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RESEARCH

Application of soil amendments to reduce the transfer of trace metal elements from contaminated soils of Lubumbashi (Democratic Republic of the Congo) to vegetables

Félicien Mununga Katebe · Gilles Colinet · Jean-Marc Kaumbu Kyalamakasa · Michel Mpundu Mubemba · M. Haïssam Jijakli

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Abstract The extraction of copper and cobalt from mines has led to the contamination of agricultural soils by trace metal elements (TMEs) (e.g. Cu: 204 to 1355 mg/kg). The mining industry is one of the sources of metal discharges into the environment, contributing to water, soil, and air contamination and causing metabolic disorders in the inhabitants of the city of Lubumbashi (R.D. Congo). This study assessed the effectiveness of organocalcareous soil improvers applied to TME-contaminated soils to reduce their transfer to plants. Following a factorial design, increasing doses of organic soil improvers (chicken droppings and sawdust) and agricultural lime were applied to the soils of three market gardens (high, medium, and low Cu contamination). The experiment was monitored for 60 days. Soil physicochemical properties (pH, TOC, and total and available copper, cobalt, lead, cadmium, and zinc (mg/kg)) were determined for the three gardens and in the vegetable biomass. The daily consumption index of the vegetables was determined based on total TME content. The results show that organocalcareous soil improvers did not promote plant growth and survival on soils with high and medium levels of copper contamination. However, on soils with low copper content, organocalcareous soil improvers improved germination and plant survival and reduced the transfer of metals from the soil to the plants. The best germination and plant survival rates were obtained with the lightly contaminated market garden. In addition, the organo-limestone amendments applied to the soils slightly increased the soil pH from acidic to slightly acidic, with pH values ranging from (5.43 ± 0.07 to 7.26 ± 0.33). The daily vegetable consumption index obtained for cobalt in the low-contaminated garden ranged from (0.029 to 0.465 mg/60 kg/day), i.e. from 0.5 to 8.45 times higher than the FAO/WHO limit, unlike the other trace metals (Cd, Cu and Pb) for which the daily consumption index found was lower than the FAO/WHO limit. Organocalcareous soil improvers can only be applied to soils with low levels of TME contamination, but for soils with medium to high levels of metal contamination, new soilless production techniques such as hydroponics or bioponics are needed.

F. M. Katebe (✉) · M. H. Jijakli
Centre de Recherches en Agriculture Urbaine (C-RAU), Gembloux Agro-Bio Tech, University of Liège, Passage Des Déportés 2, 5030 Gembloux, Belgium
e-mail: munungakatebe@gmail.com

F. M. Katebe · J.-M. K. Kyalamakasa · M. M. Mubemba
Ecology, Ecological Restoration and Landscape, Agronomy Faculty, University of Lubumbashi, Route Kasapa, Campus Universitaire, Lubumbashi, Kinshasa, Congo

G. Colinet
Water, Soil & Plant Exchanges TERRA, Gembloux Agro-Bio Tech, University of Liège, Passage Des Déportés 2, 5030 Gembloux, Belgium

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Introduction

Lubumbashi, a city in the Katanga copper belt rich in copper and cobalt, is facing environmental problems that are extremely worrying for the human health of the population, due to mineral processing activities and the intensification of mining company activities. These activities have resulted in soil, water, plant, and atmospheric pollution. The presence of important metals, such as copper, cobalt, arsenic, and cadmium, exceeds the limits set by the World Health Organization (WHO) and is found in agricultural and residential soils (Alfaro et al., 2022; Jiang et al., 2022; Shutcha et al., 2015). Contaminated soils transmit metals to plants, disrupting the functioning of living organisms (Briffa et al., 2020; Okereafor et al., 2020). Research carried out in Lubumbashi showed that vegetables grown in gardens and sold on various markets were contaminated with heavy metals, ranging from 13.1 to 39.3 mg/kg for copper and 0.33 to 2.94 mg/kg for cobalt (Mubemba et al., 2014; Mununga Katebe et al., 2023). Toxicity thresholds for copper and cobalt have been suggested by the WHO, namely around 10 and 1 mg/kg vegetable dry matter (Radwan & Salama, 2006). The same observations made by (Golia et al., 2023), showed that the pollution of agricultural soils and green spaces in downtown Thessalonica was due to human activities, notably rail and road passenger transport.

