
RESEARCH ARTICLE

Multi-metal screening of candidate herbaceous plants for bioretention under preference uncertainty using SMAA–PROMETHEE II

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ABSTRACT

Aqueous-phase concentration reduction, accumulation in harvestable shoots, and root retention in bioretention systems may favor different plant species, whereas fixed criterion weights cannot represent uncertainty in management preferences. In pot experiments with four landscape herbaceous species, this study measured aqueous-phase concentration reduction and organ accumulation of Cd, Cu, Pb, and Zn in *Poa annua*, *Lolium perenne*, *Axonopus compressus*, and *Festuca arundinacea*. Four criteria were constructed: aqueous-phase concentration reduction, shoot accumulation, scenario-dependent root allocation, and a composite measure of cross-metal performance balance. The species were ranked using SMAA–PROMETHEE II with 100,000 sets of Dirichlet-distributed random weights. The species favored by aqueous-phase concentration reduction differed from those favored by tissue accumulation. Under the harvestable-shoot-accumulation scenario, *L. perenne* had a first-rank probability of 83.92%. Under the root-retention scenario, the first-rank probabilities of *L. perenne* and *P. annua* were 57.47% and 42.53%, respectively. Changes in preference thresholds and the structure of g4, as well as comparisons with equal-weight PROMETHEE II, TOPSIS, and VIKOR rankings, did not change the leading candidate, although probability distributions and lower ranks varied. The framework replaces a single fixed-weight ranking with a probabilistic account of candidate competition across management preferences and provides a transparent, reproducible basis for prioritizing subsequent validation and planting decisions under multi-metal exposure.

KEYWORDS

bioretention; multiple heavy metals; plant screening; SMAA–PROMETHEE II; rank acceptability probability; preference uncertainty

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1. Introduction

The expansion of urban impervious surfaces has made stormwater runoff an important pathway by which heavy metals enter receiving waters. Bioretention systems combine growing media, vegetation, and rhizosphere processes to retain runoff and reduce pollutant concentrations and are widely used as green infrastructure for low-impact development. Plants can alter water movement, rhizosphere conditions, and particle retention and may take up and accumulate metals in their tissues. However, a decline in effluent concentration is a system-level response of a planted unit and cannot be attributed directly to plant uptake. Media adsorption, precipitation, and surface retention may also contribute to aqueous-phase concentration reduction, so high reduction rates can coexist with low tissue accumulation (Chen et al., 2026; Grela et al., 2026). Comparisons among candidate plants should therefore distinguish water-treatment performance at the system level from metal accumulation in plant organs rather than combine them into an unverified mass balance.

Plant responses to metals vary among species, elements, and organs (Dradrach et al., 2024; Nuscis et al., 2026; Šotek et al., 2026). For management involving regular harvesting, the mass accumulated in harvestable shoots is more directly relevant than tissue concentration alone because accumulated mass depends on both concentration and biomass (Acharya et al., 2025; Huang et al., 2025). For management favoring in situ retention, the root accumulation mass fraction describes the distribution among organs at the experimental endpoint. It does not, however, substitute for evidence of long-term stability from measurements of metal bioavailability in the medium, leaching, or remobilization after root senescence. Studies of phytoremediation and green infrastructure commonly use bioconcentration factors, translocation factors, aqueous-phase reduction rates, or deterministic composite indices (Aarthi et al., 2026; Deng et al., 2025; Ni et al., 2025). These measures describe particular aspects of performance but do not readily address differences in scale among metals, conflicts between management objectives, and the lack of agreement on criterion weights.

Multi-criteria decision analysis provides a transparent way to organize these conflicting indicators, but fixed weights yield a ranking for only one assumed preference structure and may conceal the dependence of candidate comparisons on management priorities. Stochastic multicriteria acceptability analysis (SMAA) samples the feasible weight space and reports how often a candidate attains each rank (Lahdelma et al., 1998; Tervonen & Figueira, 2008). PROMETHEE II uses pairwise preferences and net flows to produce a complete ranking (Brans & Vincke, 1985). Their combination shifts the question from identifying a single leading candidate to identifying the range of preferences under which a candidate most often ranks first. When the inputs are treatment-level summary values, random-weight sampling propagates uncertainty in criterion preferences, not biological variability, analytical error, or the probability of engineering success.

Against this background, the present study examined *Poa annua*, *Lolium perenne*, *Axonopus compressus*, and *Festuca arundinacea*. Pot experiments provided information on aqueous-phase concentration reduction and organ accumulation of Cd, Cu, Pb, and Zn, which was then used for a multi-criteria evaluation under multiple metals and management objectives. We constructed four criteria covering aqueous-phase concentration reduction, accumulation in harvestable shoots, scenario-dependent root allocation, and a composite measure of cross-metal performance balance. Harvestable-shoot-accumulation and root-retention scenarios were evaluated using SMAA–PROMETHEE II to estimate rank acceptability and pairwise winning probabilities. Sensitivity to preference thresholds and criterion structure was assessed, and rankings were compared with equal-weight PROMETHEE II, TOPSIS, and VIKOR. The study asked whether different functional indicators favor the same species, how management preferences alter candidate competition, and whether the leading candidate is maintained under the tested parameter and model settings.

2. Materials and Methods

2.1 Study species and overall analytical framework

The study examined *Poa annua*, *Lolium perenne*, *Axonopus compressus*, and *Festuca arundinacea*. Pot experiments were used to evaluate aqueous-phase concentration reduction and metal accumulation in plant tissues under Cd, Cu, Pb, and Zn exposure. The resulting measurements were then incorporated into a multi-criteria evaluation spanning multiple metals and management objectives.

Two independent sets of pot experiments were conducted. The first evaluated aqueous-phase concentration reduction in artificial rainwater under the different planted treatments. The second characterized accumulation and allocation of Cd, Cu, Pb, and Zn between shoots and roots. The two classes of indicators were therefore integrated only at the species level to compare candidate priorities under different management objectives. They were not interpreted as a simultaneous heavy-metal mass balance within the same experimental unit.

