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Mineral Condition Changes in Amended Soils and Woody Vegetation Installed on a Polluted Soil with Trace Metals in Lubumbashi (DR Congo): Results of a Four-Year Trial

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Abstract

The use of trees to revegetate urban areas contaminated by mining activity is a low-cost, low-maintenance technique, of which the success will depend on the plant species, planting methods, and geochemical processes at the soil-plant interface. This study analyzed the evolution of mineral composition in the rooting soil, tree, and herbaceous vegetation on soils contaminated by As, Cd, Cu, Co, Pb, and Zn. An in-situ experiment was carried out in Lubumbashi (South-eastern DR Congo) with six tree species (*Acacia auriculiformis*, *Albizia lebbeck*, *Delonix regia*, *Leucaena leucocephala*, *Mangifera indica*, and *Syzygium guineense*), in 0.187 m^3 pits amended with municipal compost and limestone. After planting in the amended and unamended (control) pits, soil samples were taken for chemical analysis. Eighteen months after planting, a floristic inventory was carried out to assess the spontaneous colonization of herbaceous species. The results show an increase in metal concentrations in the rooting soil between 2019 and 2023 (Cu: 725 ± 136 to 6141 ± 1853 mg kg^{-1}; As: 16.2 ± 1.4 to 95 ± 28.5 mg kg^{-1}; Cd: 2.7 ± 1.3 to 8.7 ± 2.0 mg kg^{-1}; Co: 151 ± 36.3 to 182 ± 113 mg kg^{-1}; Zn: 558 ± 418 to 1098 ± 1037 mg kg^{-1}), with a stable pH and a decrease in nutrients (P, K, Ca, and Fe). The trees planted in the amended pits showed better height and diameter growth and greater survival than the controls, reaching average heights of 8 m and a DBH of up to 22 cm four years after planting. A total of 13 spontaneous herbaceous species were recorded, with an increased abundance during the second inventory. These results confirm the effectiveness of pit amendment for the rapid revegetation of urban soils polluted by trace metals.

Keywords: municipal compost; growth dynamics; trees; polluted soils; trace metals; phytotechnologies; Lubumbashi; Katangese Copperbelt

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1. Introduction

Soil pollution by trace metals is a recurring environmental problem in urban areas throughout the world, particularly in industrial regions or mining areas [1,2]. This pollution has harmful effects on ecosystems and human, animal, and microbial health, as well as

on plant health [3,4]. For example, these effects can lead to respiratory and cardiovascular diseases, reproductive disorders, cancers, and impaired cognitive development in humans [5,6] and can also affect plant nutrition, reducing growth and development [7].

In sub-Saharan Africa, in the south-eastern region of the DRC, more specifically in the Katangan Copperbelt (KCB), hills enriched in Cu and Co outcrop at the surface and host a unique metallophytic flora with nearly 600 metallophytes [8,9]. Mining activities in this region date back more than a century [10] and have left visible traces, particularly bare patches of soil allowing the dispersion of contaminated particles by water erosion in the rainy season and wind erosion in the dry season into other environmental compartments (air, garden soil, surface, and groundwater) [11]. Recent studies in the region have demonstrated the negative impact of mining activities on soils [12–14] surface water, and groundwater [15,16], with considerable repercussions for the food chain and people's health [17–19].

For all these reasons, soil remediation is essential to combat this pollution. The remediation process consists of eliminating, reducing, or mitigating polluted and destroyed soils using biological and physicochemical techniques [20]. Biological remediation methods, such as phytoremediation, are more effective and environmentally friendly [21]. Phytoremediation uses plants (both accumulators and non-accumulators) to remediate soils contaminated with trace metals, offering a cost-effective and environmentally friendly solution [22,23]. However, revegetating soils polluted with trace metals is a difficult task because the edaphic conditions (low fertility, low pH, low OM content, low CEC, etc.) are not conducive to plant growth. Trees, in particular, are known for their ability to improve soil quality by absorbing various elements [24,25]. Their root systems secrete enzymes that facilitate the absorption of nutrients into the soil, thereby contributing to the dynamics of mineral conditions in the rhizosphere, the zone of the soil influenced by the presence of plant roots. Because of the uptake of metals by roots, the rhizosphere is often more concentrated in trace metals than other parts of the soil [26]. This can significantly influence tree growth and the establishment of sustainable vegetation [27].

In this context, studying changes in soil mineral composition in the root zone and the growth of plants established on metal-polluted soils becomes crucial for an in-depth understanding of the processes that influence their development. This approach provides a better understanding of the factors that regulate plant growth and changes in soil mineral composition. It is proving useful in identifying the tree species best suited to specific environmental conditions, as well as in conserving biodiversity and making decisions about the management of polluted land [28]. In Lubumbashi in particular, the area exposed to the south-easterly trade winds from the metal plant has soils with exceptionally high concentrations of copper (>30,000 $mg \cdot kg^{-1}$) and other metals (Cd, Co, Pb, and Zn). As a result of these activities, the original Miombo forest has disappeared, leaving bare soil surfaces subject to erosion [29,30].

To contain this contamination, efforts have been made to revegetate the bare soil with trees. The operation involves excavating contaminated soil and replacing it with non-contaminated soil improvers [31,32]. Encouraging results have been obtained as this approach appears to be effective while offering less risk of contamination for crop products [32]. In addition, this method encourages the spontaneous establishment of herbaceous vegetation that provides year-round soil cover in the corridors of planted trees, thereby preventing erosion [33]. However, despite these advances, no study has evaluated the monitoring of the mineral composition of the root growth zone, the growth dynamics of the trees, or the timing of the appearance of herbaceous plants via experimental plantations on polluted soil. Therefore, obtaining primary data on soil mineral composition and tree survival and growth is essential for developing predictive models for the evolution of

woody cover to propose large-scale remediation. In addition, these models can be used to assess environmental impacts, such as climate change or ecosystem rehabilitation [25,27].

Approaches to monitoring tree growth dynamics are based on various methods such as dendrometric measurements, an analysis of annual rings, photosynthesis monitoring, sap flow measurements, remote sensing, and modeling [34,35]. The choice of monitoring method depends on the objectives of the study. In this study, direct dendrometric measurements, which measure tree height and diameter, were chosen for their ability to provide precise and accurate data on tree growth over time.

The general objective of this study was to show the evolution of the mineral composition of the soil and woody vegetation on soils heavily polluted with metals. More specifically, we (i) assessed the dynamics of mineral conditions in the root growth zone of woody plants in the medium-term (4 years) and (ii) assessed the dynamics of vegetation established on contaminated soils, including woody plants and herbaceous plants. The results of this study will be of crucial use in guiding decisions on the large-scale remediation of soils polluted with trace metals in Lubumbashi and elsewhere.

2. Materials and Methods

2.1. Study Site

The study was carried out in the city of Lubumbashi, specifically on the grounds of the Gécamines-Sud hospital in the Penga Penga district (11°40′42″ S latitude, 27°27′56.50″ E longitude, elevation 1215 m) (Figure 1). At this site, the trial was set up on a rhodic allisol [36] subject to polymetallic contamination, with particularly high concentrations of Cu (>17,000 mg·kg^{-1}), but also of As, Cd, Co, Pb, and Zn when compared to uncontaminated soils in the region [37]. The city's climate is of the *Cw* type, characterized by the alternation of a well-defined dry season (May to September) and a rainy season (November to March), separated by two transitional months (April and October) [38]. Annual rainfall varies between 1200 and 1300 mm, and the average annual temperature is 20 °C [39].