Soil pH, organic matter, metal, and redox levels can promote the release of Cu and Co from parent materials and their dispersion in the environment in various forms: solid, colloidal, and soluble (Hooda, 2010; Jadoon et al., 2024). In this way, the ability of metals to move in soils depends on the control of certain physicochemical parameters such as pH, total organic carbon, clays, oxides, sulfides, and carbonates. In addition, redox potential can promote the mobility and speciation of metals in soil (Hooda, 2010; Kabata-Pendias, 2004). Metals are transferred in solid, colloidal, and soluble forms. However, the distribution of plants in the natural environment is influenced by Cu and Co availability on the one hand and physicochemical conditions on the other (Faucon et al., 2011; Jiang et al., 2022; Lange et al., 2014; Saad et al., 2018). The mobility and bioavailability of Cu and Co can be transferred to the various components of the environment, such as water, soil, air, plants, and the food chain (Banza et al., 2009; Katemo Manda et al., 2010; Lange et al., 2014, 2016; Mwanamoki et al., 2014). The toxicity threshold for TMEs was exceeded in the urine of individuals living near ore processing facilities who were exposed to contamination by these TMEs. The TME concentrations observed were 17.8 ppm As, 0.75 ppm (Cd), 15.7 ppm (Co), 17.1 ppm (Cu), 3.17 ppm (Pb), and 0.028 ppm (U). However, the WHO recommended limits were 8, 24, 0, 20, 0, 36, and 0.008 mg/kg respectively for As, Cd, Co, and U in urine (Banza et al., 2009; Ilechukwu et al., 2021; Song & Li, 2015). This situation contrasts with individuals who are far removed from sources of pollution.

There are three ways in which humans can be exposed to metal contamination, namely inhalation, ingestion, and skin contact (Acosta et al., 2014; Rajan et al., 2023). In the environment, high levels of TMEs can cause adverse consequences for human health, such as respiratory problems, DNA damage, sperm mobility, and sperm count. These metabolic problems can persist in the human body (Waqas et al., 2024). What's more, the effects of metals are not the same in humans. For example, mercury, and lead have an impact on the reproductive, nervous, and gastrointestinal systems (Mashyanov et al., 2017; Pratush et al., 2018; Vöröš et al., 2018). On the other hand, As, Zn and Ni can cause dysfunction in the heart, liver, and DNA (Chao et al., 2017; Sanchez et al., 2018; Stefanowicz et al., 2020). According to Izah et al (2016) and Nordberg et al (2018), Cu, Cr, and Cd impact the circulatory, pulmonary, and intestinal systems. Research in Sri Lanka has shown that consumption of cadmium-contaminated rice was responsible for the onset of kidney failure in 5,000 people living in an agricultural area (Bandara et al., 2008; Cao et al., 2020; Ghayoraneh & Qishlaqi, 2017; Gómez-Meda et al., 2017; Rahman et al., 2022). TME-contaminated soils can be sustainably treated using organic and calcareous amendments (Sarwar et al., 2017; Wan et al., 2016) to reduce the transfer of metals from soil to plants. After using organic amendments based on water hyacinth (*Eichhornia crassipes*) and agricultural lime, copper concentrations in the aerial parts of *Microchloa altera* plants decreased from

(76.3 ± 22.1 mg/kg) to (25.2 ± 3.4 mg/kg) (Jaskulak et al., 2020; Lin et al., 2022; Shutcha et al., 2015). Soil pH, cation exchange capacity, and metal stability in soils were improved through the use of chicken droppings and limestone, which reduced the transfer of metals from the soil to the various plants grown on contaminated soils. However, the majority of this research demonstrates that the quantities of organic soil improvers and limestone used are extremely high. Different types of organic matter and crops need to be tested. Our research aims to validate the use of organocalcareous soil improvers in contaminated soils on the one hand and to test whether combining small quantities of different types of organic matter with lime would reduce the transfer of heavy metals (Cu and Co) from soil to plants. We expect to achieve quality vegetable production in the city of Lubumbashi. This article is part of a research project to propose solutions to the various environmental problems of urban agriculture in Lubumbashi. Firstly, we showed that garden soils were slightly, moderately, and heavily contaminated with trace metals and that vegetables bought at the market were heavily contaminated (Mununga Katebe et al., 2023). Subsequently, this study aims to reduce the transfer of metals from soil to plants using the combination of low quantities of different organic matter and lime. The study of metal transfer from soil to plants has never focused on these types of organic matter and the vegetable crops used (Fig. 1).

