

Evaluation of metal levels in commercial organic amendments in Chile: Compliance with national standards

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ABSTRACT

Commercial amendments can introduce hazardous chemical constituents into the soil profile, resulting in the long-term accumulation of heavy metals within the edaphic matrix. Fluctuations in key physicochemical parameters can trigger metal remobilization, thereby increasing their bioavailability within the terrestrial food chain and posing a severe risk to human health. We evaluated the concentrations of Cd, Cu, Cr, Ni, Pb, and Zn in ten commercial organic amendments from the local market in Chillán, Chile, benchmarking them against the national standard NCh 2880. Following physicochemical characterization, the burden of metals was quantified using inductively coupled plasma optical emission spectroscopy (ICP-OES). The results revealed significant variation ($p < 0.05$) in metal content, reflecting the diverse origins of the studied amendments. While Cd, Cr, Ni, and Pb showed moderate fluctuations, Cu and Zn reached concentrations as high as 197.84 and 214.07 mg kg⁻¹, respectively. Such pronounced heterogeneity underscores the importance of tailored site assessments to prevent excessive metal loading. Furthermore, uncontrolled production processes resulted in critical pH and salinity levels which, combined with the presence of metals, suggest that phytotoxicity from these factors could pose a serious health menace to soil and human. Significant inter-brand variations emphasize that quality is directly contingent upon manufacturing processes and raw material selection. These results confirm that despite general regulatory compliance, the inherent heterogeneity of these amendments requires individual monitoring to prevent long-term metal accumulation in agricultural soils.

Key words: Biofertilizers, compost, organic waste, soil contamination, soil remediation.

INTRODUCTION

Organic amendments are materials of natural origin—including animal, plant, or biodegradable industrial sources—added to the soil not only for nutrition but primarily to enhance its physical, chemical, and biological properties (Tsabedze et al., 2025). While compost quality depends on various physicochemical properties, environmental and public health standards focus on pathogens, degree of stability, and toxic compounds such as heavy metals (Bernal et al., 2017). During composting, chemical and biological transformations determine their maturity and their ability to provide nutrients without inducing phytotoxic effects (Xiong et al., 2023). However, soil amendments may contain heavy metals, and their presence can be harmful, depending on the type and origin of the amendment (Stehouwer et al., 2022).

Metals such as Cd, Cu, Cr, Ni, Pb, and Zn—can be toxic to both the environment and human health (Prashanth et al., 2015). Although these chemicals occur at low concentrations, their buildup poses significant environmental and health concerns. Specifically, the accumulation of these metals in soils treated with compost can threaten human health through food chain transfer or direct exposure, particularly with heavy metals like Pb, Cd, Cr, and Ni, which are widely recognized for their toxic potential (Newman, 2015).

Some evidence has stated that parameters like pH, electrical conductivity (EC), and organic matter (OM) directly influence the mobility, speciation, and behavior of heavy metals, affecting their stability in the soil (Kercheva et al., 2025). For instance, pH is a critical factor as higher values favor metal adsorption, reducing their mobility (Kargar et al., 2015). Similarly, OM can act in immobilizing metals through complexation with humified functional groups (Gao et al., 2023). Conversely, high EC levels (above 5 mS cm⁻¹) can trigger saline stress and negative phytotoxic effects, explaining over 50% of observed detrimental impacts in amended soils (AASHTO, 2024). Furthermore, organic amendments can modify soluble and complexed fractions of Cu, Zn, and Pb in contaminated soils, often reducing their exchangeable forms by creating stable complexes that limit immediate plant uptake (Cuske et al., 2017). The quality of compost remains a decisive factor, as commercial products can exhibit significant variability in Cu, Zn, Cr, and Pb levels, underscoring the need for stringent regulations and periodic safety assessments (Bernal et al., 2017). In this context, the targeted evaluation of elements such as Cd, Cu, Cr, Ni, Pb, and Zn in commercial organic amendments is essential to guarantee safe application and prevent the accumulation of metal loads in agricultural soils (Ding et al., 2017).

To ensure safety, analytical techniques such as inductively coupled plasma optical emission spectroscopy (ICP-OES) are employed for precise multi-elemental quantification (Vegi et al., 2025). In Chile, the NCh 2880 standard regulates these materials, establishing strict thresholds for Class A and Class B compost (INN, 2004). The city of Chillán represents a critical location for this assessment due to its high concentration of agrochemical trade and the increasing use of organic amendments to improve regional volcanic soils. Under this context, this study hypothesizes that commercial amendments available in the local markets of Chillán exhibit high variability in metal concentrations due to the diversity of their raw materials. Consequently, the objective of this research was to assess Cd, Cu, Cr, Ni, Pb, and Zn concentrations in ten commercial amendments and determine their compliance with national safety standards.

