin steppe ($50^{\circ}47'33''\text{N}$, $73^{\circ}02'58''\text{E}$), located approximately 18 km northeast of the Qarmet JSC metallurgical plant. From an open chestnut soil semi-desert soil ($46^{\circ}20'31''\text{N}$, $74^{\circ}46'26''\text{E}$), located approximately 30 km south of the Balkhash Ore and Metallurgical Plant. From a chestnut soil ($47^{\circ}48'00''\text{N}$, $67^{\circ}42'00''\text{E}$), located approximately 23 km from the Zhezkazgan Ore and Metallurgical Plant. The samples were collected in clean plastic bags weighing approximately 1.0 kg. The collected samples were sequentially numbered and delivered to the laboratory. A total of 18 soil samples were taken from 6 samples from each production area.

In each region, the most contaminated area was chosen as the central sampling point, around which samples were distributed radially at varying distances. This design allowed us to estimate the spatial gradient of pollution, taking into account the prevailing wind direction and the location of the metallurgical plants in Temirtau, Balkhash, and Zhezkazgan. The placement of individual sampling points was determined by the accessibility of the area, which should be considered a limitation of the method.

These industrial centers play a key role in the country's economy. However, their work imposes significant anthropogenic loads on the ecosystem of the region. Although various preventive measures are being implemented to reduce the negative impact of industrial emissions, this issue still remains an important environmental problem for the region. It also significantly affects soil contamination with heavy metals, which raises questions about environmental sustainability and land restoration. Therefore, studying the impact of pollution on the germination of local plant seeds is of practical importance for making environmental decisions.

2.1.1. Geological and Climatic Conditions of the Studied Regions

Balkhash city is located on the northwestern shore of Lake Balkhash. Geology: Rich in deposits of copper, lead, zinc and other metals, which contributed to the development of metallurgical production. The region is characterized by the presence of metasomatically zoned porphyry copper deposits. The rocks include granodiorites and volcanic sedimentary formations [46]. Sandy loamy soils with natural salinity and low biological activity prevail. Chestnut and saline soils are common, but anthropogenic influences have led to significant contamination of copper and cadmium. Accumulation of heavy metals such as copper, lead, and cadmium is observed near tailings dumps [47]. The water needed for the city comes from the Tokyraun underground mine, and technical water from Lake Balkhash. Lake Balkhash is one of the largest reservoirs of Kazakhstan, partially divided into fresh and saline zones [48]. Water quality is deteriorating due to the deterioration of water supply networks and contamination with heavy metals. The climate is sharply continental, dry, with hot summers (up to $+40^{\circ}\text{C}$) and cold winters (up to -25°C). The average annual precipitation is about 131 mm, and evaporation reaches 950–1200 mm per year [49]. The city of Zhezkazgan, located in central Kazakhstan, has historically been associated with copper mining. The soil is black and chestnut, prone to salinization and heavy metal contamination due to long-term industrial activity [50]. Water resources are limited. The main sources of water supply are the Kengir reservoir and the Uytas-Aidos and Eskula underground springs. Water quality depends on the filling of the reservoir and the condition of the water supply networks [48]. The climate is continental, dry, characterized by sharp temperature changes. In winter, it can reach -30°C , and in summer $+38^{\circ}\text{C}$ [49]. Temirtau is an important industrial center of Central Kazakhstan. The region is characterized by the presence of iron ores and other minerals, which led to the development of the metallurgical industry. Chestnut and technogenic soils are polluted with metallurgical emissions. The main source of water supply is the Nura River, which is subject to anthropogenic pollution. The climate is continental, with little precipitation, harsh winters (up to -30°C), and warm summers ($+35^{\circ}\text{C}$) [49].

2.1.2. Plant Selection

Table 2 listed seven species of native wild plants were selected for assessment of the ecological status of the environment: *Medicago sativa* L., *Brassica juncea* L., *Dactylis glomerata* L., *Chenopodium album* L., *Suaeda salsa* L., *Trifolium repens* L. and *Artemisia absinthium* L.

