

Multivariate evaluation of the influence of soil perturbation on REE distribution and accumulation patterns in plants

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ABSTRACT

The demand for Rare Earth Elements (REE) is rapidly increasing due to their widespread use in advanced technologies, making them emerging environmental contaminants. Although non-essential for plants, REE can accumulate in plant tissues and transfer through trophic levels, raising questions about how plants respond to changes in soil REE composition. This study investigates the effect of soil REE perturbation on their accumulation and distribution in *Vitis vinifera* L. To this end, a full factorial (3^2) experimental design was implemented, combining three levels of treatment (control, low, high) with three sampling positions (soil, roots, leaves). The contribution of treatment, position, and their interaction was assessed using ANOVA–Simultaneous Component Analysis (ASCA) with permutation-based significance testing. The consistency of the inferred results was evaluated across different data processing strategies. First, inter-individual dispersion among experimental replicates was minimized through an orthogonal projection. Second, a dedicated ASCA without soil samples was performed to highlight if the significance of the position effect was driven by the artificial addition of REE. Results showed that treatment was the main driver of REE accumulation. Notably, the interaction between treatment and position explained more variance than position alone, indicating that REE distribution across compartments is modulated by soil enrichment level. The proposed approach offers a robust framework for investigating complex soil–plant interactions and supports targeted sampling strategies for field-based REE monitoring.

1. Introduction

Rare Earth Elements (REE), including the lanthanides and yttrium, are critical for numerous advanced technologies due to their unique chemical and physical properties. Often referred to as “industrial vitamins” [1–3], REE are widely used in clean energy (e.g., Nd, Dy, Sm, Gd, and Tb in magnets and solar cells), defense (e.g., Nd, La, Eu, Y, and Tb in engines and guidance systems), electronics (e.g., Eu, La, Lu, Y), medical imaging (e.g., Gd), and coatings (e.g., Y, La, Ce, Pr, Nd) [4–8]. Global REE demand is projected to increase by up to 30% by 2040 for clean energy alone, driven by the rapid expansion of renewable energy and electric mobility sectors, with Nd and Dy expected to rise by 700% and 2600%, respectively [9]. Meanwhile, REE mine production has tripled between 2017 and 2023 [10]. This rapid growth has raised increasing

environmental concerns, particularly regarding the dispersion of REE into natural ecosystems [11–14]. Concerns about potential REE contamination are not related only to the disposal of industrial production and electronic waste, but also to agricultural practices. Indeed, elements such as La, Ce, Nd, Sm, Eu, and Tb are applied as micro-fertilizers and animal feed additives and may also reach soils as impurities in phosphate fertilizers and soil amendments, altering natural soil REE profiles [5,15,16]. As a result, REE which were once primarily associated with mining pollution, are now recognized as emerging environmental contaminants [15–18].

Although REE seem to be non-essential for plants, they can reach plant tissues and potentially bioaccumulate along the food chain, raising concerns about their ecological and health impact [19–22]. However, systematic investigations into plant responses under modifications of

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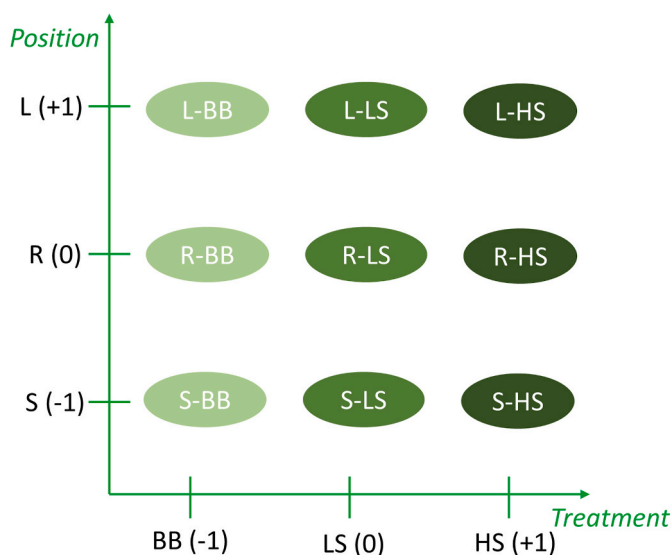


Fig. 1. Scheme representing the full factorial 3^2 experimental plan carried out and the mathematical codification of the levels in $-1/0/+1$. In particular, the following abbreviations are used: L = leaves, R = roots, S = soil represent the three levels of factor position; BB = control (not stressed), LS = low stressed, HS = high stressed, represent the three levels of factor treatment.

soil REE content remain limited. Indeed, most studies have been conducted under hydroponic conditions [23,24], which do not reflect biotic and abiotic effects of natural soils [25,26]. On the other hand, some studies have relied on commercial REE mixtures for agricultural use but including only a subset of REE [27,28]. Therefore, an extension to real environmental conditions is critical to ensure a comprehensive understanding of the issue. In addition, interpreting REE mobility in soil/plant systems is complicated by the natural disparity in REE abundances: light REE (LREE, from La to Gd) are typically much more prevalent than heavy REE (HREE, from Tb to Lu plus Y), with soil concentrations ranging from a few μgkg^{-1} (e.g., Lu) to several mgkg^{-1} (e.g., Ce), and the characteristic ‘zig zag’ trend is retained along the whole series [22,29,30]. To address such complexity, chemometric strategies, particularly Multivariate Design of Experiment (MDoE) based approaches, offer powerful tools for determining the effects of multiple interacting variables [31]. Indeed, MDoE systematically varies the levels of two or more factors to assess their influence on one or more response variables. This approach is particularly valuable when working with natural samples, which often present high inter-individual variability that may obscure relevant patterns [32]. Despite its widespread application in analytical chemistry and industrial optimisation, MDoE based approaches have rarely been applied to REE-related studies in environmental matrices. Previous works have focused mostly on optimizing REE extraction or recovery processes [33–35], while its potential to investigate REE bioaccumulation in plants remains largely unexplored.