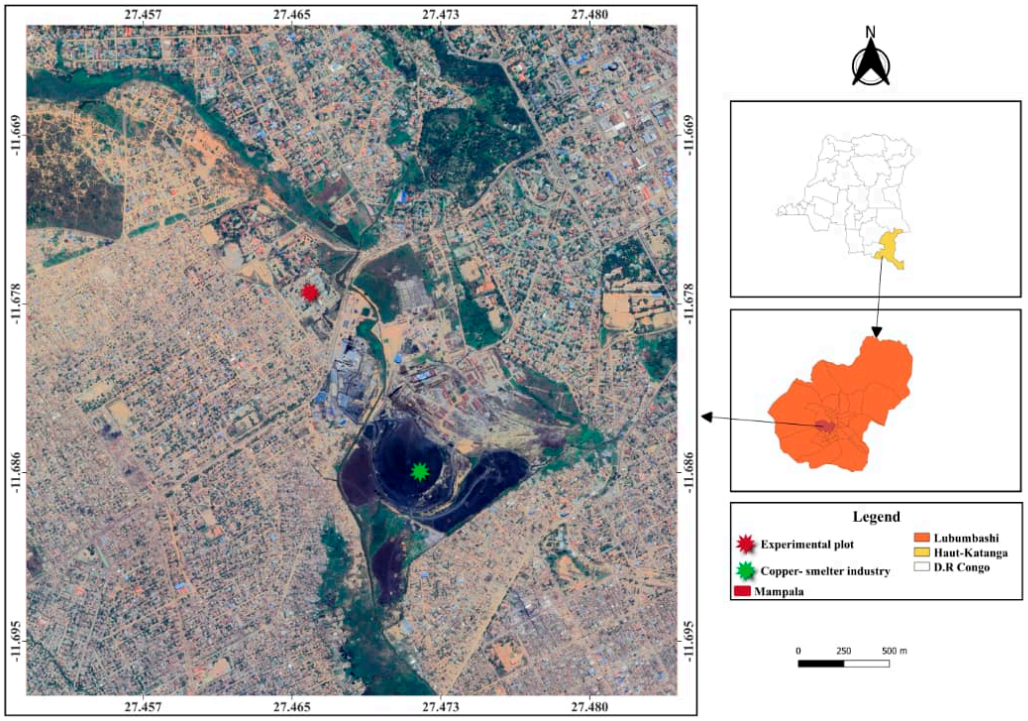

Figure 1. Location of the GCM/Penga Penga experimental plot. The red dot indicates the location of the experimental plot and the green dot indicates the mountain of slag from the Gécamines copper smelting industry.

2.2. Plant Material

Six woody species, belonging to four families (Table 1, Figure 2), formed the biological material for the present study. These species were selected based on their tolerance to trace metals, their rapid growth, and their high biomass production, coupled with their deep root system and the edible nature of their fruit. They generally reach heights of 10–25 m in normal, uncontaminated soil. Except for *M. indica*, the other woody species have already been used to rehabilitate soils polluted with trace metals by mining activities [40–43].

Table 1. List of species tested in the remediation of soils polluted by trace metals. TM: metal tolerance, CR: rapid growth, PBE: high biomass production, SR: deep root system, FC: edible fruit.

Family	Species	Original Status	Functional Group
Fabaceae	*Acacia auriculiformis* A. Cunn. Ex. Benth	Ex	TM/CR/PBE/SR
Fabaceae	*Albizia lebbeck* (L.) Benth	Ex	TM/CR/PBE/SR
Fabaceae	*Delonix regia* (Bojer ex Hook.) Raf.	Ex	TM/PBE/SR
Fabaceae	*Leucaena. Leucocephala* (Lam.) de Wit	Ex	TM/CR/PBE/SR
Myrtaceae	* *Syzygium guineense* (Willd) DC. Sub *macrocarpum*	In	TM/CR/PBE/SR/FC
Anacardiceae	*Mangifera indica* L.	Ex	TM/SR/FC

In: indigenous species; Ex: exotic species. Species marked with * are characteristic of the *Miombo* forest [44,45].

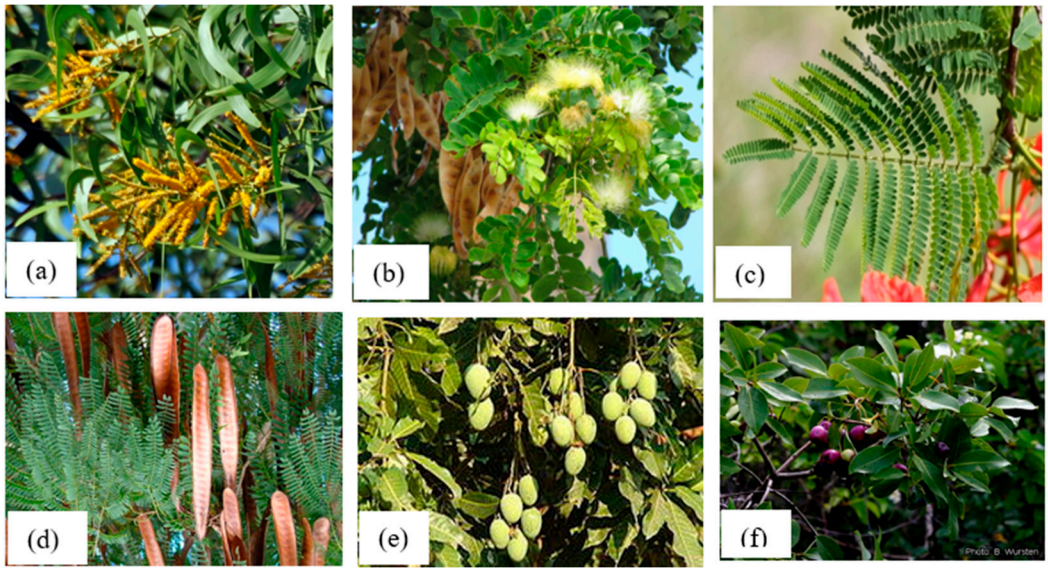

Figure 2. Overview of the six-tree species planted in the phytostabilisation experiment. (**a**) *Acacia auriculiformis*, (**b**) *Albizia lebbeck*, (**c**) *Delonix regia*, (**d**) *Leucaena leucocephala*, (**e**) *Mangifera indica*, and (**f**) *Syzygium guineense*. (Photo by Serge Langunu).