M. sativa is a perennial plant used for phytoremediation, mainly due to its high biomass yield, which can be harvested several times a year and does not require any special agronomic measures during the growth cycle [51]. *M. sativa* can easily absorb both organic pollutants and heavy metals from contaminated soils, which has been confirmed in various studies [52]. *B. juncea* can accumulate toxic metals in large quantities and can be used for phytoremediation of soils contaminated with heavy metals [53]. *D. glomerata*, commonly known as garden grass, is a very robust plant in phytoremediation studies. It does not require high temperatures for vigorous growth and is very winter-hardy. It appreciates high soil moisture. *D. glomerata* can be successfully grown on a wide range of soils. It is suitable for both mowing and grazing [54]. In addition, *D. glomerata* able to effectively clean and restore soils contaminated mercury and other heavy metals [55,56]. There are approximately 250 plant species worldwide belonging to the genus *Chenopodium* of the family Chenopodiaceae, of which approximately 25 are recognized as weeds [57]. *C. album* is considered a potential candidate species for phytoremediation in a variety of environments with different nutrient contents [58] due to its remarkable adaptability and tolerance to extreme environmental conditions [59]. *S. salsa* is an annual herbaceous plant of the family Chenopodiaceae that is highly resistant to coastal tidal flats and heavy metal pollution, and is well adapted to saline soils [60,61]. The phytoremediation potential of halophytes is significant as they thrive in saline ecosystems and represent a cost-effective approach to combat metal pollution. These plants efficiently accumulate significant amounts of heavy metals, offering a sustainable solution for improving soil quality in contaminated areas [62]. White clover (*T. repens*) is the most commonly planted legume in temperate grasslands and can grow in a wide range of climatic conditions. It can also be used for phytoremediation of soils contaminated with heavy metals [63]. When properly managed, *T. repens* can establish itself in a variety of soil and climatic conditions; active growth from germinating seeds or existing plants begins at lower temperatures and higher moisture levels and continues until frost [64].

Table 2. Plant species used in the study.

Scientific name	Family	Genus
<i>Chenopodium album</i> L.	Chenopodiaceae	<i>Chenopodium</i>
<i>Suaeda salsa</i> L.	Chenopodiaceae	<i>Suaeda</i>
<i>Medicago sativa</i> L.	Fabaceae	<i>Medicago</i>
<i>Trifolium repens</i> L.	Fabaceae	<i>Trifolium</i>
<i>Dactylis glomerata</i> L.	Poaceae	<i>Dactylis</i>
<i>Brassica juncea</i> L.	Brassicaceae	<i>Brassica</i>
<i>Artemisia absinthium</i> L.	Asteraceae	<i>Artemisia</i>

Such selection was based on the wide distribution of these species in Central Kazakhstan and their adaptation to stressful conditions, limited vegetation conditions. These species represent different ecological groups and functional roles: dominants (*A. absinthium*, *S. salsa*), environment-forming (*M. sativa*, *T. repens*, *D. glomerata*), indicators (*C. album*, *B. juncea*).

2.2. Research Methods

2.2.1. Chemical Analysis of Heavy Metal in Soil Samples

Laboratory analysis of soil samples was performed to determine heavy metals. Soil samples were air-dried and subjected to standard preparation procedures for further analysis. Samples were

pre-ground and homogenized to a particle size of <200 mesh using a Pulverisette 2 (Frich, Germany). The concentrations of the following heavy metals Pb, Zn, Cu, Cr, Ni, As, Sr, Co, V in the prepared soil samples were analysed using a WEPER XRF2500 X-ray fluorescence spectrometer (Rigaku, Tokyo, Japan). Calibration was per-formed using standard protocols and reference materials. The concentrations of Cd and Hg were measured using an atomic absorption spectrometer (AAS, Shimadzu AA-7000, Kyoto, Japan). As a result, the concentrations of heavy metals were obtained in milligrams per kilogram (mg/kg) (Figure 5). Nutrient solutions containing the concentrations of selected heavy metals for the study were prepared.

2.2.2. Quality Assurance/Quality Control (QA/QC)

Procedural blanks (one per batch) and duplicate samples (every 10th sample) were analysed to monitor contamination and analytical precision. Certified reference materials (CRM) and calibration standards were measured with recoveries maintained between 95–105%. Limits of detection (LOD) were determined for key metals (Pb: 0.5 mg/kg, Zn: 0.2 mg/kg, Cu: 0.3 mg/kg, Cd: 0.01 mg/kg, Hg: 0.02 mg/kg), and values below LOD were sub-stituted with LOD/2 for statistical evaluation. Instrument calibration was verified daily for both XRF and AAS systems, and drift was checked every 20 samples to ensure analytical reliability.