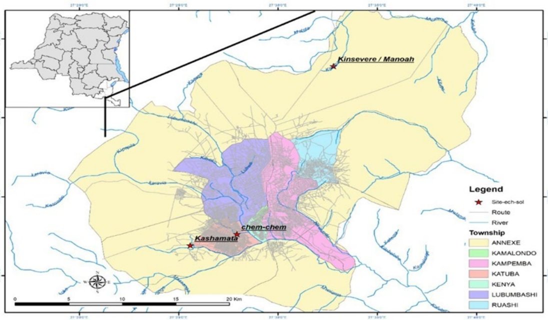

Fig. 1 Illustration of sampled urban and peri-urban market gardens in Lubumbashi

Materials and methods

Study area

The city of Lubumbashi (11° 36′ 30.6" S and 27° 28′ 35.7" E) currently comprises seven communes, including Annexe, Kamalondo, Kampemba, Katuba, Kenya, Lubumbashi and Ruashi (Fig. 2), and covers an area of 747 km^2. Lubumbashi's climate is classified as CW6 according to the Köppen classification system, characterized by three distinct seasons: a rainy season from November to March, a dry season from May to September, and two transitional months (April and October). Average annual rainfall in the region is estimated at around 1,200 mm, with an average annual temperature of 20 °C at an altitude of between 1,200 and 1,300 m. Soils in the Lubumbashi region belong to the ferralitic soil category, with a pH of around 5.9, and are mainly colonized by cupricolous plant species such as *Cynodon dactylon, Haumaniastrum katangense, Microchloa altera, Imperata cylindrica, and Bulbostislis pseudoperenis.*

Experimental design, soil sampling and crop selection

An experiment was conducted to evaluate the efficacy of organocalcareous amendments on the transfer of metals from soil to plants, following a completely randomized factorial design. The treatments included

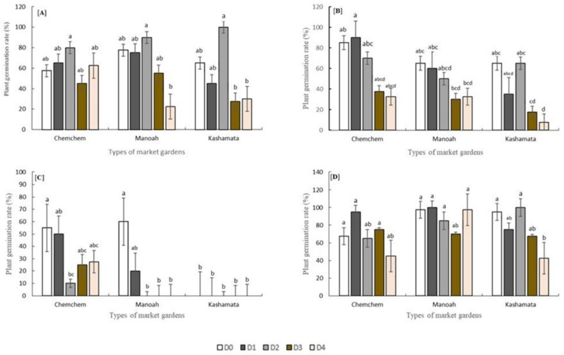

Fig. 2 Effect of organocalcareous amendments on the germination rate of four plants grown on contaminated soils. Legend: [A]: *A. Vulgaris;* [B]: *B. chinesis*; [C]: *B. vulgaris*; [D]: *B. carinata*; D0: no amendments; D1: 150 g sawdust; D2: 150 g hen droppings; D3: 75 g sawdust + 15 g lime; D4: 75 g hen droppings + 15 g lime

five levels of amendment (D0: no amendment; D1: 150 g sawdust; D2: 150 g chicken droppings; D3: 75 g sawdust and 15 g agricultural lime; D4: 75 g chicken droppings and 15 g agricultural lime) and three types of urban market garden soils with low, medium, and high copper contamination (Kashamata, Manoah Kinsevere, and Chem-Chem), with four replications applied to the four market garden crops (*Brassica chinensis, Amaranthus vulgaris, Beta vulgaris, and Brassica carinata*).

Vegetable crops: Among the twenty most cultivated and consumed species in the city of Lubumbashi, four vegetable plants (*Brassica chinensis, Amaranthus vulgaris, Beta vulgaris, and Brassica carinata*) were used in these trials. Improved seeds were purchased from local stores in Lubumbashi. After 60 days of cultivation, all plants were harvested and then dried in an oven to determine the levels of trace metals in the produced biomass and to assess the sanitary quality of the vegetables produced after applying organocalcareous amendments to soils contaminated with metals.