2.3. Experimental Plot

A random block layout with a factor (municipal compost + limestone × species) covering an area of 0.27 ha was installed. Planting pits measuring 0.187 m^3 (0.50 m wide × 0.50 m long × 0.75 m deep) were dug in this area at a spacing of 5 m × 5 m (Figure 3). Each pit was filled with a mixture of 350 kg of municipal compost and 6 kg of dolomitic limestone ($CaCO_3$, $MgCO_3$) containing 52% Ca and 25% Mg. The municipal compost came from the public landfill on the Lubumbashi University campus, and its characteristics are given below (Table 2). The dolomitic limestone came from the Likasi limestone quarry. Municipal compost and limestone were used as amendments in the restoration of contaminated pits due to their effectiveness in improving the physico-chemical properties of degraded soils. The compost provides essential nutrients (N, P, and K), increases organic matter content, stimulates microbial activity, improves soil structure, and reduces the bioavailability of trace metals through complexation mechanisms. Limestone was primarily applied to

correct soil acidity, common in the study area, by raising the pH to levels favorable for plant growth while immobilizing trace metals through precipitation reactions, thereby limiting their mobility and toxicity. Moreover, the use of municipal compost aligns with a circular economy approach by valorizing abundant urban waste in the region, contributing to urban sanitation, and reducing rehabilitation costs for contaminated soils, as well as affordability (low cost) for the population who may wish to plant trees on their residential properties.

Table 2. Physicochemical properties of soil from the site and urban waste used (n = 10). Average (minimum–maximum) As_T Cd_T Co_T Cu_T Pb_T and Zn_T = total concentrations of As, Cd, Co, Cu, Pb, and Zn; Cd_S, Co_S, Cu_S, Pb_S, and Zn_S = soluble concentrations (extractable with 0.01 M $CaCl_2$).

Parameters	Test Soil	Municipal Compost
pH_{kcl}	5.5 (4.5–5.6)	7.2 (7.2–7.3)
TOC	1.9 (0.8–2.6)	-
Fe (%)	-	5.4 (4.7–6.2)
P (mg kg^{-1})	5,3 (2.8–8.9)	1327 (413.3–1898)
K (mg kg^{-1})	1.0 (0.7–1.3)	3133 (2995.2–3238)
Ca (mg kg^{-1})	9.5 (3.6–20.6)	21,797 (6153–30,348)
Mg (mg kg^{-1})	1.4 (1.1–2.0)	2791 (1542–3457)
$As_{(T)}$ (mg kg^{-1})	232.1 (254.7–396.6)	16.2 (14.1–17.2)
$Cd_{(T)}$ (mg kg^{-1})	33 (23.5–52.3)	2.7 (4.3–1.4)
$Cu_{(T)}$ (mg kg^{-1})	17,330 (1462–29,216)	725 (707–896)
$Co_{(T)}$ (mg kg^{-1})	295 (276–505)	151 (149–187)
$Pb_{(T)}$ (mg kg^{-1})	1168 (1213–1723)	62 (35–104)
$Zn_{(T)}$ (mg kg^{-1})	3189.7 (2878–5347)	558 (173–1114)
$Cd_{(s)}$ (mg kg^{-1})	2.8 (1.5–4.5)	0.01 (0.008–0.035)
$Cu_{(s)}$ (mg kg^{-1})	104.9 (39.2–199.6)	0.709 (0.177–1.631)
$Co_{(s)}$ (mg kg^{-1})	19.8 (13.3–29.3)	0.089 (0.007–0.263)
$Pb_{(s)}$ (mg kg^{-1})	3.05 (0.7–7.3)	0.128 (0.105–0.152)
$Zn_{(s)}$ (mg kg^{-1})	152.7 (124.7–195.3)	0.470 (0.033–1.277)

After the addition of amendments, a period of 30 days was observed before planting. Finally, six woody species were planted, totaling 115 individuals, distributed as follows: *A. lebbeck* (26 individuals, including 21 in amended pits and 5 in non-amended pits), *S. guineense* (26 individuals, including 21 in amended pits and 5 in non-amended pits), *A. auriculiformis* (29 individuals, including 25 in amended pits and 4 in non-amended pits), *L. leucocephala* (8 individuals, equally distributed between amended and non-amended pits), *D. regia* (13 individuals, including 9 in amended pits and 4 in non-amended pits), and *M. indica* (13 individuals, including 9 in amended pits and 4 in non-amended pits). In total, 89 seedlings were planted in amended pits and 26 in non-amended pits. This experiment was conducted during the rainy season, from November to December 2019. To ensure proper seedling establishment, supplemental irrigation was provided during the first dry season following planting. Moreover, the unequal number of individuals between the amended and unamended pits is due to a pre-selection carried out during preliminary studies conducted under controlled conditions [42,46].

2.4. Plantation Monitoring and Species Inventory

In this study, we assessed plant survival and growth (height) at regular intervals throughout the experimental period (50 months), starting when the plants were planted. To obtain the survival rate, the number of individuals alive at the last sampling was divided by the total number of individuals initially planted, multiplied by 100. We also measured the height of the plants every six months over the four years to determine their growth over time. To classify the stand into diameter classes, the diameter at breast height (DBH) of all surviving individuals was measured in cm at 1.3 m above the ground using a forest

tape, while height was measured in meters using a SUUNTO clinometer [47,48]. Juvenile trees from the regeneration of initially planted species were counted systematically, and flowering and fruit production were monitored.

To assess the spontaneous establishment of herbaceous species, they were characterized using the Braun–Blanquet phytosociological abundance-dominance method [49]. The floristic inventory was carried out using well-defined 5 m × 5 m (25 m^2) quadrats [50] in which herbaceous species were counted and identified at two different times (2021 and 2023).

2.5. Chemical Analysis

Samples were taken before the trial was set up and three years after planting directly in the root growth zone to assess changes in soil mineral composition over time. A soil probe was used to take samples from a depth of 0 to 30 cm. These samples were dried at room temperature (<35 °C) and sieved to 2 mm, and a sub-sample was ground to 200 µm to enable fine analysis of the mineral composition of the soil. It should be noted that chemical analyses were conducted only on amended soil samples (n = 10). Non-amended soils were sampled and analyzed before the implementation of the experiment (i.e., before pit amendment and planting) and served as the initial baseline for comparison (Table 2).

The chemical analysis methods were described by Lienard and Colinet [51]. Soil pH was measured potentiometrically in a 1:2.5 (w/v) suspension in water and 1N KCl, while total organic carbon (TOC) was determined using the Springer–Klee method. Concentrations of the major elements (Ca, Mg, K, and P) and trace elements (Fe, As, Cd, Co, Cu, Pb, and Zn) were determined after (a) extraction with $CH_3COONH_{(4)}$ (0.5 M) and EDTA (0.02 M) at pH 4.65 (w/v ratio 1:5) and stirring for 30 min (concentration of available metals), and (b) digestion with aqua regia according to ISO 11466 (concentration of total metals), respectively [52]. Concentrations in the solutions were measured by flame atomic absorption spectrometry (AAS, Varian 220, Agilent Technologies, Santa Clara, CA, USA) for major elements, except P (colorimetry), and by ICP-OES for metal content in aqua regia.

2.6. Statistical Analysis

The Chi-square test (χ^2Pearson) was used to compare the survival of individuals between the two soil types. A normality test was applied to the data on woody growth parameters. As the distributions were not normal, even after transformations, the non-parametric Kruskal–Wallis (KM) test was used to compare plant height and diameter at breast height (DBH). The relative abundance of the species richness of spontaneous herbaceous species in the tree corridors was determined after transforming the Braun–Blanquet coefficients into percentages. The relative abundance of species was calculated by dividing the number of individuals of the species by the total number of individuals of the species multiplied by 100. All the analyses were carried out using R Studio software (version 4.0.3).