2.2.3. Statistical Processing of Data

Seed germination was assessed as the percentage of germinated seeds per Petri dish; three Petri dishes for each treatment were considered biological replicates, from which the mean was calculated. Data were analysed using a two-way ANOVA (factors: heavy metal type × plant species), which allowed us to evaluate both the main effects of the factors and their interactions. Tukey’s post hoc test (HSD) was used for multiple comparisons at a significance level of $\alpha = 0.05$. Before conducting the analysis, the assumptions of normal distribution (Shapiro–Wilk test) and homogeneity of variances (Levene’s test) were checked. Percentage germination data were transformed using the arcsine square root to meet the assumptions of the ANOVA. Data visualization was performed using the Python programming language (v3.10).

2.2.4. Pre-Germination of Plants in Heavy Metal Concentrations

Local plants near the industrial zones of Central Kazakhstan (Table 2) were collected in October and November 2024. They were dried at room temperature for a week, and then the seeds were extracted. The seeds were peeled, disinfected with a 3% hydrogen peroxide solution for several minutes, and washed in distilled water. Filter paper was placed in each sterile Petri dish, and 20 seeds were placed in each dish. 5 ml of heavy metal solutions at the concentrations indicated above were added to each Petri dish. The experiment was repeated three times. In order to compare the results, this group of plants was grown in pure distilled water without the addition of heavy metals (control). The experiment lasted for 14 days. To account for evaporation, the heavy metal solution was added every 2 days for 2 weeks. The seeds were grown in a thermostat at a controlled temperature of 22 °C. Humidity, temperature, and lighting parameters were constantly monitored. Table 3 presents the solutions of heavy metal salts used in laboratory experiments on seed germination.

Table 3. Experimental conditions for the preparation of solutions of heavy metal salts of priority importance for Central Kazakhstan (concentration, volume, pH).

Metal	Salt	Working Concentrations (mg/L, solution)	Volume per dish	pH adjustment
Pb	Pb (NO ₃) ₂	1089.3	5 mL	not adjusted
Zn	ZnSO ₄ ·7H ₂ O	647.3	5 mL	not adjusted

Cu	CuSO ₄ ·5H ₂ O	376.3	5 mL	not adjusted
Cr	Cr ₂ (SO ₄) ₃	137.2	5 mL	not adjusted
Cd	CdSO ₄	12.6	5 mL	not adjusted
Ni	Ni (NO ₃) ₂	46.5	5 mL	not adjusted

The selection of working concentrations of metal salt solutions was based on con-tamination levels detected in soils from the industrial areas. Concentrations of all heavy metals exceed maximum permissible concentrations (MPC) [65].

Germination of plants at different concentrations of heavy metals (%), which indicates the proportion of germinated seeds out of the total number of seeds sown. The calculation was carried out according to the following formula:

$$GP\ (\%) = (N_{germ} / N_{total}) \times 100,$$
 (1)

where *N*_{germ} -is the number of germinated seeds, *N*_{total} -is the total number of seeds sown.

The cumulative dynamics of seed germination (%) represents the percentage of seeds germinated up to each observation day relative to the total number of seeds sown. The values were calculated using the following formula:

$$G_{cum,i}(\%) = (\sum_{k=1 \rightarrow i} N_k / N) \times 100,$$
 (2)

where *G*_{cum,i} - cumulative germination rate per day, *N*_k - number of seeds germinated per day, *N* - total number of seeds sow, $\sum_{k=1 \rightarrow i} N_k$ - sum of all germinated seeds from day 1 to day *i*.

The average plant height (cm) at heavy metal concentrations was measured on a specific observation day. Based on the data obtained, the average plant height was calculated using the following formula:

$$H_{avg} = (\sum H_i) / n,$$
 (3)

where *H*_{average} - average plant height (cm), *H*_{*i*} - height of each individual plant (cm), *n* - total number of plants measured in the group.