Soil: The experiments conducted in 2019 were carried out in polyethylene pots containing 2.5 kg of soil and placed in a greenhouse in the experimental garden of the Faculty of Agronomic Sciences at the University of Lubumbashi. Three categories of market garden soils were selected based on different levels of copper contamination (204 mg/kg, 535 mg/kg, and 1355 mg/kg of copper), respectively, for the soils from the Kashamata, Manoah Kinsevere, and Chem-Chem gardens (Fig. 1). Soil samples were taken from five different locations in each of the three urban market gardens, at a depth of 0 to 20 cm, and each batch of five samples was mixed to form a composite sample. 500 g of the composite sample were preserved for laboratory analysis to determine the physico-chemical characteristics of the market garden soils and to minimize soil heterogeneity within the same market garden. Soil samples were air-dried for 14 days, crushed in a porcelain mortar, and sieved with a 2.0 mm sieve. The sieved soil samples were stored in polyethylene bags for 7 days before being transported to the laboratory for analysis. The pH and trace metal content of the soil samples were determined. According to the International Soil Classification, the soils of Lubumbashi belong to a group known as Ferralsoils (WRB, 2022).

Physicochemical characteristics of garden soils

Three types of urban market gardens (Chem-Chem; Kashamata and Manoah Kinsevere) were selected, and physicochemical characteristics were determined in each soil of these gardens (Table 1).

- **Amendments:** In this experiment, three types of amendments were applied to soils contaminated

Table 1 Physico-chemical characteristics of soils in Lubumbashi's urban market gardens

Market Gardens/Heavy metals (mg/kg)	Kashamata	Manoah Kinsevere	Chem-Chem	Toxicity threshold (mg/kg)
pH water	6,7	5,4	5,8	7
pH KCl	6,3	4,5	5	7
TOC (%)	2,54	2,3	3,14	-
Cu/total	204	535	1355	100
Cu/dispo	0,026	0,001	0,046	-
Cd/total	$<0{,}05$	$<0{,}05$	45	2
Cd/dispo	0,013	0,002	0,058	-
Co/total	Nd	Nd	Nd	30
Co/dispo	0	0,018	0,069	-
Pb/total	20	81	221	100
Pb/dispo	1,427	2,472	1,255	-
Zn/total	60	394	1470	300
Zn/dispo	0,643	0,261	1,933	-

Legend. Cu, Cd, Pb and Zn/dispo: available; <0.05: below the detection limit by trace metals, including chicken droppings, sawdust, and agricultural lime. These amendments were purchased from local markets in Lubumbashi. The use of lime-based amendments on metal-contaminated soils reduces the mobility and bioavailability of metals by increasing soil pH and solubilizing oxides, resulting in the precipitation of trace metals. In addition, organic soil improvers, notably chicken droppings and sawdust, were purchased locally in Lubumbashi and composted for 15 days before sowing the crops. Organic soil improvers are renowned for their richness in organic matter, which positively influences the mobility of trace metal elements in soils by releasing organic acids that also increase soil pH.

The various organic and calcareous amendments were analyzed to determine their nutritional quality (Table 2). The chicken droppings were purchased from an industrial farm (Congo Oeuf) located some 15 km from the Faculty of Agronomic Sciences at the University of Lubumbashi. Agricultural lime was purchased from a lime and calcium producer in Likasi, 120 km from Lubumbashi. The sawdust was purchased from the sawmills of the Texaco market, located in the city of Lubumbashi, four kilometers from the Faculty of Agronomic Sciences.

Measurement and analysis

The pH and TME content of the soil samples were determined. Water pH and KCl pH were determined using the potentiometric method (Lasota et al., 2020) and total organic carbon (TOC) by the Springer-Klee method. Total soil TME contents were measured using a portable X-ray fluorescence spectrophotometer (XRF, Olympus Delta Classic Plus, model DCC-4000), as described by (Mpinda et al., 2022). In addition, exchangeable TME contents were determined by the 0.01 M CaCl2 extraction method and measured by atomic absorption spectrophotometry (AAS, VARIAN 220, Agilent Technologies, Santa Clara, CA, USA) (Houba et al., 1996). Trace metal and major element contents were determined in chicken droppings and sawdust to determine the nutritional quality of these amendments. Extraction with aqua regia was carried out by ISO 11466:1995. For extraction, 3 g of sample and 28 ml of aqua regia were used. The extract was filtered through paper filters, diluted with demineralized water, and then digested for 20 min at 175 °C in a microwave digestion vessel. A typical calibration method was used to determine trace metals (Cu, Co, Cad, Pb) in the different materials (chicken droppings and sawdust) using Perkin Elmer's Optima 7000 DV optical plasma emission spectrometer (ICP-OES). Plant leaves from four harvested vegetables were washed with tap water to remove soil particles, to determine only the metals absorbed by the plants. The leaves were oven-dried at 95 °C for 24 h, then ground into powder in a porcelain mortar. Plant samples rendered as powders were digested in 10 ml of $HNO_3/HClO_4$ (7:1 v/v) at 130 °C, as reported by (Caçador et al., 2009; Momen et al., 2006; Otte et al., 1993). However, concentrations of trace metals such as Zn, Cu, Co, As and Cd were determined by atomic absorption spectrometry (AAS) with detection limits of 0.010; 0.10; 0.05; 0.05, and 0.05 µg/g respectively for Zn, Cu, Co, As and Cd, applying to all analytical techniques used.