The overall workflow comprised experimental measurement and compilation of indicators, criterion construction, within-metal normalization, scenario-specific criterion construction, SMAA–PROMETHEE II ranking under random weights, and sensitivity analyses of preference thresholds, criterion structure, and decision method (Fig. 1).

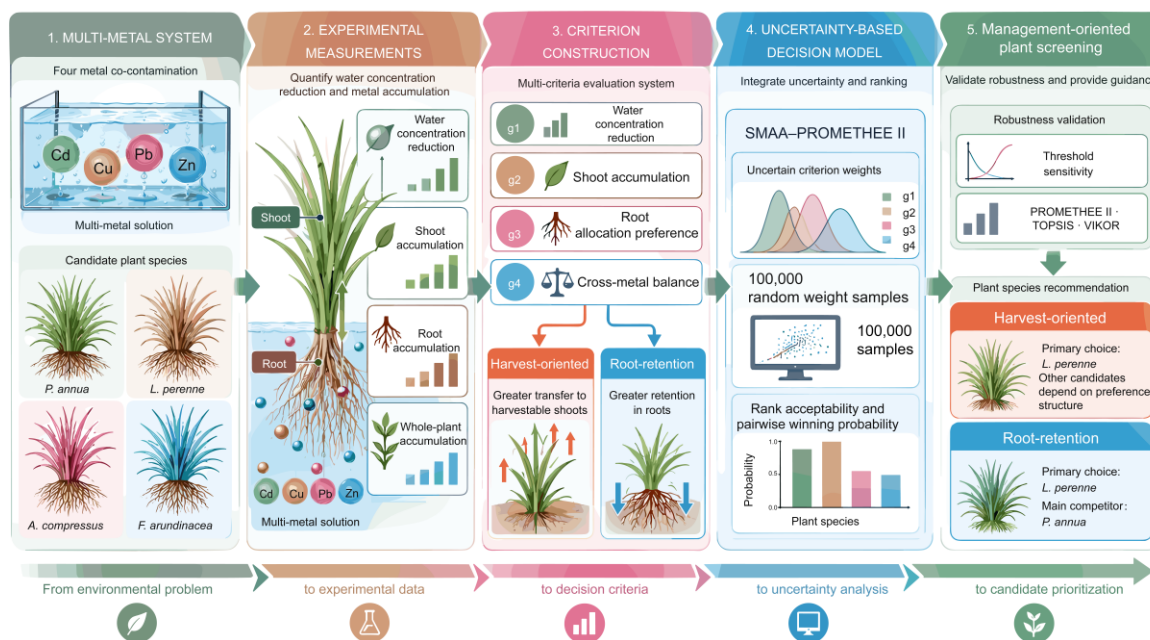


Fig. 1. Workflow for multi-metal screening of four herbaceous plant species. Evaluation criteria were constructed from aqueous-phase concentration reduction and tissue-accumulation data. Random-weight ranking, sensitivity analysis, and equal-weight method comparisons were then performed under harvestable-shoot-accumulation and root-retention scenarios. The plants and apparatus are conceptual illustrations; candidate outcomes indicate priorities for subsequent validation under the current criterion settings.

2.2 Plant cultivation and pot experiments

Seeds of the four herbaceous species were purchased from Zhongshu Dasenlin Flower Market near the east gate of the Beijing Academy of Agriculture and Forestry Sciences. The pot experiments were conducted in a glass greenhouse at the School of Environment, Beijing Normal University. For each treatment, 0.5 g of seeds was sown in a PVC pot 20 cm in diameter and 20 cm high. Approximately 4 cm of headspace was left at the top of each pot, and the seeds were covered with approximately 1 cm of growing medium. The four species were cultivated under the same conditions, with three replicate samples per treatment. Artificial rainwater applications began after approximately one month of stable plant growth. Ten applications were conducted, each supplying 1500 mL to each treatment.

Medium V was used as the growing medium. Its pH was 8.79; the mass fractions of sand and silt were 72% and 28%, respectively; organic matter content was 0.35%; cation-exchange capacity was 4.28 cmol·kg⁻¹; and infiltration rate was 1.1 cm·h⁻¹. In the aqueous-phase concentration-reduction experiment, the target concentrations of Cd, Cu, Pb, and Zn were 0.002, 0.017, 0.016, and 0.92 mg·L⁻¹, respectively. These concentrations were selected from runoff-monitoring information and the experimental design: the respective mean concentration levels were used for Cu, Pb, and Zn, and the respective maximum level was used for Cd. The plant-accumulation experiment alternated high and low metal concentrations: 0.02 and 0.2 mg·L⁻¹ for Cd and Cu, 0.05 and 0.5 mg·L⁻¹ for Pb, and 0.1 and 1.0 mg·L⁻¹ for Zn. Each application supplied 1500 mL, for a total of 10 applications. Because exposure concentrations differed between the two experiments, their indicators were combined only at the species level in the subsequent evaluation.

The aqueous-phase concentration-reduction and plant metal-accumulation experiments were conducted independently. The former yielded mean aqueous-phase concentration-reduction rates for Cd, Cu, Pb, and Zn under the planted pot treatments. The latter provided metal concentrations, biomass, and accumulated masses in shoots and roots. The two sets of summary results were not used to infer plant-uptake contributions or metal mass balances within the same experimental unit.

2.3 Plant sample preparation and metal determination

At the end of the experiment, plants were removed from the growing medium. Particles adhering to their surfaces were washed off first with tap water and then with deionized water three times; residual surface water was blotted with filter paper. Shoots and roots were separated with stainless-steel scissors and weighed fresh. The samples were then held at 105 °C for 30 min and dried at 70–80 °C for 48 h to constant mass, after which dry biomass was recorded.