The aim of this study is to evaluate how artificial perturbation of REE content in soil influences REE accumulation patterns in plants, with particular attention to differences in biological uptake across plant compartments. To this end, *Vitis vinifera* L. was selected as a model specie and cultivated in soils amended with an equimolar REE solution. To understand plant uptake preferences depending on REE availability, an experimental plan, inspired by MDoE [31], was implemented with two factors studied at three levels, namely: REE treatment (control, low, and high enrichment) and sampling position (soil, roots, leaves). The significance of those factors was assessed using ANOVA – Simultaneous Component Analysis (ASCA) [36] enabling the multivariate decomposition among factors and their interactions. Notice that, for each treatment level, 19 independent plants were analysed and, as each plant represents a distinct biological individual, a random factor nested within

treatment was included in the ASCA model to account for the inherent inter-individual variability.

2. Materials and methods

2.1. Experimental plan

For studying the effect of the artificial addition of REE on natural systems, *Vitis vinifera* L. was chosen as a model organism. Indeed, it is considered one of the most important fruit species [37] and it is globally cultivated for food production, with over 7 million hectares cultivated across diverse soils and climates [37–39]. One year-old *Vitis vinifera* L. plants were acquired from a nursery and transplanted into off-soil pots and located in a field of the Department of Agricultural, Food and Forestry Science (University of Palermo, Italy). Here they were exposed to atmospheric agents (i.e. rain, wind) and irrigation was supplied using a micro-irrigation system without phytosanitary treatments. A full factorial design [40], which consists in analyzing all the combinations between the levels of the factors, was chosen to obtain a representative evaluation of the whole experimental domain [41]. Fig. 1 shows the experimental plan focused on two factors, namely treatment and position, each in three levels (3^2 full factorial design). Notice that 19 plants were grown for each level of the factor treatment, for a total of 57 plants; in this context plants can be considered as experimental replicates of the same condition. At full vegetative development stage, soil, roots and leaves, corresponding to the levels of the factor position, were sampled and REE concentrations were determined.

The levels of the position factor correspond to the accumulation points of REE in soil and plant compartment:

- soil (=S, -1).
- roots (=R, 0).
- leaves (=L, $+1$).

The levels of the treatment factor correspond to the artificial perturbation of REE soil content and the natural soil.

- control (=BB, -1).
- low stressed (=LS, 0).
- high stressed (=HS, $+1$).

The control level corresponds to the natural state, with no addition to the soil, and serves as a reference. The LS level was carried out by adding 1 mmol kg^{-1} of the equimolar REE solution to the soil, while the HS level involved the addition of 10 mmol kg^{-1} . A multi-element equimolar REE solution was chosen to enable the assessment of REE behaviour independently of natural abundance disparities, which typically vary across the series [25]. In particular, the solution was prepared by dilution in ultrapure water of a standard stock solution containing 1000 mgL^{-1} of the following elements: Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. Concentrated REE solutions were used (1 mmol kg^{-1} , 10 mmol kg^{-1}) to enrich control soil considering potential dilution or leaching effects due to atmospheric exposure (e.g., rainfall, irrigation) throughout the experiment. This strategy allowed for reaching REE concentrations comparable to those found in natural soils [42,43], while maintaining full control over the relative distribution of REE through equimolar dosing.

2.2. Determination of REE concentration

Ultrapure nitric acid (HNO_3 , 65%) and hydrogen peroxide (H_2O_2 , 30%) (Merck, Milan, Italy) were used for all digestions. A certified multi-element standard solution ($1000 \pm 5 \text{ mgL}^{-1}$) containing REE, and rhenium (Re) as an internal standard were obtained from BDH International (East Yorkshire, UK) and CPI International (Santa Rosa, CA, USA). Ultrapure water ($18.2 \text{ M}\Omega \text{ cm}$) was produced using an EASYpureII