Estimating the daily intake of vegetables

To determine the level of heavy metal toxicity in plant biomass, the daily dose was estimated for vegetable consumption in the city of Lubumbashi for an individual over one day, one week, or even one month. This index also makes it possible to determine the quantities of metals ingested by a person of known

Table 2 Physico-chemical characteristics of hen droppings, sawdust and agricultural lime

Types of amendment	Mg (%)	Ca (%)	Heavy metals (mg/kg)					
			Cu	Co	Cd	Pb	Zn	Fe
Agricultural quicklime ($CaCO_3$ $MgCO)_3$	25	52	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05
Chicken droppings	0,11	7,48	80,5	5,6	0,04	0,3	321,3	654
Sawdust	0,05	0,12	22,6	2,4	0,3	1,9	21,6	1064

body weight, and is calculated using the following relationship (Abuzed Sadee & Jameel Ali, 2023; Adefa & Tefera, 2020):

$$EDI = \frac{C_{mg/kg} \times Intake\left(\frac{kg}{day}\right)}{BM(kg)}$$

C_{mg} /kg is the average concentration of the metal in the vegetable, where Intake represents the quantity of vegetables to be consumed per day (kg/day), and finally, BM is the average body weight of the vegetable consumer. The WHO recommends eating 300 to 350 g of vegetables a day. Then, an average of 0.325 kg/person/day was used to estimate the daily dose of vegetables to be consumed, and a body mass of 60 kg was chosen as the average body weight.

Statistical analysis

For each plant grown separately, vegetative parameters were subjected to a two-factor analysis of variance (ANOVA), and means were compared using a Tukey test with a significance level of 5%. Data was processed using R×64 4.1.2 and Minitab 21.3.1.0 statistical software.

Results and discussion

Effect of organocalcareous soil improvers on growth parameters of four vegetable crops grown on soil contaminated with heavy metals in Lubumbashi

Germination rates of four plants grown on soil contaminated with heavy metals

Figure 2 shows that plant germination rates vary from species to species and from garden to garden. Analysis of variance shows significant differences between the different types of organic material used ($p < 0.05$). However, the best germination rates of *A. vulgaris* seedlings were obtained with the D2 > D1 > D0 > D3 > D4 modality. Furthermore, germination rates of *B. chinensis* plants and analysis of variance showed that the use of organocalcareous amendments significantly influenced plant germination at 7 days, with the best germination rate obtained with modality D1 > D0 > D2 > D3 > D4 ($p < 0.05$). On the other hand, the highest germination rate of B. *vulgaris* plants was obtained with modality D0 > D1 > D4 > D3 > D2, and analysis of variance shows that the application of organocalcareous amendments significantly influenced chard plant germination ($p < 0.05$). Finally, the highest germination rate of *B. carinata* plants was obtained with modality D1 > D0 > D2 > D3 > D4, and the analysis of variance shows significant differences between the organocalcareous amendment modalities used ($p < 0.05$). The work conducted by (Mununga Katebe et al., 2023) classified the soils of the market gardens into three categories: low, medium, and high copper contamination. They found that the vegetables sold in the markets of Lubumbashi are contaminated with trace metal elements. The results of this study show that plants did not grow well in the soils of the gardens with medium and high metal contamination. The use of organocalcareous amendments aims to increase soil pH and reduce the mobility and bioavailability of metals in agricultural soils (Alam et al., 2020; He et al., 2020; Tuan et al., 2020; Yin et al., 2016). However, analysis of variance indicates that the use of various market gardens did not significantly influence amaranth plant emergence rates. This could be attributed to the low nitrogen content of the organic matter supplied to the plants (Felix et al., 2022; Xu et al., 2022). Similar conclusions were drawn by (Mpundu et al., 2014) who found that the application of organocalcareous amendments to agricultural soils had no significant effect on the growth of *A. vulgaris* amaranth plants.