For tissue metal analysis, 0.2000 g of dried plant material was placed in a digestion vessel. HNO₃ (66%; 2 mL) and H₂O₂ (30%; 1 mL) were added, and the mixture was left for 4 h before digestion at 140 °C for 5 h. After cooling, the digest was brought to a final volume of 10 mL for determination of Cd, Cu, Pb, and Zn concentrations.

Cd, Cu, Pb, and Zn concentrations in the digests and water samples were determined by inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Scientific iCAP 6000 Series).

2.4 Aqueous-phase concentration reduction and plant accumulation indicators

The aqueous-phase concentration-reduction rate for metal m under the pot treatment planted with species i was calculated using Eq. (1):

$$\eta_{im} = \frac{C_{in,m} - C_{out,im}}{C_{in,m}} \times 100\% \quad (1)$$

where $\eta_{i,m}$ is the aqueous-phase concentration-reduction rate for metal m under the pot treatment planted with species i , and $C_{in,m}$ and $C_{out,im}$ are the metal concentrations in the influent and corresponding treatment effluent, respectively. The equation describes a concentration-based indicator. It does not include influent or effluent volumes and therefore does not represent a reduction in metal mass load.

Metal accumulation in plant tissues was calculated as the product of metal concentration and the dry biomass of the corresponding organ:

$$A_{im}^S = c_{im}^S B_i^S \quad (2)$$

$$A_{im}^R = c_{im}^R B_i^R \quad (3)$$

$$A_{im}^T = A_{im}^S + A_{im}^R \quad (4)$$

where c_{im}^S and c_{im}^R are the metal concentrations in the shoots and roots, respectively; m denotes the metal; B_i^S and B_i^R are the corresponding organ dry biomasses; and A_{im}^S , A_{im}^R , and A_{im}^T are the accumulated metal masses in shoots, roots, and the whole plant, respectively. Accumulated masses are reported in μg throughout.

To describe the mass allocation of metals to roots, the root accumulation fraction was calculated as follows:

$$\rho_{im} = \frac{A_{im}^R}{A_{im}^T} \quad (5)$$

A higher ρ_{im} indicates that a larger fraction of the accumulated mass of the corresponding metal was allocated to roots at the experimental endpoint. This is an endpoint mass-allocation measure, not a conventional concentration-ratio translocation factor.

2.5 Within-metal normalization and construction of evaluation criteria

Because Cd, Cu, Pb, and Zn reduction rates and tissue accumulation have different numerical scales, direct summation across metals could allow high-magnitude indicators to dominate the evaluation. Each metal-specific indicator was therefore range-normalized across the four candidate species:

$$z_{im} = \frac{x_{im} - \min_i(x_{im})}{\max_i(x_{im}) - \min_i(x_{im})} \quad (6)$$

Here, x_{im} is the original indicator value for species i and metal m , and z_{im} is its normalized value. The normalized value indicates only the relative position among the four candidate species.

Four classes of evaluation criteria were constructed from aqueous-phase concentration reduction, tissue accumulation, and organ allocation. The aqueous-phase concentration-reduction criterion g_1 represents the combined reduction performance of the planted pot treatments across metals:

$$g_{1,i} = \text{mean}_{m \in \{\text{Cd}, \text{Cu}, \text{Zn}\}}(z_{im}^\eta) \quad (7)$$

Pb aqueous-phase concentration reduction was reported as 100.00% for all four planted treatments. At the reported precision, this indicator therefore could not distinguish among candidates and was excluded from the mean used to calculate g_1 . The shoot-accumulation criterion g_2 describes the capacity to accumulate multiple metals in harvestable tissue:

$$g_{2,i} = \text{mean}_m(z_{im}^S) \quad (8)$$

The four heavy metals were assigned equal weights within g_2 .

2.6 Harvestable-shoot-accumulation and root-retention scenarios

Two operational scenarios were constructed to examine how management preferences affect candidate rankings: one favoring accumulation in harvestable shoots and the other favoring retention in roots. Both are screening proxies based on endpoint accumulation data and do not demonstrate that phytoextraction or long-term phytostabilization has been achieved.

In the harvestable-shoot-accumulation scenario, greater shoot accumulation and a lower root accumulation mass fraction were considered more favorable for subsequent removal by harvesting. The root-allocation criterion was therefore defined as:

$$g_{3,i}^E = \text{mean}_m(1 - z_{im}^\rho) \quad (9)$$

In the root-retention scenario, a higher root accumulation mass fraction received a higher score:

$$g_{3,i}^S = \text{mean}_m(z_{im}^\rho) \quad (10)$$

Both scenarios used the same experimental inputs and differed only in the preference direction assigned to the root accumulation mass fraction. Shoot accumulation remained a benefit criterion in the root-retention scenario. This scenario thus represented a preference for root retention while retaining overall metal performance, rather than a model that minimizes shoot exposure.

A composite criterion of cross-metal performance balance was also constructed to assess how evenly each species performed across the metals. In the main model, the root-allocation component of g_4 was aligned with the relevant management objective. The following quantities were first calculated:

$$u_{im}^H = \frac{z_{im}^\eta + z_{im}^S + (1 - z_{im}^\rho)}{3}, u_{im}^R = \frac{z_{im}^\eta + z_{im}^S + z_{im}^\rho}{3} \quad (11)$$

The composite criterion was then defined as:

$$g_{4,i} = \frac{1}{1 + \frac{\text{SD}_{\text{pop}}(u_{im})}{\text{mean}(u_{im})}} \quad (12)$$

A higher g_4 indicates a more balanced overall response across metals. In the main model, g_4 was calculated separately using u values aligned with the harvestable-shoot-accumulation and root-retention objectives. Pb aqueous-phase concentration reduction did not vary among the four candidates; its normalized component was assigned a neutral value of 0.5 to avoid an undefined value from a zero range. Structural sensitivity analysis further examined three alternatives: the original uniformly directed g_4 , exclusion of the entire Pb metal-response component from g_4 , and removal of g_4 altogether. Because g_4 recombines underlying indicators, it is a composite criterion rather than an independent experimental measurement.