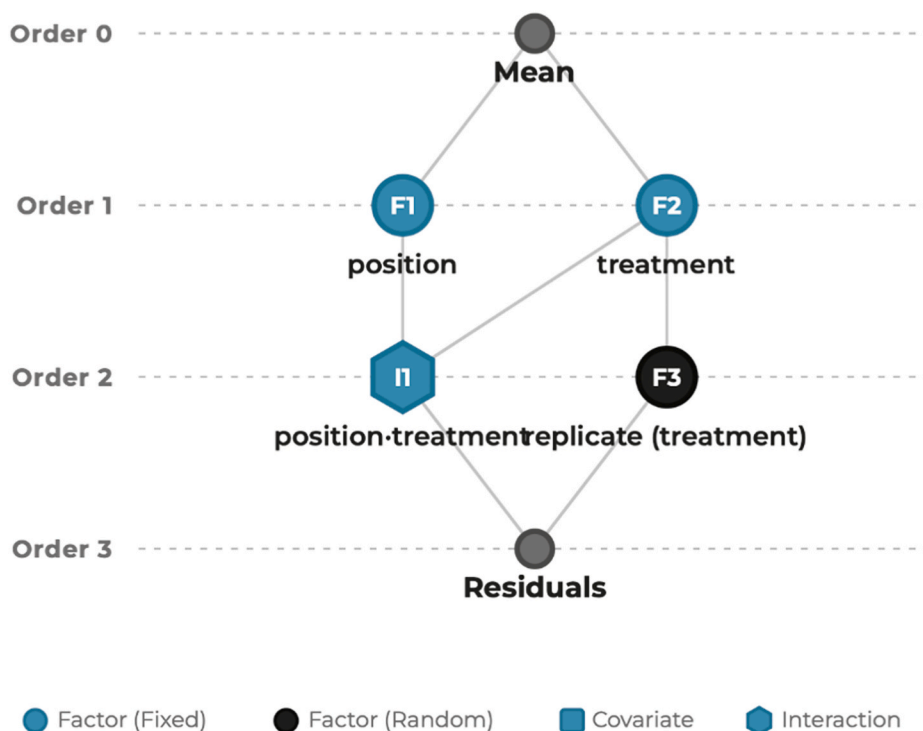


Fig. 2. Hasse diagram of the model structure. Nodes are factors (circles) and interactions (hexagons), arranged by interaction order from the overall mean (top) to the residuals (bottom).

ion-exchange system (Thermo, Milan, Italy). Samples were oven-dried at 105°C, gently crushed, and sieved to a particle size of <0.5 mm. Aliquots of 250 mg for soil and roots, and of 500 mg for leaves, were transferred to PFA microwave digestion vessels and digested in a closed Mars Xpress microwave system (CEM, Bergamo, Italy) using 4.5 mL of a 2:1 (v/v) HNO₃:H₂O₂ mixture. The temperature program consisted of a ramp from 20°C to 200°C, lasting 10 min, followed by a 50-min hold at 200°C. After digestion, samples were quantitatively transferred to graduated polypropylene tubes and diluted with ultrapure water to a final volume of 10 mL (leaves) or 100 mL (soils and roots). Procedural blanks were prepared using ultrapure water.

REE concentrations were determined using an Agilent Technologies 7500ce ICP-MS (Santa Clara, CA, USA), monitoring the isotopes ¹³⁹La, ¹⁴⁰Ce, ¹⁴¹Pr, ¹⁴⁶Nd, ¹⁴⁷Sm, ¹⁵¹Eu, ¹⁵⁸Gd, ¹⁵⁹Tb, ¹⁶³Dy, ¹⁶⁵Ho, ¹⁶⁷Er, ¹⁶⁹Tm, ¹⁷²Yb, ¹⁷⁵Lu, and ⁸⁹Y. Spectrometer conditions were as follows: power 1550 W, nebuliser gas flow 1.00 Lmin⁻¹, auxiliary gas flow 0.85 Lmin⁻¹, and plasma gas flow 15 Lmin⁻¹. The acquisition time for each determination was 180 s. Instrument performance was optimised using a tuning solution containing ⁷Li, ⁵⁹Co, ⁸⁹Y, ¹⁴⁰Ce, and ²⁰⁵Tl, achieving a precision of ≤2%. Oxide (CeO⁺/Ce⁺) and doubly charged ion (Ce²⁺/Ce⁺) interferences were monitored and maintained below 0.5%. Data quality assurance followed the procedures outlined by Barbera et al., 2023, 2025 [44,45].

2.3. Data processing

Data preprocessing, orthogonalization, and the generation of the REE distribution profiles were performed in MATLAB (MathWorks, Natick, MA, USA) using in-house developed routines. ASCA was then carried out using DathaSuite [46], and the corresponding score, loading, and Hasse diagrams were generated using the same software.

2.3.1. Data preprocessing

For each experimental point, 3 analytical replicates were carried out, thus adding up to a total of 513 REE determinations (19 plants * 3² full factorial design * 3 analytical replicates). The three replicates were

averaged obtaining the initial data matrix (171x15), containing as many rows as the number of samples (171 = 19 plants * 3² full factorial design) and as many columns as the number of REE concentrations (15). Given the wide concentration range observed across treatments and elements, a base-10 logarithmic transformation was applied, as commonly adopted in environmental multivariate analysis [47].

2.3.2. Orthogonal projection

Additionally, considering that, when working with natural samples, inter-individual dispersion among experimental replicates may mask variance ascribable to the experimental factors [31], an orthogonal projection approach was applied, following the framework described by Boulet & Roger [48]. Its combination with ASCA has already demonstrated to be effective when accounting with independent experimental replicates [49–51]. Starting from the complete data matrix described above, the independent plants within each treatment × position combination were randomly partitioned into two subsets. Four plants per combination were assigned to the W matrix (36 × 15), whereas the remaining fifteen plants constituted the X matrix (135 × 15). Subsequently, the W matrix was used to estimate the dominant replicate-related variance structure. In more detail, following the REP-ASCA strategy proposed by Ryckewaert et al. (2020) [49], W was submitted to PCA (principal component analysis) and only the information associated to the systematic sources of variability to be removed is retained; in the present study the retained component was PC1 (data not shown). The resulting loading matrix was used to obtain the orthogonalized X. This projection step redistributes variance components without modifying the experimental design structure.