MATERIAL AND METHODS

Chillán was selected as the study area due to its strategic importance as the agricultural hub of the Ñuble Region, Chile. Ten commercial organic amendments were selected from various local suppliers, including plant nurseries, retailers, and a home-scale producer. The selected amendments comprised six Class A and four Class B commercial products (Table 1).

Table 1. Type and class according to Chilean regulations (NCh 2880) of the organic amendments utilized in this study. ¹According to Chilean Standard NCh 2880 (INN, 2004), Class A compost is considered innocuous due to its low heavy metal concentrations and low electrical conductivity (salinity), thereby presenting no risk of root burn in sensitive species or food contamination. Conversely, Class B compost represents a standard-quality product that remains environmentally safe, though it exhibits higher concentrations of soluble salts and less refined chemical parameters.

Sample	Declaration of origin	Type	Class ¹
M1	Agro-industrial waste	Compost	A
M2	Household waste	Home-made compost	A
M3	Household waste	Garden compost	A
M4	Industrial waste 1	Compost	A
M5	Household waste	Compost	A
M6	Industrial waste 2	Compost	A
M7	Household waste	Home-made compost	B
M8	Agro-industrial waste	100% Natural fertilizer	B
M9	Not specified	Compost-based substrate	B
M10	Forestry waste	Composted substrate	B

Sampling followed the quartering method to ensure representativeness. The samples were oven-dried at 65 °C for 24 h until reaching a constant weight, then ground to a fine powder using a ceramic mortar and stored in labeled, airtight bags. For the physicochemical characterization, the samples were mixed with distilled water at a 1:5 (v/v) or 1:10 ratio, depending on their bulk density. The resulting suspension was mechanically stirred for 30-60 min to ensure chemical equilibrium. The pH was measured using a calibrated potentiometer (HI5221, Hanna Instruments, Woonsocket, Rhode Island, USA) directly in the suspension, while electrical conductivity (EC) was determined in the filtered extract using a conductivity meter (HI5321, Hanna Instruments, Woonsocket, Rhode Island, USA). Organic matter (OM) content was quantified by the loss-on-ignition method in a muffle furnace at 550 °C for 4 h. Finally, moisture content was determined by oven-drying at 105 °C until a constant weight was reached, ensuring all analytical results are expressed on a dry weight basis.

For metal analysis, 250 mg each sample were placed in Teflon beakers for acid digestion. Initially, 2.5 mL 1:1 HNO₃ was added; the mixture was covered with a watch glass and heated at 95 °C for 15 min, ensuring the solution did not reach boiling. After cooling, 1.25 mL concentrated HNO₃ was added for a 30 min reflux, followed by a 2 h heating period at 95 °C. Subsequently, 0.25 mL Grade 1 water and 0.75 mL 30% H₂O₂ were added to initiate oxidation. To complete the digestion, additional 0.25 mL H₂O₂ aliquots were added under constant heating until effervescence ceased. A final 2 h heating step at 95 °C was performed to stabilize the extract. Finally, 2.5 mL concentrated HCl was added and heated at 95 °C for 15 min to aid metal solubilization. The resulting extracts were filtered through Whatman N°41 paper and diluted to a final volume of 25 mL in volumetric flasks. Metal concentrations of Cd, Cu, Cr, Pb, Ni, and Zn were quantified by inductively coupled plasma optical emission spectroscopy (Optima 8000 ICP-OES Spectrometer, PerkinElmer, Waltham, Massachusetts, USA) according to the NCh 3634 standard at the Applied Biogeochemistry Laboratory of the Universidad de Concepción, Chile.

Data were subjected to ANOVA. When significant differences were detected ($p < 0.05$), Tukey's HSD test was used for mean separation. Descriptive statistics and ANOVA were performed using InfoStat software (Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina). Furthermore, a Principal Component Analysis (PCA) based on a correlation matrix was conducted to evaluate the interrelationships between metals and organic amendments, enabling a comprehensive synthesis of the chemical variability.