Survival of four vegetables grown in soil contaminated with heavy metals

Analysis of variance (ANOVA) revealed that there were significant differences between the market gardens used in terms of plant survival at all observation dates ($p < 0.05$), unlike the type of amendments applied to the contaminated soils which did not significantly influence amaranth plant survival, however, the Kashamata garden had given the highest survival rate, unlike the others. Thus, the interaction between market gardens and the type of organic and limestone amendments showed that there were significant differences between treatments in terms of plant survival at all observation dates ($p < 0.05$), except at day 15 where the ANOVA revealed no significant difference (Fig. 3I). The survival rate

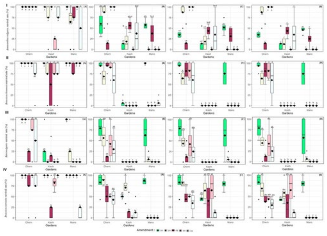

Fig. 3 Effects of organocalcareous amendments on the survival rate of I (*B. carinata); II (B. chinensis); III (B. vulgaris and IV (B. carinata)* plants grown on soil contaminated with heavy metals. Legend: (D0: no amendments; D1: 150 g sawdust; D2: 150 g hen droppings; D3:75 g sawdust + 15 g lime; D4:75 g hen droppings + 15 g lime; -: extreme values; **-**: Mean; ◇: Median; [A]: Survival rate at 15 days; [B]: Survival rate at 30 days; [C]: Survival rate at 45 days; [D]: 60-day survival rate; Amend: Types of amendment; Chem: Chem-Chem; Kash: Kashamata Daipen and Mano: Manoah Kinsevere

of *B. chinensis* plants ranged from 0 to 100%, with Analysis of Variance showing significant differences between market gardens at all observation dates ($p < 0.05$), except at day 15, where ANOVA showed no significant difference. The best survival rate of B. chinensis plants was obtained with the Chem-Chem garden. Furthermore, analysis of variance showed that there were significant differences between the types of organic and limestone amendments applied ($p < 0.05$), for *B. chinensis seedling* survival at all observation dates except day 15, where ANOVA showed no significant difference. The interaction between vegetable crops and types of organic and limestone amendments significantly influenced ($p < 0.05$) B. chinensis seedling survival at all observation dates except day 15 th, where ANOVA revealed no significant difference (Fig. 3II). Regarding the survival rate of *B. vulgaris* plants, analysis of variance shows that the use of different market gardens significantly influenced the survival of B. vulgaris plants at all observation dates ($p < 0.05$), with the highest survival rate obtained in the Manoah market garden. In all cases, organocalcareous soil amendments significantly influenced the survival rate of *B. vulgaris* seedlings ($p < 0.05$) and, the best seedling survival rate was obtained with the modalities (D1 and D0). However, the interaction between market gardens and organocalcareous amendment types significantly influenced *B. vulgaris* seedling survival at all observation dates, except on day 15 where ANOVA revealed no significant difference (Fig. 3III). As for the survival rate of *B. carinata* plants, it varied from ($0.0 + 0.00$ to $100.0 + 0.00\%$), and analysis of variance reveals that there are significant differences ($p < 0.05$) between market gardens in the survival rate of *B. carinata* plants at all observation dates, with the highest survival rate obtained in the Chem-Chem garden. The application of organic and limestone amendments had a significant influence on *B. carinata* plant survival ($p < 0.05$), with the best plant survival rate recorded in the Chem-Chem gardens. On the other hand, the combination of organic and limestone amendments had a significant influence on plant survival ($p < 0.05$) (Fig. 3IV). Furthermore, amaranth plant survival was significantly influenced by market garden types, while organic matter did not significantly influence amaranth plant survival at all observation dates. Similar results were reported by (Ullah et al., 2023; M. Wang et al., 2023a, b) who found that compost application on metal-contaminated soils did not significantly influence germination and survival of *Brassica juncea* plants in the Spanish region of Aznalcóllar (Alam et al., 2020). Our results can be explained by the fact that during the decomposition of organic matter, specific organic compounds can release substances that can immobilize heavy metals by forming precipitates or insoluble complexes. For example, sulfides released during the decomposition of organic matter can bind to heavy metals (Z. Chen et al., 2021; Kwiatkowska-Malina, 2018; Liu et al., 2022; Sun et al., 2021). The results obtained show that the application of organic amendments significantly influenced the pH of the market garden soils. However, an alkaline pH was observed in the soils of the lightly contaminated Kashamata garden with the cultivation of *B. vulgaris*. This phenomenon could be explained by the fact that *B. vulgaris* may alkalize its rhizosphere by excreting hydroxide ions (OH-) or absorbing protons (H+) at the root surface, thus facilitating the absorption of ammonium or nitrates. In contrast, other plants can acidify their rhizosphere. Our results are consistent with those of (Blossfeld et al., 2010), who showed that alpine pennycress (*Noccaea caerulescens* J. Presl & C. Presl) and ryegrass (*Lolium perenne L.*) plants alkalized their rhizosphere by approximately 1.7