2.3.3. ANOVA–Simultaneous Component Analysis (ASCA)

After data auto-scaling, factor effects were evaluated using ANOVA–Simultaneous Component Analysis (ASCA) [36]. ANOVA–Simultaneous Component Analysis (ASCA) [52,53] was used to decompose the multivariate response according to the experimental factors and to evaluate their effects. Statistical significance was assessed through permutation tests [54], whereas factor interpretation was based on the

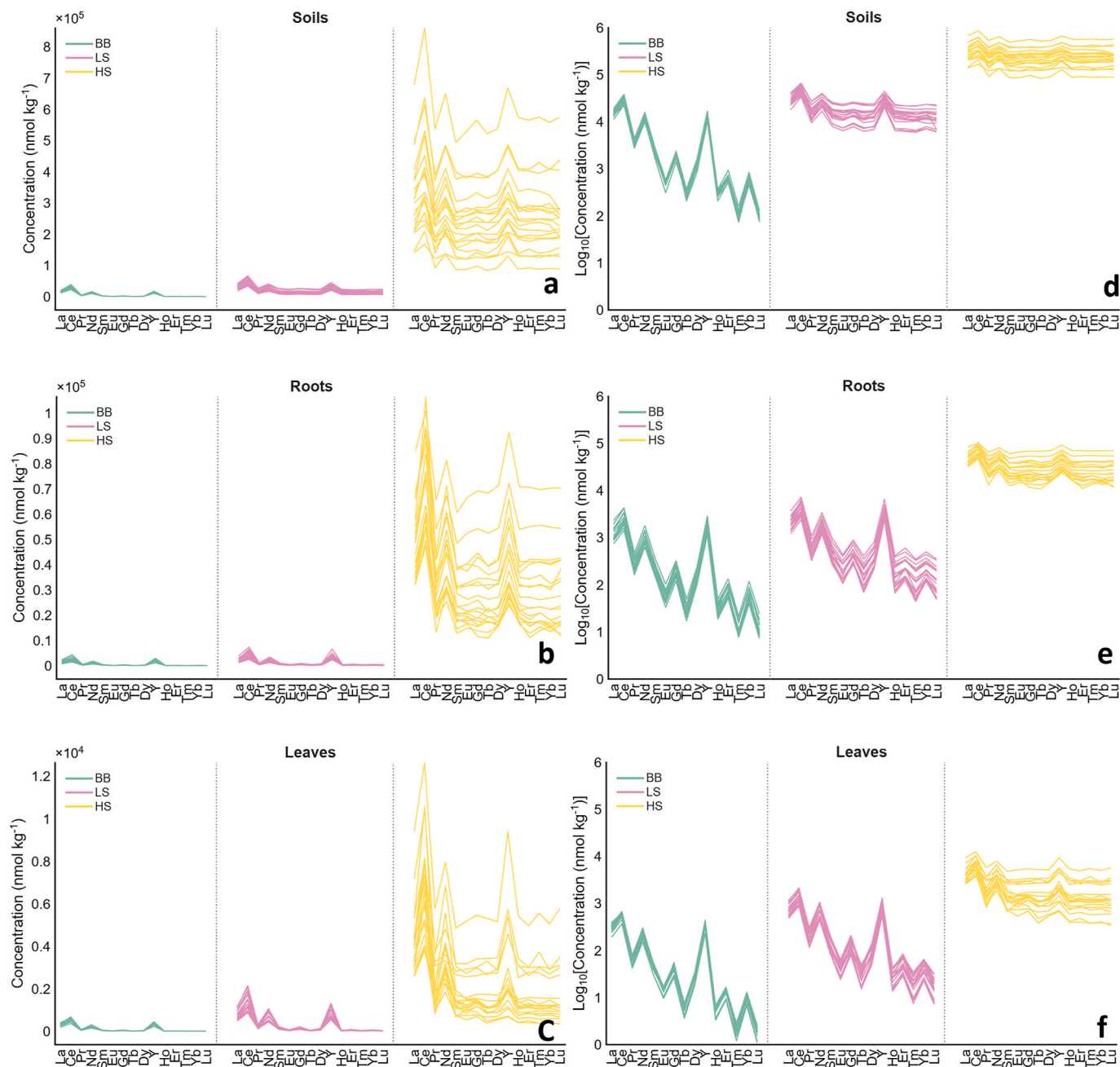


Fig. 3. REE concentration profiles in soil (a), roots (b) and leaves(c) and log10-transformed profiles of soil (d), roots (e), and leaves (f) colored according to the treatment.

score and loading plots of the corresponding ASCA sub models. For clarity, the Hasse diagram corresponding to the experimental design is reported in Fig. 2. It summarizes the hierarchical structure of the experimental factors and their relationships, providing a graphical representation of the model decomposition adopted by ASCA, including main effects, interactions and nested factor [36,55].

Moreover, considering that the significance of the position factor could be influenced by the intrinsic differences between soil and plant samples, an additional ASCA was performed on a submatrix including only the two plant compartments (roots and leaves). This analysis was carried out both before and after the orthogonalization step.

3. Results and discussions

3.1. Raw and Log10-transformed data

In this study, REE soil content represents the initial status of the soil–plant system and reflects the effective REE availability. Therefore, as a first step, to assess the actual differences across the stress conditions, the mean total REE concentrations in soils were evaluated. The S-BB showed a total REE concentration of approximately $80 \mu\text{mol kg}^{-1}$, compared to $290 \mu\text{mol kg}^{-1}$ in the S-LS and $4000 \mu\text{mol kg}^{-1}$ in the S-HS. These values correspond to an increase of approximately 4-fold in LS and 50-fold in HS relative to the control. These measured concentrations are distributed within the range typically found in natural soils, where total REE content has been reported to span from 20 to $8280 \mu\text{mol kg}^{-1}$ [42, 43]. This confirms that the enrichment levels used in this study,