RESULTS

Physicochemical characterization of the studied organic amendments studied is presented in Table 2. The pH values exhibited a trend toward neutrality and slight alkalinity (ranged from 6.17 to 8.86). While 90% of the commercial samples align with the NCh 2880 quality standard for pH (5.0-8.5), sample M7 (home-made compost) exceeded this threshold. Electrical conductivity (EC), an indicator of soluble salts and osmotic stress, showed that 60% of the samples exceeded the 3 dS m⁻¹ limit set by the NCh 2880 standard. Notably, M7 (7.47 dS m⁻¹) and M8 (5.4 dS m⁻¹) showed the highest levels, while only M5, M6, M9, and M10 complied with the regulation.

Table 2. Physical and chemical characterization of the ten organic amendments studied. OM: Organic matter; EC: electrical conductivity; OC: organic C; M1: agro-industrial compost; M2: home-made compost; M3: garden compost; M4: industrial waste-compost 1; M5: household waste-compost; M6: industrial waste-compost 2; M7: home-made compost; M8: natural fertilizer; M9: compost-based substrate; M10: forestry composted substrate.

Amendments	pH	OM %	EC dS m ⁻¹	OC %	Humidity %
M1	7.2	34.0	4.56	18.9	24.0
M2	7.4	31.3	3.43	17.4	34.1
M3	7.2	33.9	3.17	18.8	24.4
M4	7.4	45.2	4.03	25.1	38.3
M5	7.0	29.1	2.71	16.1	18.1
M6	6.8	37.7	2.57	20.9	28.3
M7	8.9	38.3	7.47	21.3	59.9
M8	7.3	54.7	5.40	30.4	51.3
M9	6.2	38.4	1.96	21.3	29.1
M10	8.2	22.0	1.70	12.2	34.5

Significant differences ($p < 0.05$) across all evaluated metals found in the amendments studied herein (Table 3) confirm a high degree of chemical heterogeneity linked to the amendments' origins. Concentrations ranged from 0.11-0.25 mg kg⁻¹ for Cd to a maximum of 214.07 mg kg⁻¹ for Zn, which displayed the highest variability. These contrasting results underscore the critical need for site-specific characterization to prevent excessive metal loading. Such accumulation not only might degrade soil fertility but also poses a long-term risk of heavy metal bioaccumulation in the food chain, potentially impacting human health through the ingestion of contaminated plant tissues. This is a subject that requires deeper investigation.

Table 3. Mean concentrations $\pm$ standard deviation found in the organic amendments studied here. Different letters in the same column indicate statistical significance (ANOVA, Tukey's HSD, $p < 0.05$). M1: Agro-industrial compost; M2: home-made compost; M3: garden compost; M4: industrial waste-compost 1; M5: household waste-compost; M6: industrial waste-compost 2; M7: home-made compost; M8: natural fertilizer; M9: compost-based substrate; M10: forestry composted substrate.

	Cd	Cu	Cr	Ni	Pb	Zn
	mg kg ⁻¹					
M1	0.15 $\pm$ 0.02 ^{abc}	121.21 $\pm$ 6.86 ^{bc}	24.62 $\pm$ 1.43 ^e	9.70 $\pm$ 0.27 ^{cd}	9.56 $\pm$ 0.80 ^{ef}	158.27 $\pm$ 3.11 ^{de}
M2	0.16 $\pm$ 0.03 ^{bc}	132.92 $\pm$ 7.47 ^{bc}	20.80 $\pm$ 1.40 ^d	9.88 $\pm$ 0.73 ^{cd}	9.52 $\pm$ 0.19 ^{ef}	138.64 $\pm$ 3.49 ^{cd}
M3	0.17 $\pm$ 0.02 ^{bc}	140.52 $\pm$ 2.24 ^c	17.67 $\pm$ 0.88 ^{cd}	8.66 $\pm$ 0.64 ^{bc}	8.33 $\pm$ 0.63 ^{de}	127.19 $\pm$ 0.26 ^c
M4	0.19 $\pm$ 0.03 ^c	149.00 $\pm$ 3.49 ^c	20.89 $\pm$ 1.56 ^d	9.58 $\pm$ 0.70 ^{cd}	8.95 $\pm$ 0.43 ^{ef}	162.13 $\pm$ 11.41 ^e
M5	0.12 $\pm$ 0.02 ^{ab}	43.13 $\pm$ 5.25 ^a	11.70 $\pm$ 1.33 ^{ab}	6.81 $\pm$ 1.32 ^{ab}	5.83 $\pm$ 0.20 ^c	66.43 $\pm$ 4.61 ^a
M6	0.11 $\pm$ 0.01 ^a	30.74 $\pm$ 4.28 ^a	14.56 $\pm$ 2.28 ^{bc}	9.44 $\pm$ 1.38 ^c	3.26 $\pm$ 0.57 ^b	77.84 $\pm$ 1.90 ^{ab}
M7	0.16 $\pm$ 0.01 ^{bc}	58.01 $\pm$ 2.93 ^a	18.22 $\pm$ 0.48 ^d	4.60 $\pm$ 0.12 ^a	7.16 $\pm$ 0.18 ^{cd}	192.40 $\pm$ 9.92 ^f
M8	0.25 $\pm$ 0.01 ^d	197.84 $\pm$ 15.30 ^d	25.68 $\pm$ 0.43 ^e	10.87 $\pm$ 0.81 ^{cd}	9.90 $\pm$ 0.80 ^f	214.07 $\pm$ 4.40 ^g
M9	0.14 $\pm$ 0.02 ^{ab}	102.73 $\pm$ 34.71 ^b	9.99 $\pm$ 0.78 ^a	6.20 $\pm$ 0.49 ^a	6.24 $\pm$ 0.18 ^c	88.90 $\pm$ 15.04 ^b
M10	0.17 $\pm$ 0.02 ^{bc}	29.78 $\pm$ 1.34 ^a	14.38 $\pm$ 0.39 ^{bc}	11.73 $\pm$ 0.03 ^d	1.77 $\pm$ 0.32 ^a	69.87 $\pm$ 2.11 ^{ab}