2.7 SMAA–PROMETHEE II multi-criteria evaluation

PROMETHEE II was used to compare the overall performance of the four candidate species under different combinations of criteria (Brans & Vincke, 1985). For any criterion j , the performance difference between candidates a and b was expressed as:

$$d_j(a, b) = g_j(a) - g_j(b) \quad (13)$$

A linear preference function with an indifference threshold was used:

$$P_j(a, b) = \begin{cases} 0, & d_j \leq q_j \\ \frac{d_j - q_j}{p_j - q_j}, & q_j < d_j < p_j \\ 1, & d_j \geq p_j \end{cases} \quad (14)$$

Under the baseline setting, the indifference threshold q_j and strict preference threshold p_j were set to 5% and 20%, respectively, of the range of the corresponding criterion among the four candidate species.

For a given weight vector $\mathbf{w} = (w_1, w_2, w_3, w_4)$ satisfying $w_j \geq 0$ and $\sum_{j=1}^4 w_j = 1$, the overall preference index of species a over species b was calculated as:

$$\pi(a, b) = \sum_{j=1}^4 w_j P_j(a, b) \quad (15)$$

The PROMETHEE II net flow was defined as:

$$\phi(a) = \frac{1}{n-1} \left[\sum_{b \neq a} \pi(a, b) - \sum_{b \neq a} \pi(b, a) \right] \quad (16)$$

Here, $n = 4$. A larger net flow indicates a higher overall ranking under the specified criterion weights.

2.8 Random weights and rank acceptability probabilities

To reduce the subjectivity of specifying a single weight vector in advance, the SMAA approach was applied (Lahdelma et al., 1998; Tervonen & Figueira, 2008). A Dirichlet(1,1,1,1) distribution was used to draw 100,000 jointly constrained weight vectors at random from the four-dimensional weight simplex, with the random seed fixed at 20260913. The four weights were not mutually independent, and each vector summed to 1.

For each random weight vector, the PROMETHEE II net flows and rankings of the four species were recalculated. The probability that species i attained rank r was defined as:

$$\beta_i^r = \frac{1}{T} \sum_{t=1}^T I[\text{rank}_i^{(t)} = r] \quad (17)$$

Here, $T = 100000$, and $I[\cdot]$ is the indicator function.

The pairwise winning probability between species was also calculated:

$$P_{ik} = \frac{1}{T} \sum_{t=1}^T I[\phi_i^{(t)} > \phi_k^{(t)}] \quad (18)$$

These probabilities are the frequencies with which a candidate attained a given rank or had a greater net flow than another candidate under the specified weight distribution. They describe uncertainty in preference weights only. They are neither confidence probabilities estimated from replicate experiments nor probabilities of long-term remediation or engineering success.

2.9 Sensitivity analysis and comparison of decision methods

Sensitivity to the PROMETHEE II preference thresholds was examined using three settings: Sensitive, Baseline, and Tolerant. Here, R_j denotes the range of criterion j among the four species. The Sensitive setting used $q_j = 0$ and $p_j = 0.10R_j$; the Baseline setting used $q_j = 0.05R_j$ and $p_j = 0.20R_j$; and the Tolerant setting used $q_j = 0.10R_j$ and $p_j = 0.40R_j$. Each setting was recalculated with the same random seed and number of draws.

Under equal weights for the four criteria, PROMETHEE II, TOPSIS, and VIKOR were each used to rank the candidates (Brans & Vincke, 1985; Hwang & Yoon, 1981; Opricovic & Tzeng, 2004). TOPSIS calculated relative closeness from Euclidean distances to the positive and negative ideal solutions (Hwang & Yoon, 1981). VIKOR ranked candidates using group utility, individual regret, and the composite index Q , with $v = 0.5$ (Opricovic & Tzeng, 2004). This comparison examined only whether algorithm choice altered the ranking under equal weights; it did not establish cross-algorithm robustness over the entire random-weight space. The VIKOR ranking was not interpreted as necessarily satisfying all compromise-solution conditions.

The multi-criteria evaluation used treatment-level summary values. Summary values were not treated as replicate-level observations for inferential comparisons among species. The 100,000 simulations represented preference-weight samples only and did not increase the experimental sample size. Structural sensitivity analyses compared the scenario-aligned g_4 of the main model, the original uniformly directed g_4 , removal of the entire Pb metal-response component from g_4 , and omission of g_4 ; all other parameters, the random seed, and the number of draws were held constant.

3. Results

3.1 Aqueous-phase concentration reduction by the four species

Aqueous-phase metal concentration reduction differed among the four planted pot treatments (Fig. 2). Cd reduction ranged from 92.37% to 100.00% and was highest under *L. perenne* (100.00%). Zn reduction ranged from 88.63% to 97.25% and was also highest under *L. perenne* (97.25%). Cu reduction ranged from 3.28% to 34.97%; the rates under *P. annua*, *L. perenne*, *A. compressus*, and *F. arundinacea* were 34.97%, 27.25%, 24.92%, and 3.28%, respectively. Pb aqueous-phase concentration reduction was reported as 100.00% under all four planted treatments and could not distinguish among candidates at the reported precision. These rates are system-level indicators for planted units and do not separate the contributions of plants and growing medium.