The plant growth inhibition index (%) at different concentrations of heavy metals indicates the degree of plant growth inhibition caused by heavy metals. It is calculated according to the following formula:

$$GI\ (\%) = ((H_{control} - H_{treat}) / H_{control}) \times 100,$$
 (4)

where *GI* is the growth inhibition index, expressed as a percentage, *H*_{control} is the average plant height in the control group (cm), *H*_{treat} is the average plant height in the experimental heavy metal concentration (cm).

3. Results

3.1. Concentrations of Heavy Metals in Soil

Figure 5 shows the concentrations of heavy metals (Pb, Cu, Zn, Sr, Cr, As, V, Ni, Cd, Co and Hg) in soil samples taken from the vicinity of production areas as a result of experimental studies. The vertical axis shows the concentration of heavy metals (mg/kg), and the horizontal axis shows the names of heavy metals. Blue columns indicate soil samples taken from five points on the territory of the Balkhash Ore and Metallurgical Plant (Balkhash), green columns indicate the Karaganda Metallurgical Plant (Temirtau), and red columns indicate soil samples taken from five points on the territory of the K. Satpayev Zhezkazgan Ore and Metallurgical Plant (Zhezkazgan).

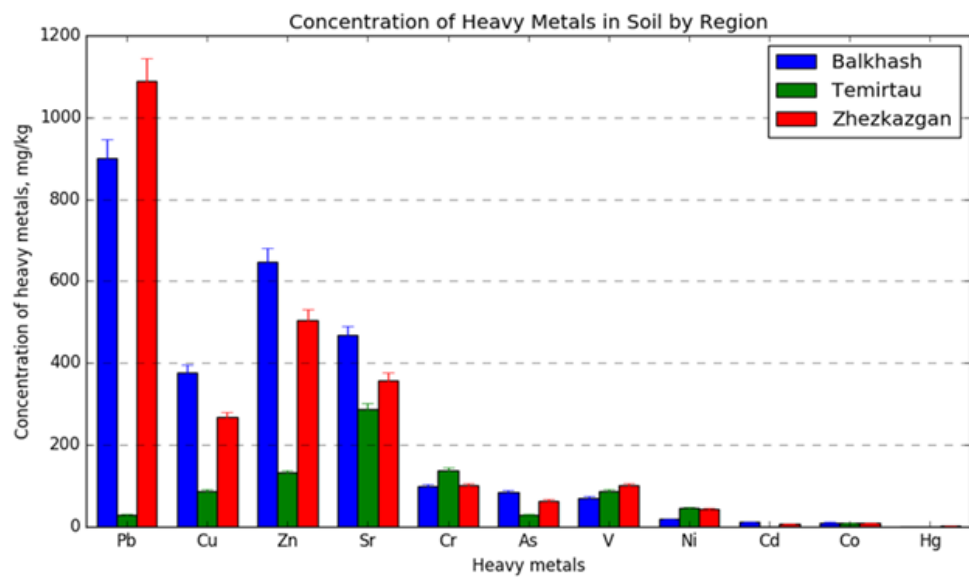


Figure 3. The amount of heavy metals in soil (mg/kg).

The following heavy metal concentrations with high concentrations in soil samples were selected for the experiment: lead (Pb) 1089.3 mg/kg; zinc (Zn) 647.3 mg/kg; copper (Cu) 376.3 mg/kg; chromium (Cr) 137.2 mg/kg; cadmium (Cd) 12.6 mg/kg; nickel (Ni) 46.5 mg/kg. Table 4 shows the assessment of the excess concentrations of these heavy metals in relation to the maximum permissible concentrations (MPC) [65]. Table 4 presents the comparison between maximum permissible concentrations (MPC) and measured concentrations (C) of heavy metals in soil.

Table 4. MPC values and exceedance factors of heavy metals in soil.

Metal	MPC (mg/kg)	Exceedance factor (C/MPC)
Lead (Pb)	32	34
Zinc (Zn)	23	28
Copper (Cu)	3	125
Chromium (Cr)	6	23
Cadmium (Cd)	0.5	25
Nickel (Ni)	4	12

3.2. The Effect of Heavy Metal Concentrations on Seed Germination

Figure 6 shows the germination percentage of four plant species—*B. juncea*, *C. album*, *D. glomerata* and *M. sativa*—in response to six heavy metals (Cd, Cu, Ni, Pb, Cr, Zn) and under control conditions (without the addition of metals). The effect on seed germination was assessed using the germination percentage—GP [66].