The Principal Component Analysis (PCA) yielded a robust biplot model (Figure 1) that accounted for 86.4% of the total system variance, with Dim1 and Dim2 explaining 66.6% and 19.8% of the variability, respectively. The Dim1 reflects the metal load, heavily driven by the Cu, Zn, Pb, Cr, and Cd vectors pointing toward the positive extreme. Amendment M8 stands alone at the far right (Dim1 > 3.5), confirming the highest overall metallic load and the most critical phytotoxic risk. In contrast, amendments M5, M6, and M9 group in the left quadrant, statistically proving they have the lowest contaminant concentrations. The intermediate cluster includes amendments M1, M2, M3, and M4, which show moderate accumulation (near the origin). The Dim2 highlights the independent dynamics of Ni. In terms of chemical orthogonality, the Ni vector projects almost vertically along Dim2, forming a near-90° orthogonal angle with the Cu, Zn, and Pb group. This geometric configuration confirms that Ni behavior is entirely decoupled from the other metals, implying a unique matrix-binding mechanisms for Ni within the amendments. Consequently, Dim2 successfully discriminates amendment M10 (associated with elevated Ni content), which features critically high Ni levels from amendment M7 at the opposite negative extreme, representing the lowest concentration of this element.

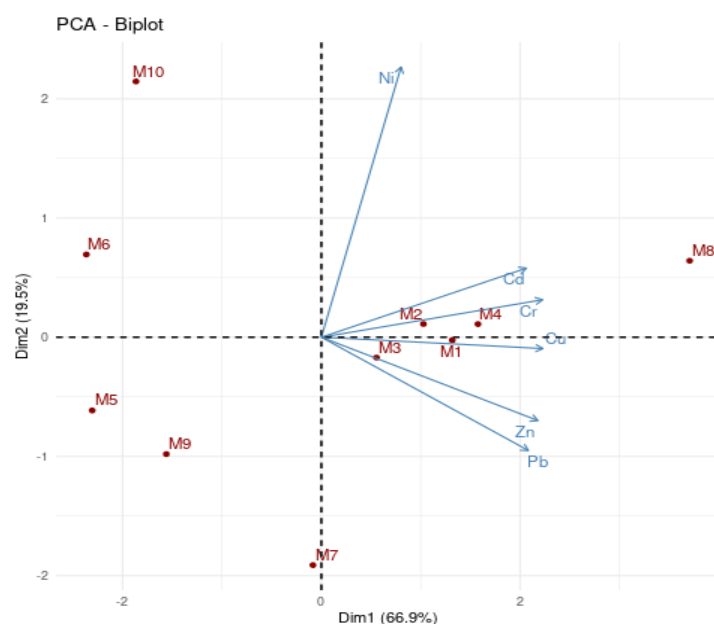


Figure 1. Principal Component Analysis (PCA) between metals (Cd, Cr, Cu, Ni, Pb, Zn) and the organic amendments (M1 to M10). M1: Agro-industrial compost; M2: home-made compost; M3: garden compost; M4: industrial waste-compost 1; M5: household waste-compost; M6: industrial waste-compost 2; M7: home-made compost; M8: natural fertilizer; M9: compost-based substrate; M10: forestry composted substrate.