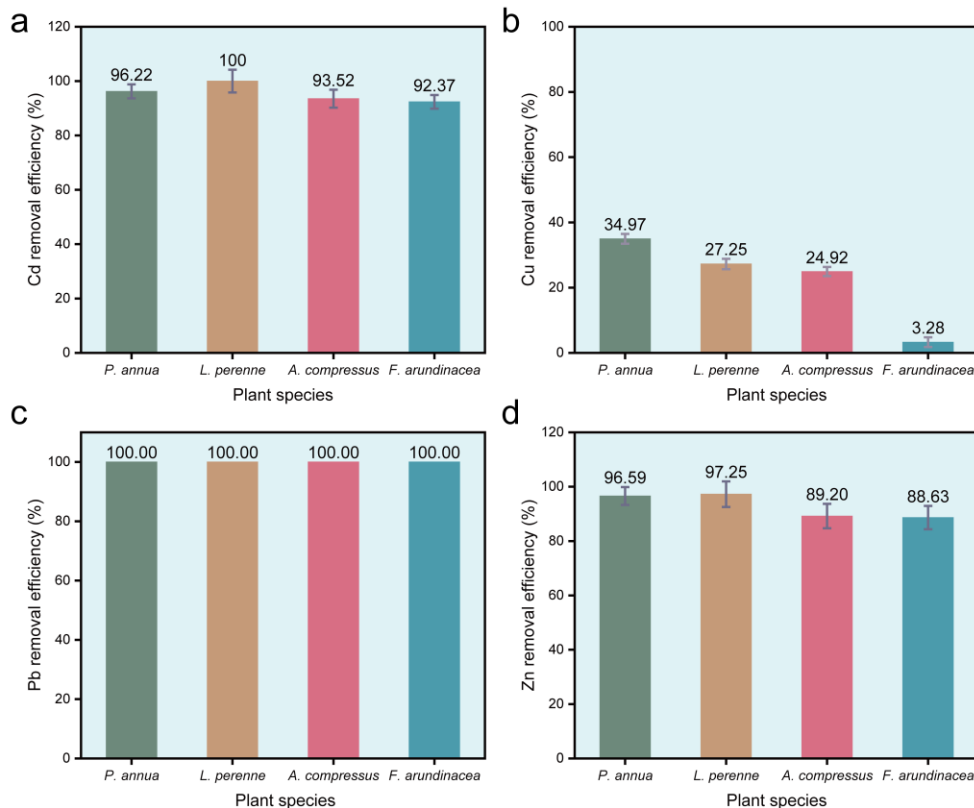


Fig. 2. Aqueous-phase concentration-reduction rates for Cd (a), Cu (b), Pb (c), and Zn (d) under the four herbaceous plant treatments. Each treatment had three replicate samples. Values are means of three replicates; error bars are shown as recorded in the original experimental data ($n = 3$).

3.2 Metal accumulation in plant tissues and organ allocation

Shoot, root, and whole-plant metal accumulation for the four species are shown in Fig. 3. Whole-plant Cd, Pb, and Zn accumulation was highest in *L. perenne*, at 36.47, 181.18, and 1741.91 μg , respectively. *A. compressus* had the highest whole-plant Cu accumulation (354.16 μg). Although the *P. annua* treatment had the highest aqueous-phase Cu reduction rate, its whole-plant Cu accumulation was only 216.22 μg , lower than that of the other three species. Thus, aqueous-phase reduction and tissue accumulation did not consistently favor the same species.

For shoot accumulation, *L. perenne* had the highest Cd mass (10.58 μg); *A. compressus* had the highest Cu and Zn masses (138.86 and 960.98 μg , respectively); and *F. arundinacea* had the highest Pb mass (111.24 μg). Root accumulation of Cd, Cu, Pb, and Zn was highest in *L. perenne*, at 25.88, 221.50, 73.54, and 1024.11 μg , respectively. In contrast, *P. annua* had the highest root accumulation mass fraction for all four metals. Absolute root accumulation and the root accumulation mass fraction therefore capture different properties.

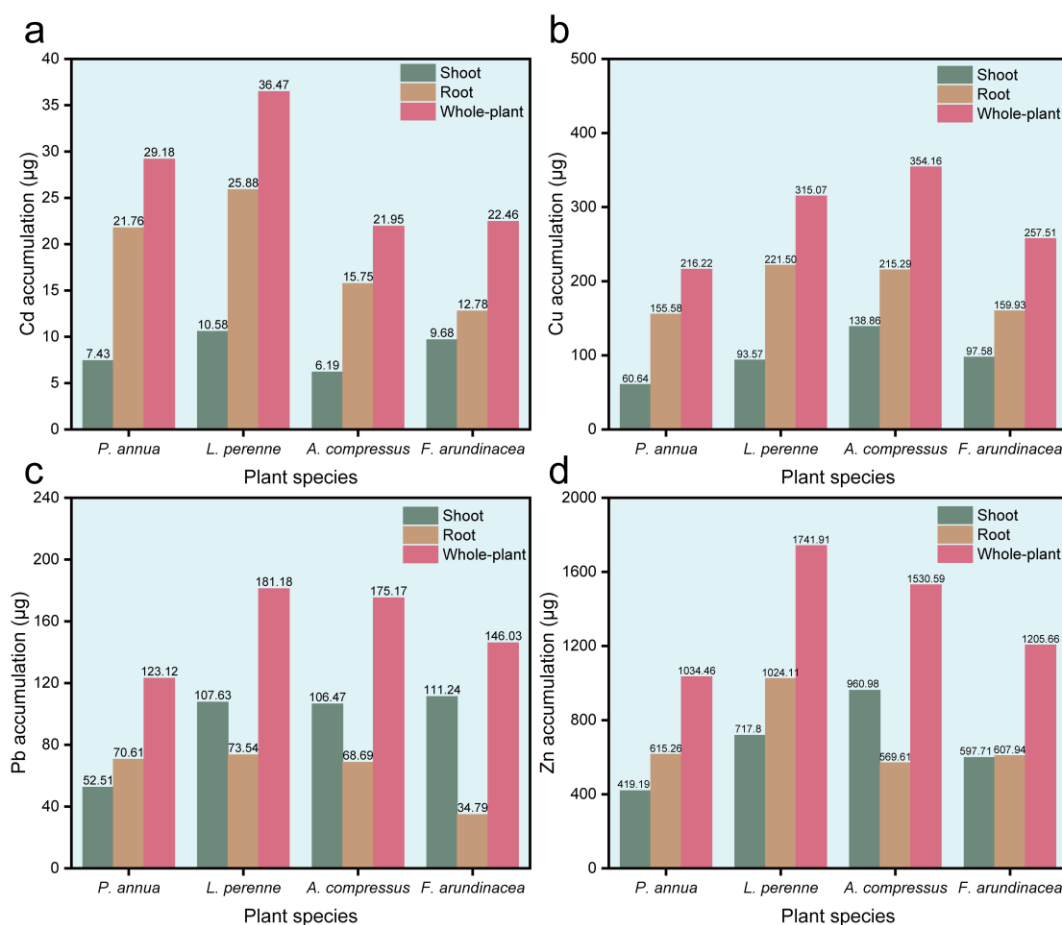


Fig. 3. Cd (a), Cu (b), Pb (c), and Zn (d) accumulation in shoots, roots, and whole plants of the four herbaceous species. Whole-plant accumulation is the sum of shoot and root accumulation and is expressed in μg .