3. Results

3.1. Dynamics of Mineral Composition in Soils over Four Years

The pHKCl values of the surface soil horizons of the species studied do not show any major variations between 2019 (7.2 ± 0.03) and 2023 (7.2 ± 0.2), in contrast to the variations observed for the other fertility parameters (Table 3). There was a downward trend in Ca, Fe, P, and K values, but an increase in Mg values (Table 3). In particular, concentrations fell by a factor of 2.5 for P (1327± 688 vs. 516 ± 71.0 mg kg^{-1}) and 1.8 for Ca (21,797 ± 10,862 vs. 12,262 ± 6062 mg kg^{-1}), while they increased on average by a factor of 1.2 for Mg (2791 ± 871 mg kg^{-1} to 3550 ± 695 mg kg^{-1}).

Table 3. Changes in pH values and total levels of major elements (P, K, Ca, and Mg) in the soil from 2019 to 2023. The trial was installed at Gécamines/Penga Penga (n = 10). The mean ± standard deviation represents values; sampling depth = 0–30 cm; n represents the number of samples.

Parameters	2019	2023
PH_{KCl}	7.2 ± 0.03	7.2 ± 0.2
Al (%)	3.1 ± 0.32	3.8 ± 0.31
Fe (%)	5.4 ± 0.61	5.0 ± 0.63
P (mg kg^{-1})	1.327 ± 688	516 ± 71.0
K (mg kg^{-1})	3133 ± 101.8	2497 ± 182.6
Ca (mg kg^{-1})	21.797 ± 10.862	12.262 ± 6.062
Mg (mg kg^{-1})	2.791 ± 871	3.550 ± 695

Concerning trace metals, a general trend of increasing concentrations was observed between 2019 and 2023 (Table 4). The greatest average increase in concentrations was observed for Cu, with values in 2023 (6.141 ± 1.853 mg kg^{-1}) eight times higher than those in 2019 (725 ± 136 mg kg^{-1}). After Cu, the increase factors were higher for As and Pb, with concentrations in 2023 six times higher than those observed in 2019 (As: 16.2 ± 1.4 mg kg^{-1} in 2019 vs. 95 ± 28.5 mg kg^{-1} in 2023; Pb: 62 ± 32 mg kg^{-1} in 2019 vs. 421 ± 160 mg kg^{-1} in 2023). Cd concentrations observed in 2023 are three times higher on average (2.7 ± 1.3 mg kg^{-1} in 2019 vs. 8.7 ± 2.0 mg kg^{-1} in 2023), while they are less than twice as high for Co (151 ± 36.3 mg kg^{-1} in 2019 vs. 182 ± 113 mg kg^{-1} in 2023) and Zn (558 ± 418 mg kg^{-1} in 2019 vs. 1098 ± 1037 mg kg^{-1} in 2023).

Table 4. Trends in trace metal concentrations in soil from 2019 to 2023. The test was installed at Gécamines/Penga Penga (n = 10). The mean ± standard deviation represents the values; sampling depth = 0–30 cm; n represents the number of samples.

Metals	2019	2023
As (mg kg^{-1})	16.2 ± 1.4	95 ± 28.5
Cd (mg kg^{-1})	2.7 ± 1.3	8.7 ± 2.0
Cu (mg kg^{-1})	725 ± 136	6.141 ± 1.853
Co (mg kg^{-1})	151 ± 36.3	182 ± 113
Pb (mg kg^{-1})	62 ± 32	421 ± 160
Zn (mg kg^{-1})	558 ± 418	1098 ± 1037

3.2. Vegetation Dynamics Between 2019 and 2024

3.2.1. Survival Dynamics, Growth, Reproduction, and Regeneration of Woody Species

The results showed that none of the trees in the untreated pits survived to March 2024, i.e., after 50 months of cultivation. In contrast, the survival rate of trees planted in amended pits was 87.6% (78 out of 89 individuals). In the case of individuals planted in amended pits, mortality was mainly observed after the first dry season in 2020. To mitigate early transplant stress and promote establishment, supplemental irrigation was applied during this initial dry period, which likely contributed to the overall success observed in the amended plots. Individuals who survived the first dry season remained alive until the last measurement in March 2024. The highest survival rate was obtained for *A. lebbeck*, *D. regia*, and *L. leucocephala* with 100% survival each, followed by *S. guineense* with 90%. Low survival rates were observed for *A. auriculiformis* and *M. indica*, with 72% and 77%, respectively. Individuals planted in the pits amended in 2019 reached average heights ranging from 3.0 to 8.6 m in 2024 (Figure 3). The general trend of the curves presented in Table 4 shows an acceleration in the increase in height during the second year of growth. However, a variation in the rate of growth in height was observed between species, characterized by differences in the value of height reached after four years of cultivation. In 2024,

individuals of *L. leucocephala* reached a higher average height (8.6 ± 0.16 m) than the other species ($p < 0.05$). They were followed by *A. auriculiformis* (6.4 ± 0.38 m) and *S. guineense* (6.1 ± 0.23 m). The slowest growth rates in height were observed for *D. regia* and *M. indica*, which reached heights of 3.2 ± 0.22 m and 3 ± 0.8 m, respectively. Most of the species appear to be promising for reforestation or ecological restoration projects because of their faster development in specific environmental and edaphic conditions. The performance of these six species in uncontaminated environments is given for comparison. Species such as *L. leucocephala* (14.53 m tall and 14.26 cm in diameter) and *A. auriculiformis* (14.16 m tall and 8.52 cm in diameter) show strong growth, while *D. regia* and *M. indica* show weak growth (5.2 m and 5.1 m, respectively) compared with *A. lebbeck* (9.45 m tall and 8.14 cm in diameter) and *S. guineense* (8.76 m tall and 8.2 cm in diameter), which show intermediate growth (Table 5). Although the durations are not the same, the performance of the trees in the plantation pits seems acceptable.

Table 5. Comparison of growth in non-contaminated and metal-contaminated environments of the six-tree species used in the remediation of metal-contaminated sites in the ACK ([40,53] Mujike et al. In press).