DISCUSSION

Compost quality depends on various physicochemical parameters and the presence of toxic metals; these factors are critical for assessing the potential for general phytotoxicity, ensuring the material is safe and effective for soil application, and preventing any risks to human health (Newman, 2015; Bernal et al., 2017; Ginocchio et al., 2024). The commercial products exhibited highly variable pH values (6.2-8.9, Table 2), broader than the stable levels (7.4-7.8) reported by Bernal et al. (2017), suggesting process instability or excess bases. Although elevated pH enhances soil metal adsorption and retention (Wu et al., 2025), which could benefit acidic soils in central-southern Chile, such alkalinity may compromise nutrient balance in volcanic soils of the Ñuble Region and impair crop nutritional quality (Leiva-Vega et al., 2023). This potential risk to the food chain warrants further investigation.

The values of EC in the M1, M2, M3, M4, M7, and M8 amendments exceeded the national thresholds, and notably M7 (7.47 dS m⁻¹) and M8 (5.4 dS m⁻¹) with the highest EC levels (Table 2). The high salt content in an organic amendment primarily depends on the origin of the feedstock and the intensity of the decomposition process (Stehouwer et al., 2022; Ucaroglu and Ozbek, 2025). While elevated salinity can inhibit germination and degrade soil structure (Bernal et al., 2017), these amendments contribute to long-term improvements in soil structure through enhanced porosity and aggregate stability (Elmeknassi et al., 2024). For general horticultural use, the levels in M1 and M4 require split applications or salt leaching to protect sensitive seedlings.

All amendments met the > 20% organic matter (OM) requirement (NCh 2880; INN, 2004), with M8 showing the highest OM (54.7%) and heavy metal concentrations (Cu, Cr, Pb), confirming that feedstock quality dictates final safety (Amery et al., 2026). While humic/fulvic acids immobilize metals (Kwiatkowska-Malina, 2018), high complexation potential depends on stabilization to ensure maturity, which reduces mineralization and drives metals into less mobile fractions (Liu et al., 2019).

Cadmium concentrations (Table 3) were remarkably low (0.11 ± 0.01 to 0.25 ± 0.01 mg kg⁻¹), ensuring full compliance with the NCh 2880 standard (≤ 2 mg kg⁻¹ for Class A; ≤ 8 mg kg⁻¹ for Class B) and indicating high feedstock quality in Chillán. Beyond compliance, these amendments can mitigate existing soil Cd toxicity through stable organometallic complexation that reduces bioavailability (Xu et al., 2021). Paradoxically, high-

OM amendments like M8 (54.7% OM) may offer superior phytotoxicity protection due to a high density of functional groups that govern metal(loid) immobilization (Liu et al., 2026).

Chromium concentrations (Table 3) ranged from 9.99 ± 0.78 to 25.68 ± 0.43 mg kg⁻¹, well below the NCh 2880 thresholds for Class A (120 mg kg⁻¹) and Class B (600 mg kg⁻¹) composts, indicating a low risk of phytotoxicity. Beyond safe total levels, OM input accelerates the reduction of highly toxic Cr(VI) to less mobile Cr(III) (Lacalle et al., 2020), a process driven by dissolved organic C acting as a reducing agent (Xu and Tsang, 2022). Furthermore, OM addition shifts Cr partitioning from labile phases toward stable fractions bound to OM and Fe oxides, reinforcing the soil barrier function against leaching, particularly in high-OM samples like M8 (Xu et al., 2021). These Cr levels align with international literature reporting values between 9 and 23 mg kg⁻¹ for various commercial organic amendments (Moreno-Robles et al., 2026). This is crucial, as low total Cr levels, combined with the reducing capacity of OM described by Lacalle et al. (2020), ensure that the availability of toxic forms such as Cr(VI) is practically null in these products.