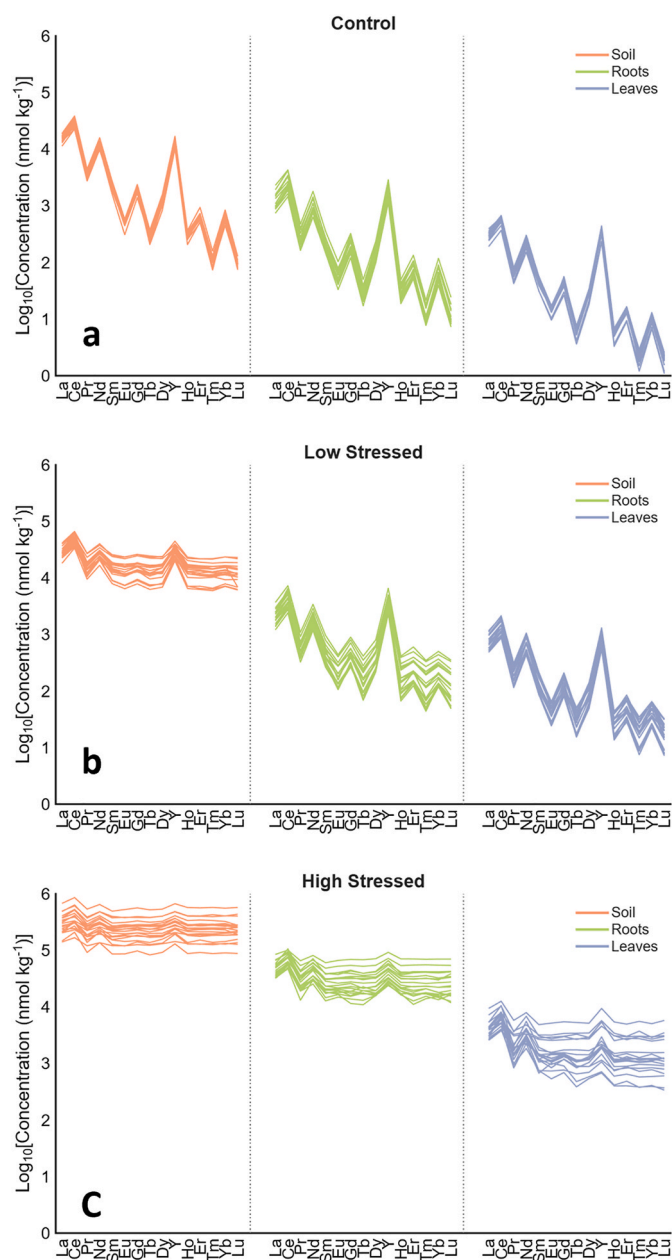


Fig. 4. $\log_{10}$ -transformed profiles in control (a), low stressed (b), high stressed (c) treatment colored according to the position.

although artificially induced, are representative of naturally occurring REE variability.

REE concentration profiles across treatments and plant compartments are shown in Fig. 3 (a, b, c) (the values are reported in Supplementary Materials, Table S1), and revealed that, within each treatment, concentrations spanned up to three orders of magnitude (Fig. 3a–c), making direct interpretation difficult. To address this, raw data were $\log_{10}$ -transformed (Fig. 3d–f), enabling direct comparisons of REE distribution patterns and highlighting distinct trends. In soils, the typical zig-zag pattern observed under control conditions was flattened under both LS and HS levels, reflecting the equimolar addition of REE (Fig. 3d). In roots, the zig-zag pattern persisted under LS conditions, though less pronounced than in the control, while under HS conditions, the root profile was completely flattened (Fig. 3e). In leaves a clear treatment effect was observed only at the HS level, where the REE distribution flattened similarly to that in soils and roots (Fig. 3f).

When data were grouped by plant compartment (Fig. 4), the control

systems maintained the expected soil-root-leaf gradient [22,43,56]. Under moderate REE enrichment (LS, $\sim 4\times$ control), roots appeared to act as a barrier, limiting REE translocation to aerial parts and preserving the natural REE distribution in leaves. However, this buffering capacity was overcome under high enrichment (HS, $\sim 50\times$ control), leading to almost uniform REE profiles across compartments. These findings indicate that *Vitis vinifera* L. dynamically modulates REE accumulation in a dose-dependent manner, aligning with recent reports in which REE retention in roots increases with exposure levels [57]. This adaptive response likely reflects a protective mechanism to minimize phytotoxicity and maintain metabolic function, as roots actively restrict upward REE transport, to shield sensitive organelles and sustain growth [58]. The distribution pattern across compartments reveals a visible vertical spread among experimental replicates, which becomes more pronounced at higher enrichment levels (HS condition).

3.2. ASCA on $\log_{10}$ -transformed matrix

To evaluate the relative contribution of treatment, position and their interaction to the overall multivariate structure of the data, ASCA was applied to the $\log_{10}$ -transformed data matrix.

The ASCA variance decomposition showed that treatment accounted for 49.65% of the explained variance, position for 46.71% and their interaction for 1.91%, while variance associated with replicates was limited to 1.10%. All effects were statistically significant ($p < 0.001$).

To better understand the behavior of the sample groups and interpret the role of the original variables, Fig. 5 shows the score and loading plots obtained computing PCA on the sub-matrices of treatment (Fig. 5a and b), position (Fig. 5c and d) and interaction (Fig. 5e and f). In more detail, Fig. 5a shows the distribution of the samples in the orthogonal space defined by PC1 and PC2, accounting for a total of 49.6% variance. According with the treatment factor, the three groups of samples appear clearly separated with higher PC1 values for the HS samples, followed by the LS; the control ones (BB) are characterized by the lowest values of PC1 with a reduced dispersion around the centroid of the group. Although all REE contribute positively to PC1, the loading values (Fig. 5b) show a gradual increase along the lanthanide series. This trend is consistent with the concentration profiles, where the equimolar REE enrichment produces larger relative increases for elements with lower natural abundances, progressively reducing the differences in the relative abundances of the individual REEs observed in the control samples. Moving to the PCA performed on the position sub-matrix, the contribution of the original variables in constructing PC1 is similar to the one of the treatment factor (Fig. 5d). Soil samples present the highest values of PC1 scores (explaining the 46.7% of the variance), followed by roots and the leaves, highlighting a dilution effect inside the different compartments of the plant (Fig. 5c). The loading pattern (Fig. 5d) generally shows higher PC1 loadings for the relatively more abundant REE, indicating that the separation among compartments primarily reflects differences in absolute concentration levels.