Species	*A. auriculiformis*	*A. lebbeck*	*D. regia*	*L. leucocephala*	*M. indica*	*S. guineense*
Height (m)	14.16	9.45	5.2	14.53	5.1	8.76
Diameter (cm)	14.26	8.14	5.6	8.52	5.2	8.2
Metal-contaminated Environments						
Height (m)	6.4	5.5	3.2	8.6	3.0	6.1
Diameter (cm)	8.2	10.2	4.9	10.3	4.9	8.4

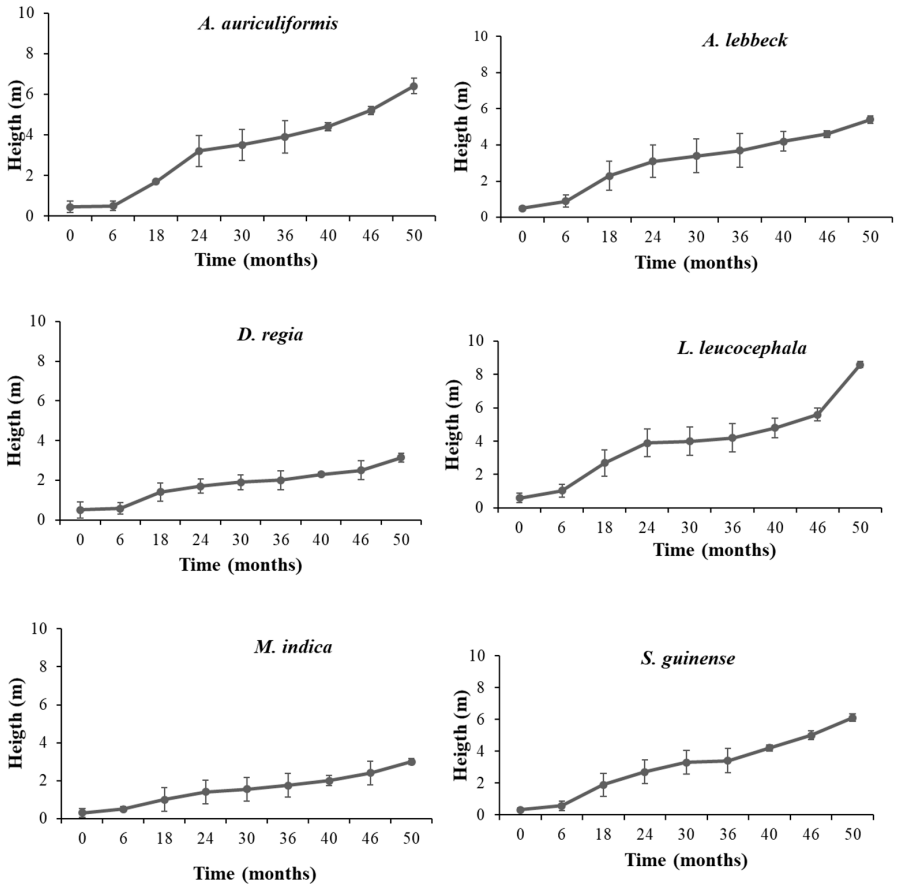

Figure 3. Growth in height of the six woody species grown in the trial over 50 months.

The DBH values in 2024 range from 2.1 to 21.6 cm for all species combined. The diameter structure of the woody stand in 2024 (Figures 4 and 5) shows a greater contribution from the youngest classes (<10 cm), with 51 individuals, or 65.3%. If the 10–15 cm classes are included, the number of individuals rises to 73, representing 93.5%. The 15–22 cm classes represent only 5 trees, or 6.5%. The distribution of diameters is not uniform between species. DBH classes 16–22 are only represented by individuals of *A. lebbeck* and *S. guineense*, while all *D. regia* and *M. indica* individuals had DBH < 10 cm in just over four years. The KW test indicated that there was a significant difference in DBH in 2024, with higher mean values for *L. leucocephala* (10.3 ± 3.4 cm) and *A. lebbeck* (10.2 ± 4.6 cm). These two species were followed by *S. guineense* (8.4 ± 3.5 cm) and *A. auriculiformis* (8.2 ± 2.4 cm), while the lowest values were observed for *D. regia* (4.9 ± 2.2 cm) and *M. indica* (4.9 ± 0.6 cm).

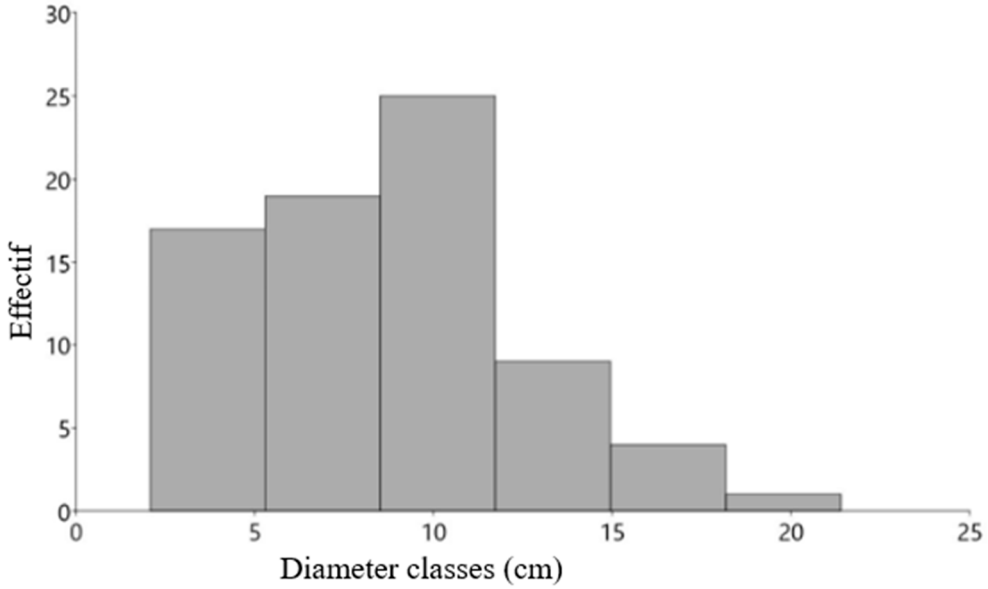

Figure 4. Diameter structure of the woody stand installed at Penga Penga after 50 months of cultivation.



Figure 5. Overview of tree planting on metal-polluted soil at 4 years of growth. Photo by Serge Langunu, April 2024.

Figure 6 shows the results of the relationship between tree frequency and diameter at breast height (DBH) for each species. A diversity of species can be observed with significant variations in terms of frequency and growth, which could indicate varied adaptations.

A. auriculiformis and *A. lebbeck* are frequent with moderate to high DBH. *D. regia* and *M. indica* are less frequent and have a smaller DBH, while *S. guineense* is the most frequent. In terms of comparison between species, *A. lebbeck* has the widest range of DBH, suggesting that it can grow over a wider range, while *S. guineense* is the most widespread species; it does not reach DBH values as high as those of *A. lebbeck*. The other species have a moderate frequency and DBH distribution.

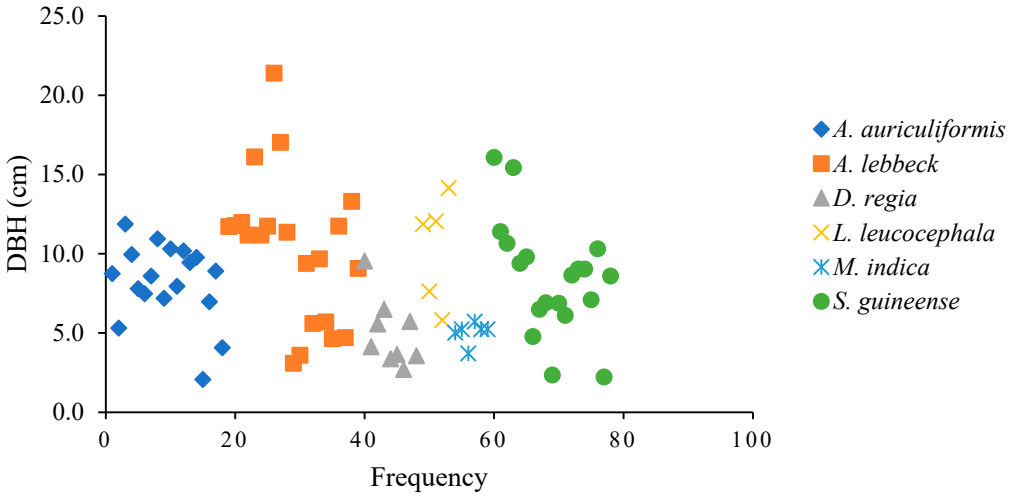

Figure 6. Relationship between tree frequency and diameter at breast height at 50 months for each species grown in trials.