3.3 Scenario-specific criteria and rank acceptability probabilities

Following within-metal normalization, the species showed different combinations of advantages (Fig. 4a,b). *L. perenne* had a score of 0.919 for the aqueous-phase concentration-reduction criterion g1 and 0.728 for the shoot-accumulation criterion g2. *A. compressus* had a similar g2 score (0.730) but a g1 score of only 0.300. Under the harvestable-shoot-accumulation scenario, g4 scores for *P. annua*, *L. perenne*, *A. compressus*, and *F. arundinacea* were 0.808, 0.840, 0.666, and 0.713, respectively; under the root-retention scenario, they were 0.904, 0.868, 0.786, and 0.738. The g1 score of 0 for *F. arundinacea* indicates only that it ranked lowest among the four candidates on each of the Cd, Cu, and Zn components included in that criterion; it does not mean that no aqueous-phase concentration reduction occurred.

In the main model, the first-rank probability of *L. perenne* under the harvestable-shoot-accumulation scenario was 83.92%. Corresponding probabilities for *P. annua*, *A. compressus*, and *F. arundinacea* were 0, 1.75%, and 14.32%, respectively (Fig. 4c). Under the root-retention scenario, *L. perenne* and *P. annua* had first-rank probabilities of 57.47% and 42.53%, respectively, whereas the other two species had probabilities of 0 (Fig. 4d). These probabilities represent the frequencies with which candidates attained the corresponding ranks in the symmetric Dirichlet preference-weight space.

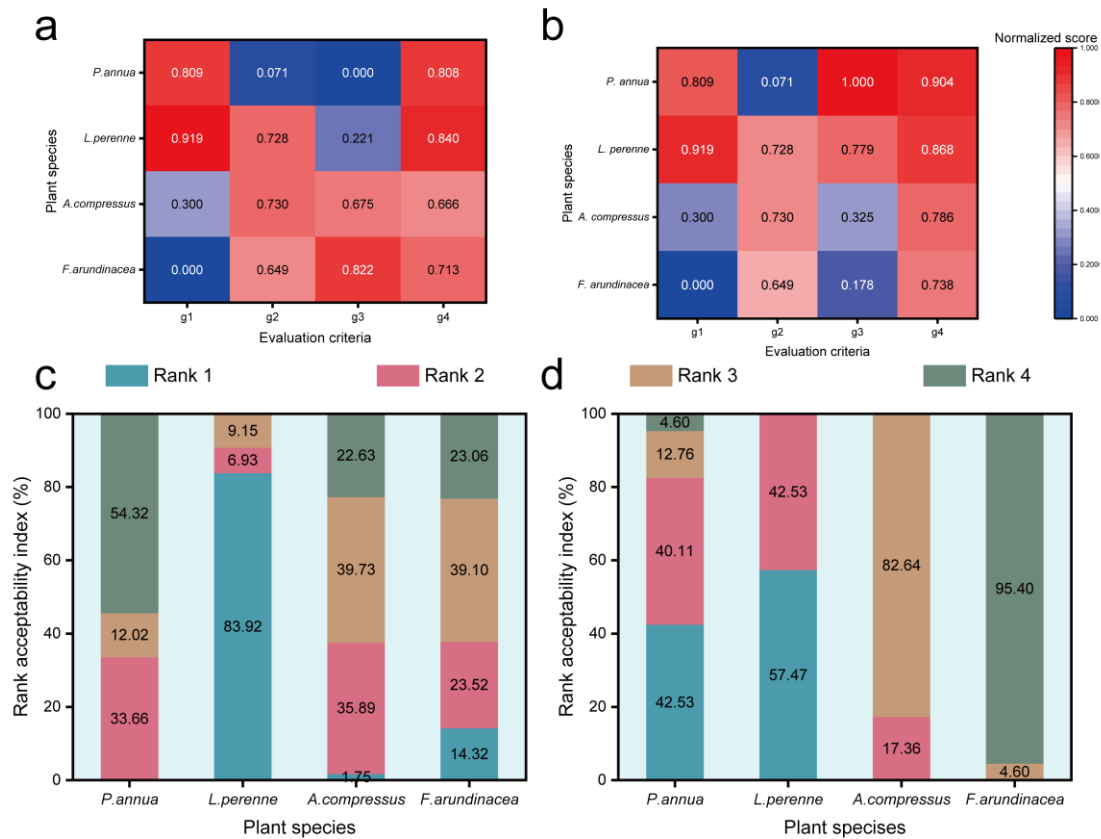


Fig. 4. Criterion scores and rank acceptability probabilities in the main model for the harvestable-shoot-accumulation (a,c) and root-retention (b,d) scenarios. Criteria g1–g4 represent aqueous-phase concentration reduction, shoot accumulation, scenario-dependent root allocation, and the composite criterion of cross-metal performance balance, respectively. The direction of root allocation within g3 and g4 is aligned with the corresponding management objective.