Considering the results of PCA performed on the interaction sub-matrix, in the score plot (Fig. 5e) representing PC1 vs PC2 and accounting for a total of 96.6% variance, it is possible to identify overlapping between different groups such as the roots high stressed (HS-R) with the low-stressed soil (LS-S); this behavior is ascribable to the fact that both treatment and position influence the overall increase in REE concentration profiles. Consistently, the loading plot (Fig. 5f) shows uniformly positive PC1 loadings for all REEs, indicating that the interaction effect is predominantly associated with an overall variation in REE concentration rather than with the behaviour of specific elements.

3.3. ASCA on orthogonalized matrix

Variance partitioning obtained by applying ASCA on the orthogonalized matrix indicated contributions of 50.04% for treatment, 22.44% for position and 17.99% for their interaction, while variance associated

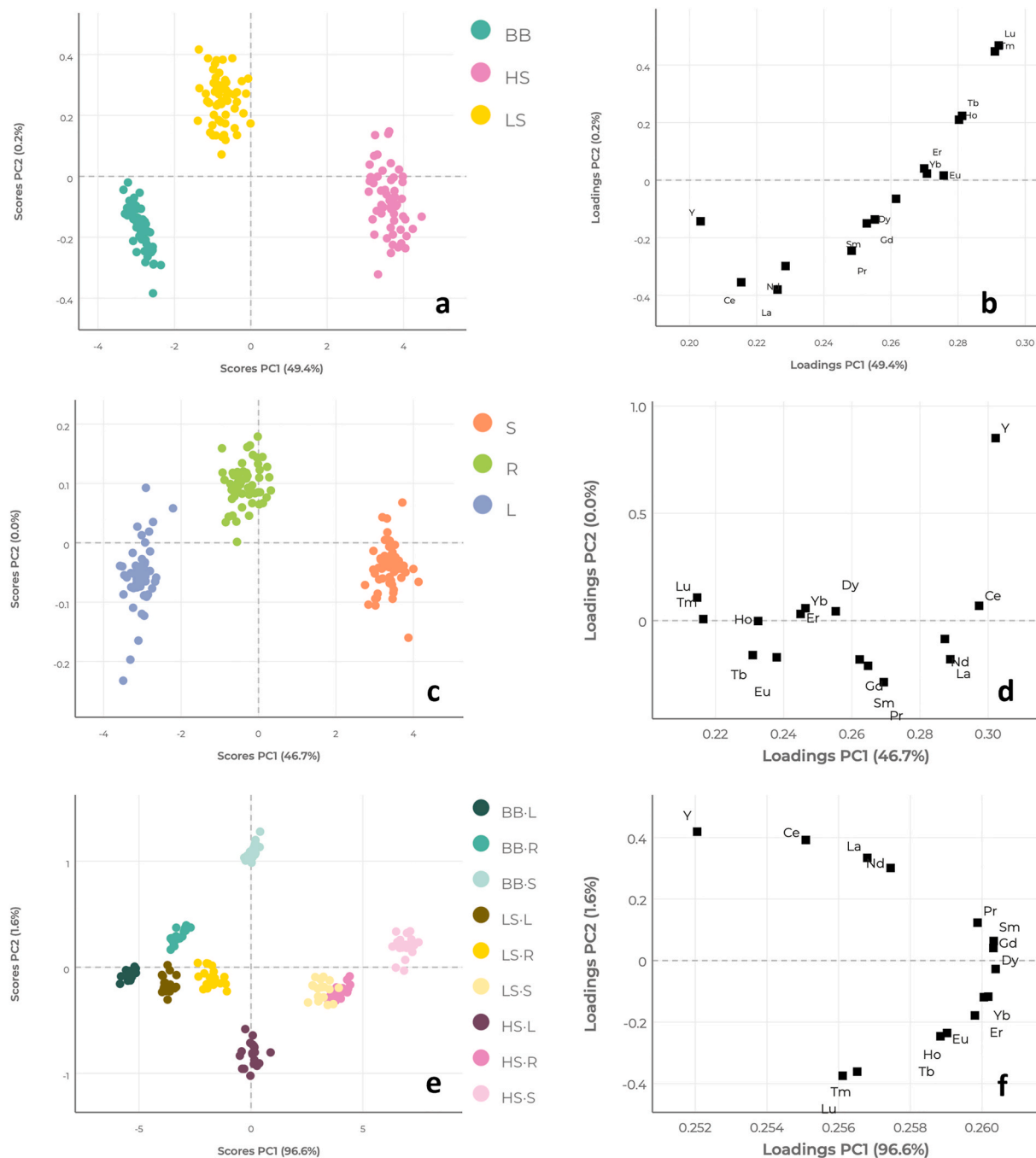


Fig. 5. ASCA results obtained from the $\log_{10}$ -transformed data matrix. Score and loading plots of the treatment (a–b), position (c–d), and interaction (e–f), obtained by PCA of the corresponding ASCA sub-matrices.

to replicates was limited to 3.27%. The effects of treatment and position remained statistically significant ($p < 0.001$) as in the ASCA performed on the $\log_{10}$ -transformed matrix, but it is interesting to notice that the effect of the interaction increases while decreasing the one for the position; the treatment appears to be the factor which affects most the system with a contribution higher than 50%. Moreover, the orthogonalization is confirmed to be the proper transformation for minimizing the differences among the replicates; in fact, the effect of the replicates appears to be non-significant (Table S2a and b).