Copper concentrations showed high variability, ranging from 29.78 ± 1.3 (M10) to 197.84 ± 15.30 mg kg⁻¹ (M8). Under the Chilean standard (NCh 2880), samples M5, M6, M7, and M10 comply with Class A limits (100 mg kg⁻¹), whereas M1, M2, M3, M4, M8, and M9 fall into Class B (≤ 300 mg kg⁻¹), indicating that some feedstock sources in Chillán possess higher metal loads. Nevertheless, the organic matrix strongly mitigates immediate bioavailability, as compost and biochar enhance Cu(II) immobilization through high affinity for the functional groups of humic substances (Jones et al., 2016). Sequential extractions confirm that Cu preferentially associates with soil organic fractions, reducing leaching risks compared to metals like Cd (Ali et al., 2024). Consequently, although the OM input is beneficial and these amendments improve soil properties and fertility, long-term monitoring is essential to prevent metal accumulation (Montoya et al., 2019).

Nickel concentrations (4.60 ± 0.12 to 11.73 ± 0.03 mg kg⁻¹) complied with the NCh 2880 Class A threshold (20 mg kg⁻¹), indicating proper raw material management in Chillán. These levels are considerably lower than those found in sewage sludge (up to 134.1 mg kg⁻¹; López-Núñez et al., 2020) and municipal waste compost under European regulations (Prasad and Foster, 2023), closely aligning instead with high-quality green waste and biosolid composts (13-15 mg kg⁻¹; Welikala et al., 2018). Environmentally, these amendments pose zero risk of contamination; furthermore, the aromatic organic substances within the compost matrix reduce Ni mobility and limit its bioavailability to plants, thereby promoting metal retention and mitigating phytotoxic potential within the agroecosystem (Welikala et al., 2018).

Lead concentrations (1.8-9.9 mg kg⁻¹) were significantly below environmental alert levels, demonstrating remarkable consistency with mushroom residues and biochar (Wang et al., 2024), as well as source-separated agricultural manures (Moreno-Robles et al., 2026). These low values contrast sharply with the elevated levels found in unseparated municipal solid waste compost (Caporale et al., 2023), underscoring the high quality of the raw materials used in Chillán. Furthermore, the commercial maturity of these amendments, combined with low total contents, ensures that Pb remains in highly stable forms, eliminating the risk of long-term soil accumulation and subsequent translocation into food crops.

Zinc concentrations ranged from 66.43 to 214.07 mg kg⁻¹, with all samples falling well below the NCh 2880 Class B limit (2000 mg kg⁻¹) and only M8 exceeding the Class A threshold (200 mg kg⁻¹). While these levels are higher than those reported by Cuske et al. (2017), moderately high Zn concentrations can be beneficial as an essential plant micronutrient that enhances crop yields and acts as a slow-release fertilizer (Dawar et al., 2022). Furthermore, high cation exchange capacity and organic C content mitigate phytotoxicity by promoting stable Zn complexation, reducing leaching and excessive biota uptake (Maqueda et al., 2015; Liu et al., 2026).

Finally, the high cumulative variance observed in the PCA validates the model's precision in segregating organic amendments by their heavy metal burden, mirroring the categorization efficacy reported by Hussain et al. (2022). While both studies successfully distinguish between "eco-safe" green wastes and high-risk materials, the present model goes further by isolating a specific Ni anomaly in M10—attributing it to point-source contamination instead of regional trends. Rather than causing sudden soil contamination, these amendments might contribute to a chronic enrichment of the soil matrix, potentially leading to the "naturalization" of high metal baselines over decades. This is an issue that requires more research.

CONCLUSIONS

All the organic amendments evaluated in this study presented differences in metal concentrations. Most of the commercial organic amendments analyzed here comply with the Chilean standard (NCh 2880), particularly regarding Cd, Cr, Ni and Pb levels, thus ensuring minimal risk of soil contamination during long-term applications. However, high metal variability exists among brands and product types (compost, fertilizers, and substrates). Unlike industrial products, which tend toward neutrality, the home-made compost showed a critical imbalance related to pH and electrical conductivity, both exceeding national regulatory limits. This implies that under technically uncontrolled conditions—such as composting conducted without professional supervision, measuring tools, or established scientific protocols—alkalinity and salinity pose an additional phytotoxic risk alongside heavy metal.

Author contributions

Conceptualization: W.E. Formal analysis: V.B. Investigation: V.B., W.E. Resources: C.G., W.E., M.S. Data curation: W.E., J.C. Writing-original draft: V.B., J.C. Writing-review & editing: W.E., C.G., M.S. Visualization: V.B., W.E. Supervision: W.E., C.G., M.S. Project administration: W.E. Funding acquisition: W.E., C.G., M.S. All co-authors reviewed the final version and approved the manuscript before submission.

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