The time from planting to flowering was not uniform for the six species grown in the trial (Figure 7). Flowering and fruit production were observed from the third growing season for *L. leucocephala*, the fourth growing season for *A. lebbeck* and *D. regia*, and the fifth growing season for *A. auriculiformis* and *S. guineense*. No flowering was reported for mango individuals until the end of the observations (March 2024).

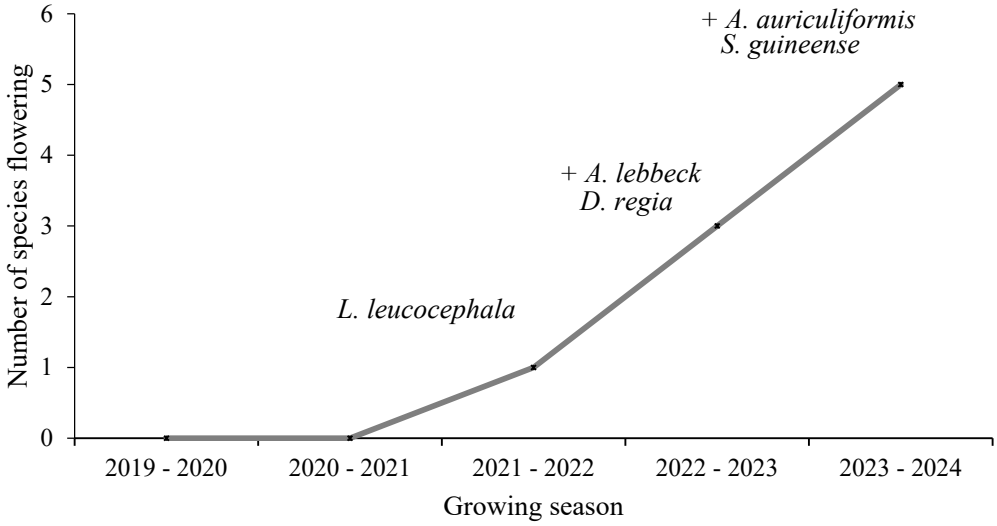

Figure 7. Flowering of woody species in the 2019–2020 to 2023–2024 cropping seasons.

A total of 98 new individuals from natural germination (height > 30 cm) were observed at the end of the 2023–2024 season. Two species contributed most to the number of juveniles recorded: *L. leucocephala* with 79 individuals (80.6%) and *A. lebbeck* with 19 individuals (19.4%). However, many germinations were observed with seedlings at the 3 to 4-leaf stage for *A. auriculiformis*, *A. lebbeck*, and *L. leucocephala*.

3.2.2. Dynamics of the Herbaceous Layer

A total of 13 spontaneously established herbaceous species were identified since their appearance during the 2020–2021, 2021–2022, 2022–2023, and 2022–2024 growing seasons (Table 6). These species were observed at the base and/or 1 m from the trees in the amended areas and also between the corridors. *Bulbostylis pseudoperennis*, *Microchloa cupricola* (Rendle) Stapf, *Imperata cylindrica* (L.) P. Beauv, *Celosia trygina* L., and *Setaria pumila* mainly established themselves on the unamended soil of the corridors formed by the lines of the ligneous plantations. These species were all observed at the end of the first year of cultivation in 2020. *Ageratum conyzoides* L., *Euphorbia hirta* L., and *Tithonia diversifolia* (Hemsl.) became established during the second growing season (in 2021). *Crassocephalum rubens* (Jus. Ex Jacq.), *Cynodon dactylon* (L.) Pers, *Nicandra physaloïdes* (L.), and *Panicum maximum* Jacq. became established during the 2022–2023 season, mainly in the amended growing halos of woody species.

Table 6. Dynamics of spontaneous herbaceous vegetation between tree species plantation corridors (**RA** (%): relative abundance, **ΔR** = difference in cover between measurement dates).

Species	Family	2021	2023	ΔR (%)
Bulbostylis pseudoperennis Goetgh.	Cyperaceae	86	48	−38
Microchloa cupricola (Rendle) Stapf	Poaceae	49	68.6	+19
Imperata cylindrica (L.) P. Beauv.	Poaceae	12	19	+7
Celosia trygina L.	Amaranthaceae	3.2	6	+2.8
Setaria pumila (Poir.) Roem. & Schult.	Poaceae	2.2	0.2	−2
Teramnus labialis (L.f.)	Fabaceae	2	9	+7
Ageratum conyzoides L.	Asteraceae	1.2	5.8	+4.6
Euphorbia hirta L.	Euphorbiaceae	0.4	5	+4.6
Tithonia diversifolia (Hemsl.)	Asteraceae	0.2	1	+0.8
Crassocephalum rubens (Jus. Ex Jacq.)	Asteraceae	0	0.4	+0.4
Cynodon dactylon (L.) Pers.	Poaceae	0	1.2	+1.2
Nicandra physaloïdes (L.)	Solanaceae	0	3	+3
Panicum maximum Jacq.	Poaceae	0	0.2	+0.2

B. pseudoperennis and *M. cupricola* were the most abundant species. The cover change was in favor of *M. cupricola* between the observations made in March 2021 and those made in March 2023, with 68.6% compared with 48% for *B. pseudoperennis*. Except for *I. cylindrica* (19%), the other species had overlap values of less than 10% during the last observation season. Across the system as a whole, ground cover by these spontaneously established herbaceous plants was in the region of 65 to 80% (Figure 8).



Figure 8. Spontaneous colonization and undergrowth regeneration of herbaceous species. Photo by Serge Langunu, April 2024.

4. Discussion

4.1. Dynamics of Mineral Composition in the Soil Around Trees over Time

Observations made in previous studies on plantations over 15 years old showed high concentrations of metals (As, Cd, Co, Cu, Pb, and Zn) in the amended soil of trees planted at Penga Penga [32] and in the Kipushi sedimentation basin [43]. To explain this situation, and based on the literature [28], the hypothesis of enrichment due to lateral transfers from surrounding polluted soils was put forward. The results of the present study support this hypothesis based on the dynamics of metal concentrations in the root growth horizon during the observation period from 2019 to 2023. Indeed, a significant enrichment of metals was observed in the restored pits, particularly for copper (Cu), whose concentration in 2023 was eight times higher than in 2019 (Figure 4). This trend is also evident for elements typically scarce in the region's soils, such as arsenic, cadmium, and lead, supporting the hypothesis of external inputs, notably from the heavily contaminated soils of Penga Penga [12,37,54]. These findings indicate that such enrichments can occur over a relatively short period. The organic amendments used, especially municipal compost, influence the soil's chemical composition. Their heterogeneity, stemming from the nature of inputs and processing methods, can lead to either the introduction or stabilization of trace metals [55]. Some amendments add trace metals, while others stabilize contaminants by improving soil structure and nutrient availability [56]. In the former case, metals such as Cu, Zn, or Pb may be directly introduced through amendments [57,58].