Fig. 6 shows the score and loading plots obtained computing PCA on the sub-matrices of treatment (Fig. 6a and b), position (Fig. 6c and d) and interaction (Fig. 6e and f). In more detail, Fig. 6a shows the distribution of the samples according to the score values of PC1 and PC2,

accounting for a total of 50.0% of the explained variance. Comparing the behavior of the scores before and after orthogonalization, it is possible to highlight that the control group (BB) is located further from the low stressed (LS) one while keeping the same order of the samples according with the stress level. Compared with the non-orthogonalized model, the loading pattern preserves the overall organization of the individual REEs in the PC1–PC2 space (Fig. 6b). In particular, the relatively more abundant REEs (La, Ce, Nd and Pr) remain associated with lower PC1 values and negative PC2 values, whereas the relatively less abundant REEs (Lu, Tm, Tb and Ho) remain distributed towards positive PC1 values. At the same time, orthogonalization produces a broader distribution of the variables in the PC1–PC2 space, resulting in a clearer separation of the individual REEs in the loading plot. Moving to the PCA

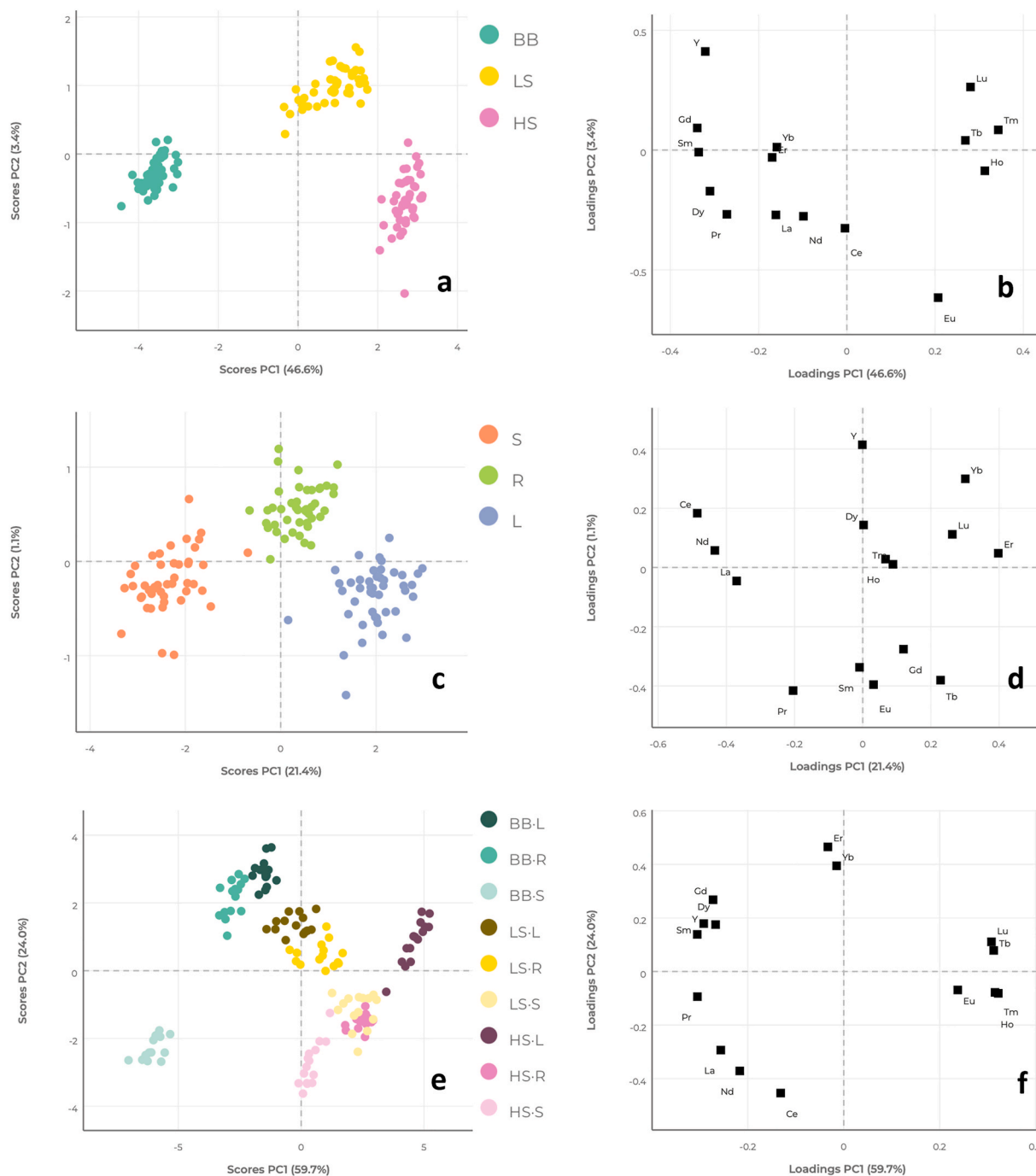


Fig. 6. ASCA results obtained from the orthogonalized data matrix. Score and loading plots of the treatment (a–b), position (c–d), and interaction (e–f), obtained by PCA of the corresponding ASCA sub-matrices.

performed on the position sub-matrix, PC1 and PC2 account for the 22.4% of the variance. In Fig. 6c the samples distribution is analogous with the one of the $\log_{10}$ -transformed data with soil, root and leaf samples maintaining the same relative distribution in the PC1–PC2 space. As observed for the treatment factor, the orthogonalized loading pattern (Fig. 6d) preserves the overall organization of the REEs, with Y maintaining its distinct position and La, Ce, Pr and Nd remaining separated from the other elements, and exhibits a broader distribution of the variables in the PC1–PC2 space. Finally, considering the results of PCA performed on the interaction sub-matrix (Fig. 6e and f), in the score plot representing PC1 and PC2 and accounting for the 83.7% of the variance, the overlapping between different groups of samples is even more pronounced. The loading pattern (Fig. 6f) shows a structured

distribution of the individual REEs in the PC1–PC2 space, with La, Ce, Nd and Pr mainly located at negative PC1 values, Lu, Tb, Tm and Ho at positive PC1 values and the remaining elements occupying intermediate or distinct positions. This pattern is consistent with the combined influence of treatment and sample position on the REE profiles rather than with a simple overall concentration effect.