and 1.5 units, respectively, while maize (Zea mays L.) plants acidified their rhizosphere.

Effects of organocalcareous soil improvers on the pH of soils contaminated by heavy metals

Table 3 shows the application of organocalcareous amendments on the three soils from the market gardens. The analysis of variance (ANOVA) indicates that there are significant differences between the three market garden soils in terms of pH for all four crops ($p < 0.05$). The highest pH was obtained with the soils from the Kashamata market garden with *Beta vulgaris* as the crop. Similarly, ANOVA reveals that the applied organocalcareous amendments significantly influenced the soil pH ($p < 0.05$) for all four market garden crops. The highest soil pH was obtained with treatment D4 (7.26 ± 0.33), with *B. vulgaris* as the crop, followed by treatments D3, D2, and D1. Additionally, the interaction between the market garden soils and the applied organocalcareous amendments significantly influenced soil pH for all four market garden crops ($p < 0.05$). The highest pH was obtained with treatment D4 (7.26 ± 0.33) on the soils from the Kashamata garden with *B. vulgaris* as the crop. Organocalcareous soil improvers are proposed as techniques for reducing the transfer of metals from soil to plants. Studies conducted by (Mubemba et al., 2014; Shutcha et al., 2015) have shown that organocalcareous amendments reduce the mobility and bioavailability of trace metals (Frick et al., 2019; Khoshru et al., 2023; Narayanan & Ma, 2023; Sarwar et al., 2017; H. Wang et al., 2023a, b; Wu et al., 2016). However, the quantities of amendments are still very large. Our results indicate that the application of organocalcareous soil improvers reduced the transfer of trace metal elements from the soil to the plants, by forming chelates with the trace metal elements, making the soils slightly acidic (Mubemba et al., 2014; Shutcha et al., 2015).

Estimation of daily consumption of leafy vegetables grown in garden soils of Lubumbashi

The estimated daily consumption of vegetables produced in Lubumbashi's urban market gardens was carried out for the Kashamata market garden, a garden with low copper contamination. In contrast, data

Table 3 Effects of organocalcareous amendments on the pH dynamics of soils contaminated with heavy metals