Each bar represents the mean germination percentage of three replicates (n = 3). Error bars indicate the standard deviation (SD) calculated individually for each treatment (metal × species). Overall, *D. glomerata* maintained the highest germination levels across metals, while *C. album* exhibited the strongest reduction. For example, *B. juncea* retained 95% germination under zinc exposure, whereas *C. album* dropped to 10% under chromium. The control group confirmed the natural germination potential in the absence of contaminants, with all species exceeding 90%.

Figure 7 shows the cumulative germination dynamics (%) of seeds of *B. juncea*, *D. glomerata*, *M. sativa* and *C. album* plants over a 14-day observation period.

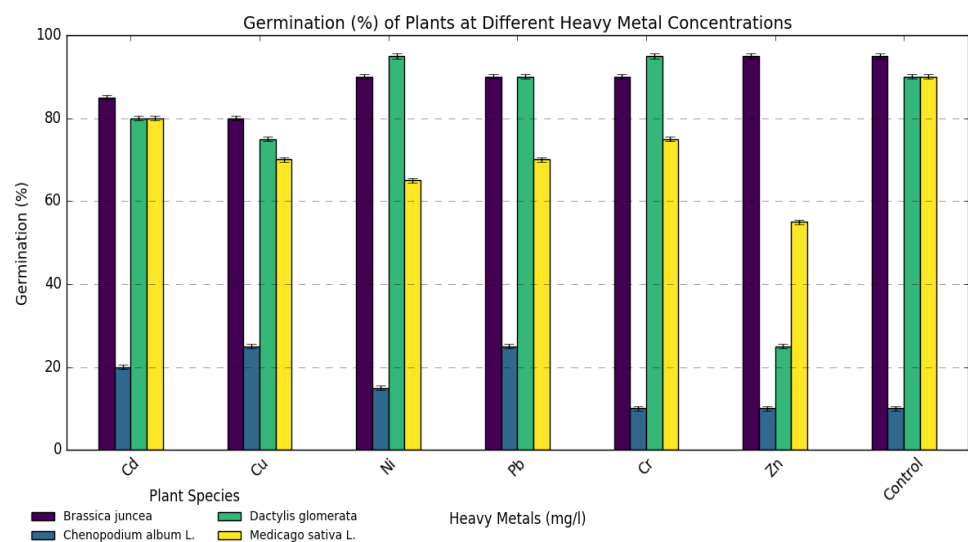


Figure 4. Plant germination (%) at different concentrations of heavy metals.

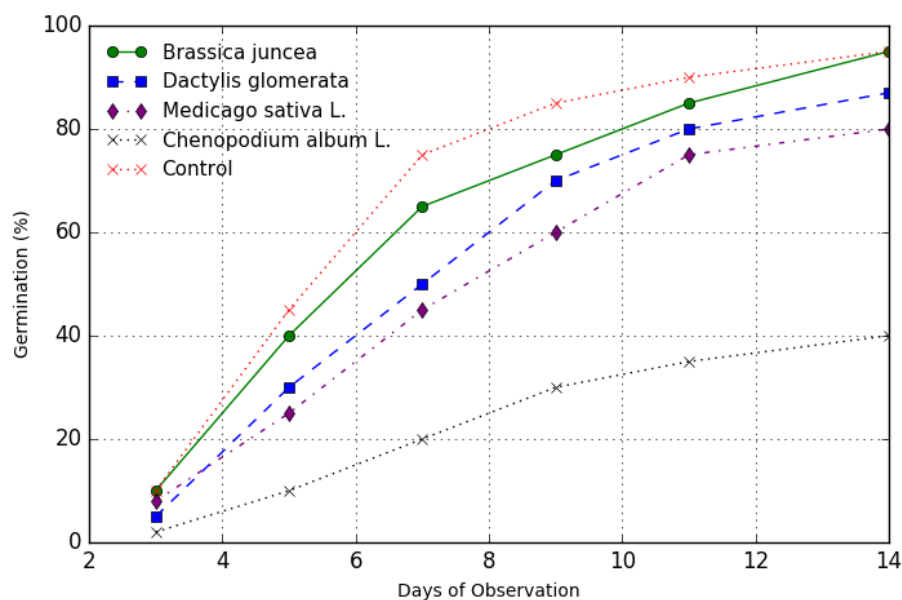


Figure 5. Cumulative germination (%) over 14 days.