The orthogonal projection provides a complementary representation of the data in which the interaction effect becomes easier to visualize, whereas the original analysis preserves the overall variance structure.

3.4. ASCA excluding soil samples

To evaluate whether the position effect was predominantly driven by

the contrast between soil (artificially stressed) and plant compartments, ASCA was repeated after excluding soil samples from the dataset. The resulting variance partitioning is reported in Table S2a and b, together with the score and loading plots in Fig. S1 and S2, respectively.

It is important to highlight that the results were consistent both with the log10-transformed matrix and with the addition of the orthogonalization step: in comparison with the ASCA results on the full matrix, the factor treatment became even more pronounced with a higher effect (more than 60% in both cases), together with an increase of the interaction effect before and after the orthogonalization (from 2.30% to 8.73%, respectively). In addition, similarly, the orthogonalized model maintained the statistical significance of treatment, position and their interaction, whereas the replicate effect was no longer significant.

This further data processing confirmed the dominance of the treatment factor indicating that the observed multivariate structure is not solely attributable to the soil–plant contrast but reflects compartment-dependent responses within the plant system.

4. Implications in environmental science

The experimental results obtained demonstrate that REE accumulation in *Vitis vinifera* L. is mainly driven by concentration gradients, as confirmed by the dominant effect of the treatment factor in the ASCA model. The presence of distinct clusters for the three treatments in the ASCA score plots further supports a lack of element-specific selectivity. On this topic, the scientific community has not reached a convergence. The findings of this study align with previous studies on vascular plants, which reported strong correlations between REE concentrations in soils and those in plant tissues [59–62]. However, on the other hand, the presented results appear to diverge from studies suggesting that soil-to-plant fractionation is controlled by liquid-solid interface reactions involving both inorganic and organic ligands [13,22,24,56,58,63]. This divergence is due to plant models often based on hydroponic systems, which reflect highly controlled and specialised conditions or seem to overlook that the natural distribution in soil of REE abundance affects the apparent reactivity of individual elements, equilibria influenced otherwise by mass effect. In this study, the use of an equimolar REE enrichment strategy enabled to assess the behaviour of each REE under chemically balanced conditions, thereby reducing interpretative bias linked to geogenic variability. Under these conditions, the results suggest that REE are absorbed collectively, likely reflecting their mutual ionic (+3) similarity and agree with their similar equilibrium constant with respect of groups present in soil, root, leaves [64]. Furthermore, the ASCA score plot for position shows subtle yet consistent differences between roots and leaves, indicating that position-related patterns within plant compartments are detectable. From an applied perspective, such compartment-specific variation could be valuable: determining which plant part best reflects changes in soil REE composition may support the selection of optimal sampling points for environmental monitoring or traceability applications [65–72]. This behavior is exemplified by observed response of roots, which, under LS condition, acted as mediators by limiting the accumulation of added REE in aerial parts. However, under HS condition this buffering effect was overridden by the intensity of the treatment, resulting in a similar REE distribution pattern across all compartments. Rather than suggesting unpredictable variations, this finding reveals that REE accumulation patterns follow consistent compartment-specific shifts under different exposure scenarios, a property that could be exploited to identify reliable plant-based indicators of soil REE status.

5. Conclusions

This study provides new insights into plant responses to soil modifications in REE levels, using *Vitis vinifera* L. as a model organism. Through the application of a full-factorial experimental design and multivariate analysis, this study demonstrated that REE accumulation in

plants is primarily driven by concentration gradients rather than element-specific selectivity. This finding is particularly relevant for environmental science, as it implies that REE distributions in plant tissues reflect the REE pattern of the surrounding soil. This may enable the reconstruction of soil alteration patterns or contamination levels through plant-based analysis. From a practical standpoint, the identification of compartment-specific response patterns is essential for the development of targeted and robust sampling strategies, supporting monitoring of anthropogenic inputs, geographical provenance studies or even the detection of product adulteration in agricultural supply chains. Methodologically, this work highlights the advantages of combining orthogonal projection-based approaches with ASCA, which account for inter-individual dispersion among experimental replicates, enabling the resolution of overlapping sources of variation (treatment vs. position). This integrated strategy offers a powerful analytical framework for exploring factors interactions. Future studies could extend this approach to different plant species, soil matrices, or pollutant mixtures, in order to assess the generalizability of these findings and validate the use of ASCA-informed compartmental analysis in broader environmental monitoring applications and environmental risk assessments.

CRedit authorship contribution statement

Marcella Barbera: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Riccardo Voccio:** Writing – original draft, Software, Data curation. **Cristina Malegori:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Paolo Oliveri:** Writing – review & editing, Software, Conceptualization. **Filippo Saiano:** Resources, Formal analysis, Conceptualization. **Sara Garglio:** Writing – review & editing. **Daniela Piazzese:** Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.chemolab.2026.105887>.

Data availability

Data are available in the Supplementary Material

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