3.4 Pairwise winning probabilities and sensitivity to parameters and structure

Pairwise winning probabilities further characterized competition among candidates (Fig. 5a,b). Under the harvestable-shoot-accumulation scenario, the probabilities that *L. perenne* outranked *P. annua*, *A. compressus*, and *F. arundinacea* were 100.00%, 89.85%, and 84.93%, respectively. Under the root-retention scenario, *L. perenne* outranked *P. annua* with a probability of 57.47% and outranked both *A. compressus* and *F. arundinacea* with probabilities of 100.00%. These probabilities are frequencies of higher net flows under random weights; they are not pollutant-reduction rates, confidence probabilities, or probabilities of engineering success.

Across the three preference-threshold settings, the first-rank probability of *L. perenne* remained highest, ranging from 78.10% to 86.64% under the harvestable-shoot-accumulation scenario and from 57.47% to 68.29% under the root-retention scenario. The corresponding first-rank probability of *F. arundinacea* in the former scenario ranged from 10.68% to 16.45%, whereas that of *P. annua* in the latter ranged from 31.70% to 42.53%, making *P. annua* the main competitor of *L. perenne* in the root-retention scenario. Changes in the thresholds did not alter the leading candidate but changed the strength of candidate competition.

Structural sensitivity analysis tested the computational convention for g4. Under the harvestable-shoot-accumulation scenario, the first-rank probabilities of *L. perenne* were 83.92%, 69.22%, 68.23%, and 60.66% for the main model, the original uniformly directed g4, exclusion of the entire Pb response component from g4, and removal of g4, respectively. The corresponding values under the root-retention scenario were 57.47%, 57.47%, 57.47%, and 78.67%. The leading candidate was unchanged across these settings, but the probability distribution varied substantially, indicating some sensitivity of candidate competition to the structure of g4.

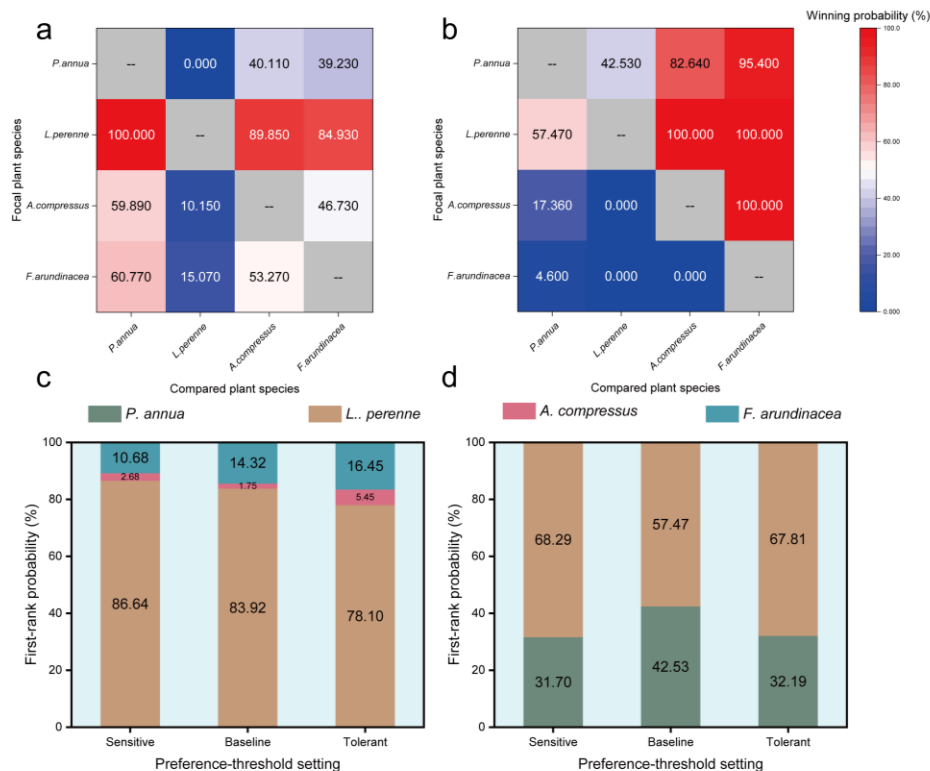


Fig. 5. Pairwise winning probabilities for harvestable-shoot accumulation (a) and root retention (b); first-rank probabilities across preference thresholds (c,d). Zero probabilities have no visible segment.

3.5 Comparison of rankings across decision methods

With equal weights for the four criteria, PROMETHEE II, TOPSIS, and VIKOR all ranked *L. perenne* first under both scenarios (Fig. 6). Under the harvestable-shoot-accumulation scenario, PROMETHEE II ranked *F. arundinacea* second, whereas TOPSIS and VIKOR ranked *A. compressus* second; *P. annua* ranked fourth under all three methods. The TOPSIS closeness values for *L. perenne* and *A. compressus* were 0.628309 and 0.621511, respectively. Under the root-retention scenario, all three methods produced the order *L. perenne*, *P. annua*, *A. compressus*, and *F. arundinacea*. Thus, the leading candidate remained the same across the tested equal-weight methods, whereas subsequent ranks under the harvestable-shoot-accumulation scenario depended on the algorithm.

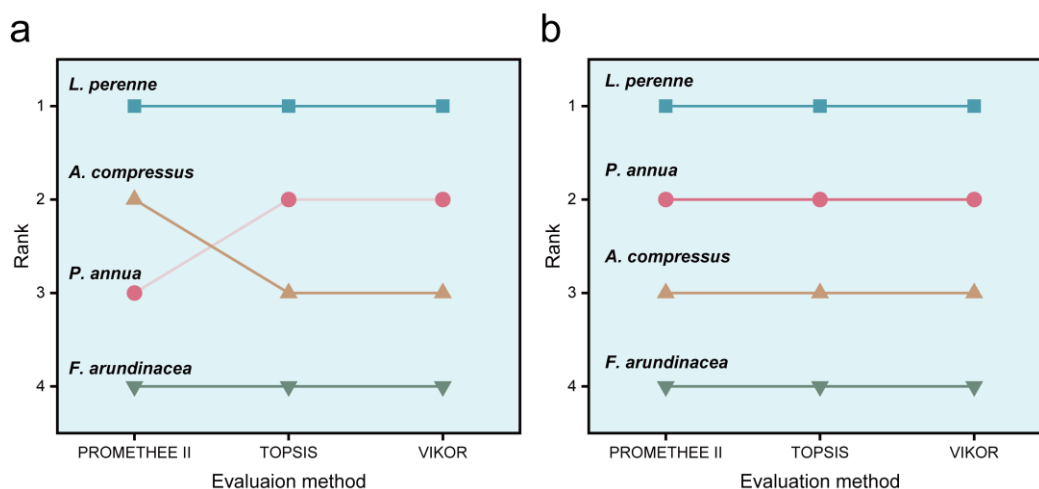


Fig. 6. Equal-weight PROMETHEE II, TOPSIS, and VIKOR rankings under the harvestable-shoot-accumulation (a) and root-retention (b) scenarios. Rank 1 denotes the highest overall ranking.