Cumulative germination increments (%) revealed species-specific dynamics. The first shoots appeared on the 3rd day after sowing, and mass shoots on the 5th day. The control group (without the addition of heavy metals) showed maximum germination on the 14th day – 95%. The fastest and highest germination was observed in *B. juncea* which reached 95% on the 14th day. *D. glomerata* and *M. sativa* showed average germination rates of 80-85% on the 14th day. *C. album* showed the lowest germination rate, about 40% on the 14th day. This indicates differences in the tolerance and adaptation of the species to growing conditions.

3.2.1. Plant Growth Under the Influence of Heavy Metals

Figure 8 shows the bar graph shows the average height of four plant species *B. juncea*, *C. album*, *D. glomerata* and *M. sativa* exposed to heavy metals (Cd, Cu, Ni, Pb, Cr, Zn) compared to the control group.

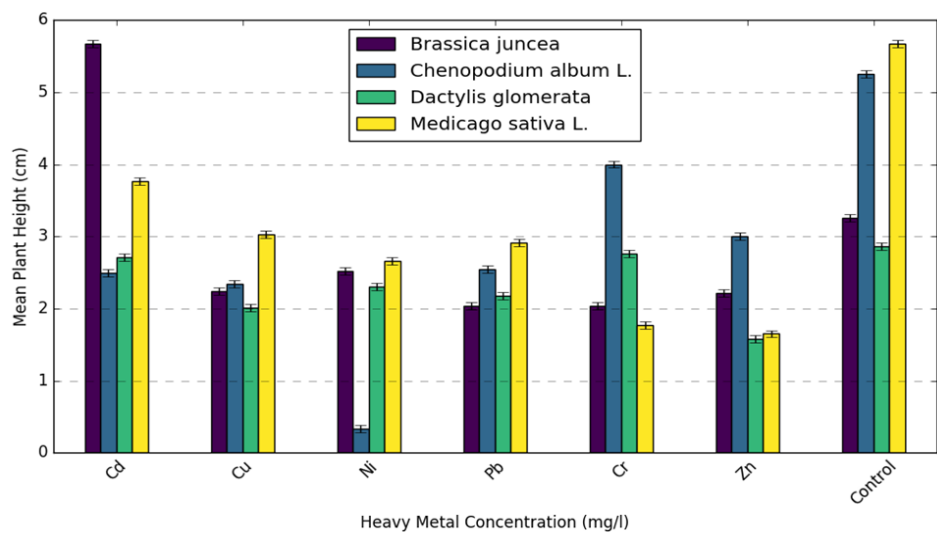


Figure 6. Average plant height (cm) at heavy metal concentrations.

Each column represents the mean plant height from three independent replicates measured on day 14 after sowing. Heavy metals inhibited plant growth to varying degrees. *B. juncea* showed the highest tolerance, reaching 5.67 cm under cadmium (Cd), while the lowest height was observed under lead (Pb). *M. sativa* reached 3.77 cm under cadmium, but showed the lowest value under zinc (Zn). *D. glomerata* had its maximum height of 1.58 cm under chromium (Cr), with the lowest under zinc (Zn). *C. album* reached 4 cm under chromium, but showed the lowest height under nickel (Ni). The control group demonstrated the highest values for all species, confirming the inhibitory effect of heavy metals on plant growth.

Figure 9 shows graphs of the plant growth inhibition index (%) for four plant species exposed to different concentrations of heavy metals (Cd, Ni, Cr, Cu, Zn, Pb). The growth inhibition index indicates the degree of toxicity of the solution.