Furthermore, the improved soil structure resulting from these amendments enhances the retention of fine particles and organic matter, facilitating the lateral migration and accumulation of metals from surrounding soils enriched in Cu and other metals due to industrial activities, particularly from the Gécamines copper smelting plant [32,59,60]. Ref. [43] reported a significant increase in Cu and Co concentrations in amended layers compared to tailing soil layers in the experimental trial with tree species on mine tailings. Biological processes also play a crucial role in this dynamic. Root activity and organic matter decomposition alter rhizosphere conditions, promoting the remobilization of adsorbed metals. Root exudates can release chelating agents, thereby increasing the solubility and bioavailability of metallic elements [61–63]. These physicochemical and biological interactions contribute to the observed reconcentration of metals, particularly Cu, in the planting pits after four years.

Alongside this accumulation of trace metals, a decline in concentrations of essential macroelements was observed, reflecting a gradual deterioration in soil fertility conditions (Figure 5). There are several possible explanations for this decline. Firstly, the increase in metal concentrations disrupts the soil's biological balance and reduces the availability of nutrients for tree roots, a phenomenon that has been widely documented [55,56,61]. On the other hand, leaching and erosion processes seem to be exacerbated by the youth of the plantation. The root system, which is still not very dense or extensive, does not effectively stabilize the soil, which encourages nutrients to migrate to deeper horizons or less concentrated neighboring areas.

An additional factor of observed variability lies in the organic amendments used, whose influence on the success of phytoremediation is well documented [11,64]. Depending on their composition and degree of stabilization, soil improvers influence the dynamics of metals and nutrients in different ways. For example, compost rich in humified organic matter plays a stabilizing role by limiting the bioavailability of metals and improving soil structure. Conversely, less stabilized compost can rapidly release nutrients, but its beneficial effect remains limited over time due to its rapid biodegradation. The heterogeneity of the effects observed between the different plots at Penga Penga therefore suggests that the quality of the soil improvers and how they are applied must be rigorously optimized

to ensure the long-term success of phytoremediation. Despite the reduction in nutrients, their concentrations in the amended zone remain higher than those in the surrounding soil (Table 3), enabling the trees to maintain healthy growth. A key factor explaining this resilience is the neutral pH observed in the amended soil (Table 3), which favors the availability of nutrients to plants, even in soil heavily polluted with trace metals. This pH stability could be the result of the interaction between the organic matter from the soil improvers and the biological activity of rhizospheric micro-organisms, helping to buffer the pH variations often observed in contaminated soils [65–67].

All these observations underline the need to adopt appropriate strategies to maximize the effectiveness of soil improvers and guarantee the optimum development of phytostabilisation trees. It seems essential to favor stabilized soil improvers rich in organic matter, such as well-matured composts, which promote nutrient retention while reducing the bioavailability of trace metals [68,69]. In addition, the application of soil improvers needs to be carefully adjusted according to soil properties and local environmental conditions, to limit the risks of leaching and erosion [70]. An approach combining organic amendments and complementary techniques, such as the introduction of symbiotic microorganisms (mycorrhizae, growth-promoting bacteria), could prove particularly effective in improving plant resilience to metal contamination [70–72]. In addition, it would be important to consider the variability of soil and environmental conditions, given that the effect of amendments varies according to soil texture, rainfall, and the initial composition of the substrate.

4.2. Medium-Term Plantation Dynamics

The planting of trees on metal-contaminated soils generally fails due to a lack of knowledge about the factors that stimulate their growth and development [73]. The choice of plant species, amendments, planting techniques, and climate are the limiting factors for plant development [74–76]. The results of this study are a first for the Katangan copper arc region, with systematic monitoring from the time the experiment was set up through to its medium-term follow-up. The conclusions of previous studies [31–33,77] presented interesting prospects for the implementation of trees in remediation strategies based on the excavation of contaminated soils by replacing uncontaminated substrates with mine tailings and soils polluted with trace metals. The results of this study confirm the success of this technique in terms of tree survival and growth. It can be seen that the planted trees reached heights of up to 8 m in a relatively short space of time (Figure 5).

Despite the tendency for metal concentrations in the planting hole to increase, better survival was observed 4 years after planting. This is evidenced by better growth in height and diameter for most species. Indeed, it has been shown that some tree species can survive and develop in soils contaminated by trace metals, despite high soil concentrations [78,79]. This ability to survive at high metal concentrations is perhaps due to their capacity to avoid, absorb, or transfer metals efficiently in their plant tissues [80], but also the fertility conditions observed in the soil (Table 3). Except for *M. indica*, the other five tree species used in this study have already demonstrated their ability to grow on mine tailings and soils polluted with trace metals by mining activities around the world [40,41,46].

The results relating to the diametric structure of the stand in this study show a distribution of trees by diameter class in an inverted "J" shape (Figure 4). This pattern indicates that there are many small-diameter trees and few large-diameter trees, indicating a stand in full regeneration and growth [81]. It has been established in the literature that a stand with such a structure can develop and grow plants over time [82]. This thesis is supported by the number of individuals who appeared in this trial. For example, *A. auriculiformis* had a large number of regenerating (+700) young plants at the three- to four-leaf stage, and *L. leucocephala* was the species that showed the largest number of juveniles that were less than 30 cm tall.

On uncontaminated soils, the species studied are characterized by rapid growth and high regeneration potential, reaching heights of up to 20 m in 6 to 8 years [83–85]. At four years, they were between 3.0 and 8.6 m tall and had diameters ranging from 4.9 to 10.3 cm, confirming their vigor and sustained growth (Table 6). These results are comparable to those reported by Gnahoua et al. [53] and Numbi et al. (in press), who observed in Côte d'Ivoire and the DRC, respectively, that individuals of *A. auriculiformis*, *A. lebbeck*, *L. leucocephala*, *D. regia*, *M. indica*, and *S. guineense* reached heights of 5.20 to 14.53 m and diameters of 5.6 to 14.26 cm at six years of age in uncontaminated soils. These growth rates are consistent with those reported in other regions with similar ecological conditions. In India, for example, *A. lebbeck* is known for its rapid growth, reaching 18 m in height and 66 cm in diameter in 10 years in unpolluted soil [40]. In the Philippines, *L. leucocephala* shows an annual growth rate of 2.5 m in height and 5 cm in diameter, reaching 20 m in just 8 years (NAS, 1984, cited by [53]. These results confirm the high potential of these species for reforestation and phytoremediation in tropical environments.