4. Discussion

4.1 Why aqueous-phase concentration reduction and tissue accumulation differ

High aqueous-phase concentration reduction in planted pots did not consistently correspond to high tissue accumulation. The *P. annua* treatment had the highest Cu reduction rate, whereas *A. compressus* had the highest whole-plant Cu accumulation. Pb reduction did not differ among the planted treatments, although organ accumulation varied by species. Medium V had a pH of 8.79, and media adsorption, precipitation, and retention on root surfaces may also have contributed to aqueous-phase concentration reduction (Chen et al., 2026; Grela et al., 2026). Because the two datasets came from independent experiments with different exposure concentrations, this study cannot quantify the contribution of plant uptake to aqueous-phase reduction or establish a metal mass balance. Aqueous-phase reduction and organ accumulation should be treated as complementary, not interchangeable, screening evidence.

Metal mass accumulated in an organ depends on both tissue concentration and dry biomass. Comparing concentrations alone may underestimate the accumulated load in high-biomass candidates, whereas comparing whole-plant masses alone obscures the management distinction between harvestable shoots and belowground roots (Acharya et al., 2025; Huang et al., 2025). The model therefore retained both shoot accumulation and the root accumulation mass fraction. The latter describes only organ allocation at the experimental endpoint. It is not a conventional concentration-ratio translocation factor and does not demonstrate long-term metal immobilization.

4.2 How management preferences alter candidate competition

L. perenne occupied the largest first-rank preference region under both management scenarios because it scored relatively highly on aqueous-phase concentration reduction and shoot accumulation. Under the harvestable-shoot-accumulation scenario, its first-rank probability was 83.92%, although *F. arundinacea* and *A. compressus* ranked first under some weight combinations. The three equal-weight methods did not fully agree on the second-ranked species. Under the root-retention scenario, the first-rank probability of *P. annua* rose to 42.53%, indicating that stronger preference for root allocation increased its competitiveness. These results define objective-dependent priorities for subsequent validation rather than a species ranking independent of management strategy.

Moving from ranking to engineering deployment requires a second stage of validation. Candidates should at least be assessed for tolerance to alternating wet and dry periods and to flooding and drought; biomass recovery and repeated harvesting; root effects on hydraulic conductivity; maintenance and disposal of contaminated biomass; and long-term metal bioavailability and leaching risks. The present results can narrow the set of experimental candidates but cannot, on their own, determine a field planting combination.

4.3 Interpretation of model probabilities and sensitivity tests

Dirichlet sampling represents the preference space arising when decision-makers lack a single agreed set of criterion weights; experimental inputs remain treatment-level summaries. Changes in preference thresholds, the original uniformly directed g4, exclusion of Pb from g4, and removal of g4 did not alter the leading candidate. All three equal-weight methods also ranked *L. perenne* first. Nevertheless, under the harvestable-shoot-accumulation scenario, its first-rank probability ranged from 60.66% to 83.92% across g4 structures, and lower ranks could change with the algorithm. The leading candidate was therefore maintained under the tested model settings, but the strength of competition remained somewhat sensitive to model structure.

4.4 Study boundaries and further validation

The study has three main limitations. First, aqueous-phase concentration reduction and tissue accumulation came from two independent experiments, and the model used treatment-level summaries without propagating replicate-level biological variation or analytical error. Second, g4 recombines components related to g1–g3 and may therefore repeat information, even though the leading candidate was unchanged in the structural sensitivity tests; equal weighting of metals is not equivalent to risk-based weighting. Third, min–max normalization depends on the current four candidates and Medium V. Adding species or changing the medium or pollutant loading may alter relative scores. Root retention also does not establish long-term phytostabilization and requires further tests of metal bioavailability in the medium, leaching, root turnover, and repeated harvesting (Khan et al., 2024; Kuang et al., 2025). Future work should obtain replicate-level raw data, propagate experimental and preference uncertainty jointly, and conduct independent pot, column, and field-threshold validation.

5. Conclusions

(1) The four planted pot treatments did not have the same advantages in aqueous-phase concentration reduction, whole-plant accumulation, and accumulation in harvestable shoots. The *P. annua* treatment had the highest aqueous-phase Cu reduction rate, *A. compressus* had the highest whole-plant Cu accumulation, and *L. perenne* had the highest whole-plant Cd, Pb, and Zn accumulation. Candidate screening should therefore distinguish system-level treatment performance from accumulation in plant organs.

(2) For the current candidate set, scenario-aligned g4 main model, and symmetric random-weight setting, the first-rank probabilities of *L. perenne* were 83.92% under the harvestable-shoot-accumulation scenario and 57.47% under the root-retention scenario, giving it a high priority for subsequent validation. *P. annua* had a first-rank probability of 42.53% under the root-retention scenario and was its main competing candidate.

(3) Varying preference thresholds, using the original uniformly directed g4, excluding Pb from g4, and removing g4 did not change the leading candidate. Three equal-weight algorithms also ranked *L. perenne* first. However, probability distributions and lower ranks changed across model settings. SMAA results should be interpreted as candidate competition in preference-weight space, not as probabilities of experimental or engineering success.

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