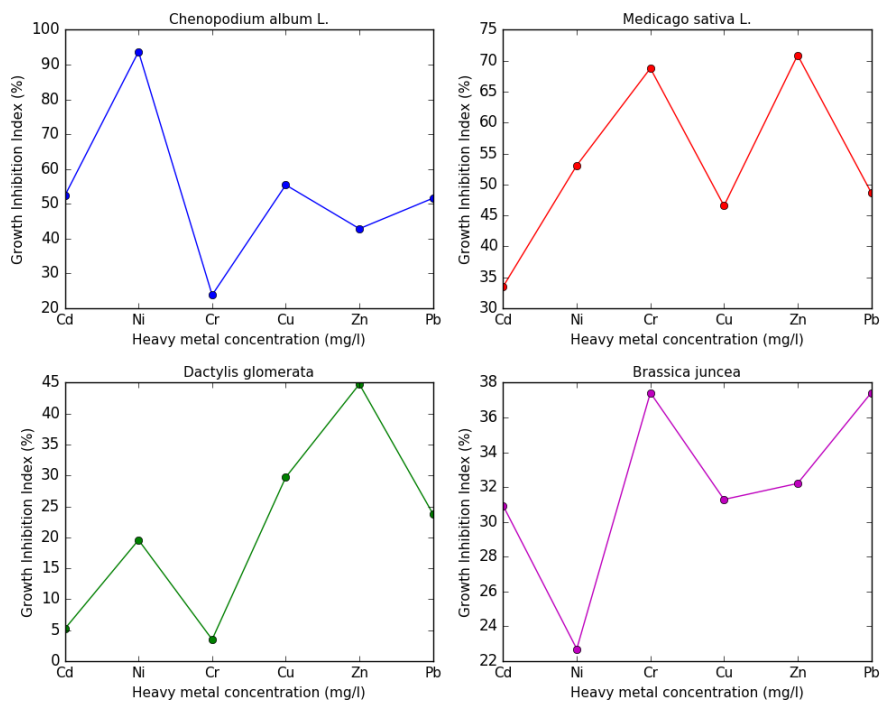


Figure 7. Plant growth inhibition index at different concentrations of heavy metals.

The growth inhibition index (GI, %) was calculated on day 14 after sowing, based on mean plant height from three independent replicates. In *C. album*, the strongest inhibitory effect was observed under Ni (94%), and the lowest under Cr (24%). In *M. sativa*, maximum inhibition occurred under Zn (71%) and Cr (69%), with the lowest under Cd (34%). In *D. glomerata*, the strongest inhibition was under Zn (45%), and the lowest under Cr (4%). In *B. juncea*, maximum inhibition was observed under Pb and Cr (37%), and the lowest under Ni (23%).

4. Discussion

The results provide data on the effects of heavy metals on seed germination and plant development parameters. Germination is one of the most important stages of the plant life cycle, as it represents the first contact with the environment [44]. Seed germination and seedling establishment are important stages of the entire plant growth cycle and are also the most sensitive period of plants to environmental changes [67,68]. Therefore, studying the inhibition of plants exposed to pollutants during this period is the best way to understand the mechanisms of toxicity of environmental pollutants to plants. Current research generally supports the use of native plant species for phytoremediation rather than exotic or genetically modified plants [69–72]. Indigenous species are typically better adapted to local climatic and edaphic conditions, which enhances their survival and remediation efficiency in contaminated environments. In recent years, numerous investigations have evaluated the phytoremediation potential of various native plant species growing in heavy metal-polluted soils [73–75].