Overall, these tree species can help restore degraded ecosystems because of their ability to fix atmospheric nitrogen in the soil and improve overall soil quality [86–88]. However, *M. indica* showed a relatively low growth rate compared with other species under the same conditions. This difference in growth can be explained by the intrinsic factors of the species, but also by competition for resources with the other species. The mango tree needs resources such as water, nutrients, and light to grow and prosper, but in situations of competition with other species, as in this study, the mango tree may grow more slowly [89].

In addition, the difference in growth observed between species is also reflected in the dynamics of the speed of flowering and fruit production. It can be seen (Figure 7) that the species entered flowering at different times. This differentiation can be explained by genetic codes and intraspecific variability, but also by environmental conditions, particularly competition for nutrients and light [90]. These results suggest that the remediation technique based on excavation/replacement by municipal compost followed by planting is a good approach for rehabilitating soils polluted by trace metals [55], but it is important to monitor the increase in metal concentrations in the amended zone to reduce the risk of contamination of the food chain through the accumulation of metals in plant shoots. In addition to growth-related findings, it is important to highlight the potential risk of metal uptake by plants, particularly for the fruit-bearing species studied here. The transfer of contaminants to edible plant parts raises significant food safety concerns, justifying targeted analyses of fruits to assess potential health risks. In this regard, the studies by [76,77] have already documented metal concentrations in various plant compartments, including fruits, leaves, and wood.

In addition, this remediation technique made it possible to trigger facilitation processes for the colonization of herbaceous species in this type of environment [33]. The trees used acted as nurse plants, encouraging the colonization of herbaceous metallophytes and/or non-metallophyte species. In fact, by modifying the soil conditions in their zone of influence, the planted trees created a microclimate that favored the establishment or spontaneous propagation of *B. pseudoperennis*, *M. cupricola*, *I. cylindrica*, C. *trigyna*, *T. labialis*, *C. dactylon*, *E. hirta*, *N. physaloïdes*, *T. diversifolia*, *P. maximum*, *A. conyzoides*, and *C. rubens* (Table 6). In addition, this spontaneous colonization of herbaceous species can be attributed to three main factors: firstly, there was an improvement in edaphic conditions with the addition of municipal compost, which enriched the soil in nutrients and improved its structure, thus creating a favorable environment for the germination and growth of herbaceous species [91,92]. Secondly, the presence of a seed bank in the soil and municipal compost meant that, as conditions improved, these seeds germinated and colonized the area. Finally,

the dispersal of seeds carried by wind, animals, and human activity from surrounding areas favored the establishment of new herbaceous species [91,93].

In addition, these species had different appearances and growth dynamics depending on the growing season. Some groups appeared one year after planting, while others appeared in the fourth year. Similar observations were made by Mwanasomwe et al. [33], who observed a high relative abundance of spontaneous colonization of herbaceous and even woody species in a mine tailing remediation trial 15 years after planting. Boisson et al. [94] noted that the installation of a pioneer plant in phytostabilization trials favored the emergence and survival of two cupricolous species in the Katangan Copperbelt. Indeed, the richness of herbaceous species in this study is clear evidence that plant–plant facilitation positively affects the environmental remediation of soils contaminated by trace metals and provides additional information on biodiversity conservation.

4.3. Implications for the Remediation of Soil Polluted by Trace Metals

The results obtained in this study highlight several major implications for the ecological management of contaminated soils and phytoremediation strategies in the Katangan Copper Arc. On the one hand, the observed effectiveness of certain woody species, notably *L. leucocephala*, *A. lebbeck*, *S. guineense*, and *A. auriculiformis*, demonstrates their potential for revegetation or ecological restoration programs in the context of severe metal pollution [40,42]. Their strong resilience, combined with their sustained growth in amended soils, confirms the relevance of their selection for environmental rehabilitation projects [40,53]. Furthermore, the progressive enrichment in trace metals observed in amended soils reveals the importance of long-term monitoring to prevent soil saturation and guarantee the sustainability of Phyto technological interventions. The maintenance of pH neutrality in amended soils, despite the accumulation of metals, testifies to the crucial role of organic amendments, which promote the chemical stability of the soil and the controlled availability of nutrients required by plants [95,96]. The observations made in this study highlight the need to favor amendments rich in organic matter to limit the mobility and bioavailability of metals and promote beneficial biological activity in the rhizosphere. The fine-tuning of amendment techniques according to local soil properties and environmental conditions is therefore essential to maximize the effectiveness of phytoremediation. Finally, the adoption of combined strategies, such as the introduction of symbiotic micro-organisms (mycorrhizae, growth-promoting bacteria), could strengthen the resilience of plantations to metal pollution. Taken together, these results open up promising prospects for the large-scale application of phytotechnologies in affected mining areas, helping to restore ecosystems and improve the environmental and health conditions of local populations.

In order to critically assess the scope and generalizability of these findings, it is also important to consider the limitations inherent to the present study: (i) soil-focused scope: the research was limited to assessing mineral dynamics in amended soils, without evaluating metal uptake in plant aerial parts or impacts on soil fauna [97,98]; (ii) lack of hydrological monitoring: potential leaching of metals into groundwater was not assessed due to the absence of appropriate tools such as lysimeters or piezometers; (iii) limited sampling frequency: although the study spanned four years, soil sampling was performed at spaced intervals, restricting detailed temporal analysis [99]; (iv) biological indicators not included: key indicators such as microbial activity and soil biodiversity were not considered, despite their importance in ecological assessment [100]; and (v) site-specific context: the results are specific to the Katangan Copperbelt and may not be directly transferable to other pedoclimatic contexts [101]. These limitations guide our future research, which

will incorporate plant biomass monitoring, soil biological indicators, and hydrological assessments to provide a more comprehensive evaluation of restoration outcomes.

5. Conclusions

This study examined changes in the mineral composition of soil and woody and herbaceous vegetation at metal-contaminated sites, using in situ experiments. The results show a change in the mineral composition of the soil, with an increase in trace metal concentrations and a decrease in nutrients over a short period. Vegetation dynamics revealed significant differences between individuals planted in amended and unamended pits, with a zero percent survival rate in the latter. The growth in height and circumference of the planted species is notable, reaching up to 8 m in height on average for *L. leucocephala* and 22 cm in circumference for *S. guineense*. In addition, 13 spontaneous herbaceous species were observed between the planting corridors of the tree species. These results show that it is possible to revegetate urban soils polluted by trace metals with fast-growing tree species and contribute to the conservation of biodiversity. To help increase the production of ecosystem services through this remediation strategy for soils polluted with trace metals, native woody species should be integrated. Building on this approach and considering the insights gained from our study, it is essential to derive broader lessons that can inform restoration practices beyond the Katanga Copperbelt. Based on the results obtained in the specific context of the Katanga Copperbelt, we suggest that future restoration initiatives in other regions consider the following: (i) the use of site-appropriate organic and mineral amendments that contribute to a successful establishment of tree species in elevated metal-contaminated soil and provide q list of indigenous and exotic species to be used for phytostabilization in tropical areas; (ii) the expansion of environmental monitoring to include groundwater, vegetation, and soil biology for an integrated assessment; (iii) the promotion of sustainable practices relying on local resources to reduce costs and support a circular economy approach; and (iv) the active involvement and capacity building of local stakeholders to ensure the sustainability of interventions. These recommendations aim to broaden the applicability of our findings while respecting regional specificities.

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