B. juncea demonstrated the highest resistance to heavy metals among the studied species. The germination of this species under polluted conditions averaged approximately 89%, and the growth inhibition index remained below 38% in all cases. Relatively high resistance was observed when exposed to Zn (95%), Pb (90%), and Cr (90%) ions, indicating the potential ability of the plant to maintain viability at the germination stage. This resistance may be associated with mechanisms of metal hyperaccumulation and their localization in vacuoles. *B. juncea* is known as a fast-growing plant capable of forming significant biomass even in soils contaminated with heavy metals. Previous studies have widely documented its application in remediation research, especially regarding cadmium [76] and arsenic contamination [77]. *M. sativa* demonstrated relatively high tolerance to heavy metals, maintaining high germination and comparatively low inhibition. However, plant growth was significantly suppressed, especially when exposed to nickel and zinc (65% and 55%, respectively). Elevated zinc concentrations are known to suppress growth, induce chlorosis, and reduce photosynthetic activity due to metal toxicity [78]. Cadmium negatively affects germination and seedling establishment, leading to morphological and physiological abnormalities [79,80]. Chromium toxicity has also been shown to exert concentration-dependent detrimental effects on alfalfa development [52]. Additionally, *M. sativa* possesses the capacity to accumulate considerable amounts of nickel in plant tissues [81]. *D. glomerata* showed moderate sensitivity to heavy metals, but at 14 days after sowing, a 25% reduction in growth was observed when exposed to zinc compared to the control. Herbaceous species such as *D. glomerata* are often characterized by their ability to tolerate soil contamination, which may contribute to their effectiveness in phytostabilization processes [82]. *C. album* demonstrated the least tolerance to heavy metals among the studied species. At 14 days after sowing, plant growth was reduced by up to 10% when exposed to Cr and Zn. Despite its sensitivity, *C. album* has been reported to accumulate multiple heavy metals, including Cu, Fe, Mn, and Zn, from contaminated soils [83]. Previous studies indicated that both roots and shoots of *C. album* are capable of accumulating substantial concentrations of Cu and Mn, often exceeding levels detected in other plant species [84]. However, under multi-metal contamination conditions involving Cd, As, Pb, Cu, Zn, and Cr, metal accumulation in *C. album* may become selective, with preferential uptake of individual elements [85]. The obtained data indicate high sensitivity of *S. salsa*, *T. repens*, and *A. absinthium* to heavy metals. Germination of these species remained low at all concentration levels, and *S. salsa* and *T. repens* seedlings did not develop properly, leaving the question of their tolerance open. Further studies on contaminated soils are required to clarify the mechanisms of adaptation of

these species. Although several studies have examined heavy metal accumulation in *S. salsa* [86,87], information regarding its efficiency in reducing pollutant concentrations remains insufficient. Similarly, previous research involving *T. repens* has mainly focused on metal uptake processes and indicated predominant accumulation of heavy metals within root tissues [88–90]. Thus, a species-specific response to heavy metal toxicity is observed, where *B. juncea* can be considered as a potentially resistant indicator species, and *C. album* as a sensitive bioindicator of soil pollution. Identifying resistant plant species opens up opportunities for the biological remediation of contaminated sites. The practical significance of this study lies in the potential for preliminary selection of resistant species for remediation and bioindication of contaminated soils, including areas located near metallurgical plants. This study assessed only germination and early growth parameters. Metal uptake, plant biomass, and organ accumulation were not measured.

Unlike most published studies in Kazakhstan, which analyze one or two plant species or consider average levels of heavy metal pollution, this study combines seven local plant species and evaluates the inhibition index of their germination and growth when exposed to metal concentrations exceeding maximum permissible concentrations (MPC). This combination of the number of species, pollution level, and multiparameter approach (germination, growth, comparison with standards) is rare in studies of Central Kazakhstan. Further physiological studies of various plant species growing in toxic conditions could contribute to a deeper understanding of their biochemistry, defense strategies, and stress-coping mechanisms, as well as improve productivity. This will allow the identification of species resistant to pollution and their potential for restoration in heavily polluted areas.

5. Conclusions

Heavy metals were detected at almost all sampling points, regardless of distance, with heavy metal concentrations increasing in the order $Pb > Zn > Cu > Cr > Cd > Ni > As > Sr > Co > Hg > V$. Pb, Zn, Cu, Cr, Cd, and Ni showed the highest measured concentrations and the largest excess factors relative to the MPC (Table 4) and were therefore selected for the germination tests. The tests revealed species-specific differences in tolerance. *B. juncea* maintained relatively high germination percentages (GP 80–95%) and low growth inhibition indices (GI 38%), indicating relative tolerance at the germination stage. *S. salsa*, *T. repens* and *A. absinthium* did not germinate at any of the tested concentrations, reflecting high sensitivity. *C. album* demonstrated a marked delay in germination (GP 10%) and high growth inhibition indices (GI 94%). Germination results reveal a species-specific gradient of metal tolerance. *B. juncea* consistently demonstrated higher germination when exposed to various metals, confirming its suitability as a tolerance candidate for subsequent soil testing. In contrast, *C. album* exhibited marked germination sensitivity to several metals, suggesting its potential utility as a bioindicator for early screening (provided it is validated under soil conditions).

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