Gardens	Amendments	pH *A. vulgaris*	pH *B. chinensis*	pH *B. vulgaris*	pH *B. carinata*
Chem-chem	D0	5.69 ± 0.03^{h}	5.69 ± 0.07^{fg}	6.07 ± 0.10^{de}	5.96 ± 0.02^{de}
Chem-chem	D1	5.85 ± 0.02^{fgh}	6.05 ± 0.06^{cd}	5.90 ± 0.12^{de}	6.08 ± 0.09^{de}
Chem-chem	D2	6.15 ± 0.04^{de}	6.18 ± 0.09^{c}	6.14 ± 0.13^{c}	6.13 ± 0.08^{d}
Chem-chem	D3	6.37 ± 0.09^{cd}	6.18 ± 0.14^{c}	5.85 ± 0.15^{ef}	$6.05 \pm 0.06d^{e}$
Chem-chem	D4	6.07 ± 0.11^{ef}	5.82 ± 0.06^{ef}	6.02 ± 0.08^{de}	6.46 ± 0.05^{c}
Manoah	D0	5.66 ± 0.03^{h}	5.55 ± 0.11^{g}	5.60 ± 0.10^{ef}	5.48 ± 0.10^{f}
Manoah	D1	5.83 ± 0.05^{gh}	5.79 ± 0.07^{ef}	5.58 ± 0.10^{e}	5.43 ± 0.07^{f}
Manoah	D2	6.33 ± 0.08^{d}	6.16 ± 0.05^{c}	5.78 ± 0.06^{ef}	5.81 ± 0.08^{e}
Manoah	D3	6.01 ± 0.06^{efg}	5.84 ± 0.05^{def}	5.71 ± 0.06^{ef}	5.85 ± 0.23^{e}
Manoah	D4	6.03 ± 0.07^{efg}	5.93 ± 0.13^{de}	5.93 ± 0.13^{de}	6.05 ± 0.06^{de}
Kashamata	D0	6.62 ± 0.12^{b}	6.97 ± 0.10^{ab}	6.33 ± 0.10^{c}	6.69 ± 0.02^{bc}
Kashamata	D1	6.77 ± 0.04^{b}	6.81 ± 0.09^{ab}	6.47 ± 0.22^{c}	6.96 ± 0.05^{ab}
Kashamata	D2	6.74 ± 0.06^{b}	6.83 ± 0.05^{ab}	6.69 ± 0.19^{bc}	7.11 ± 0.21^{a}
Kashamata	D3	6.56 ± 0.07^{bc}	6.77 ± 0.08^{b}	6.97 ± 0.08^{b}	6.76 ± 0.23^{b}
Kashamata	D4	7.22 ± 0.22^{a}	7.02 ± 0.07^{a}	7.26 ± 0.33^{a}	7.21 ± 0.18^{a}
Site effect (p-value)		0.000	0.000	0.000	0.000
Organic matter effect (p-value)		0.000	0.000	0.000	0.000
Interaction Sites x M.O (p-value)		0.000	0.000	0.000	0.000

Legend: (D0: no amendment; D1: 150 g sawdust; D2: 150 g hen droppings; D3: 75 g sawdust + 15 g lime; D4: 75 g hen droppings + 15 g lime

Table 4 Daily consumption of leafy vegetables in Lubumbashi (mg/60 kg/day)

Crop types	Gardens	Types of amendment	Trace metals			
			Cd	Cu	Pb	Co
Limit WHO/FAO			**0,06**	**3**	**0,214**	**0,055**
Amaranthus vulgaris	Kashamata	D0	0,023	0,375	0,004	**0,449**
Amaranthus vulgaris	Kashamata	D1	0,007	0,182	0,005	**0,102**
Amaranthus vulgaris	Kashamata	D2	ND	ND	ND	ND
Amaranthus vulgaris	Kashamata	D3	0,002	0,461	0,013	**0,056**
Amaranthus vulgaris	Kashamata	D4	0,001	0,805	0,023	**0,101**
Brassica chinensis	Kashamata	D0	0,005	0,231	0,004	**0,177**
Brassica chinensis	Kashamata	D1	0,004	0,223	0,004	0,05
Brassica chinensis	Kashamata	D2	0,002	0,208	0,003	0,027
Brassica chinensis	Kashamata	D3	0,005	0,389	0,003	0,029
Brassica chinensis	Kashamata	D4	0,002	0,288	0,004	0,05
Brassica carinata	Kashamata	D0	0,009	0,363	0,004	**0,326**
Brassica carinata	Kashamata	D1	0,005	0,385	0,007	0,052
Brassica carinata	Kashamata	D2	0,002	1,03	0,055	**0,119**
Brassica carinata	Kashamata	D3	0,003	0,526	0,029	**0,063**
Brassica carinata	Kashamata	D4	0,002	0,947	0,036	**0,086**
Beta vulgarus	Kashamata	D0	0,015	0,612	0,012	**0,465**
Beta vulgarus	Kashamata	D1	0,007	0,346	0,008	**0,084**
Beta vulgarus	Kashamata	D2	ND	0,779	0,029	**0,075**
Beta vulgarus	Kashamata	D3	ND	ND	ND	ND
Beta vulgarus	Kashamata	D4	ND	ND	ND	ND

Legend: ND: not determined

from the Chem-Chem and Manoah Kinsevere market gardens are not presented in Table 4, as the majority of treatments applied did not result in sufficient biomass for analysis of metal concentration. This is due to moderate and high levels of trace metal contamination. In the Kashamata vegetable garden, the daily vegetable consumption indices are below the FAO/WHO limits for daily vegetable consumption per person for most trace metals (Cu, Cd, and Pb). However, concerning cobalt, the results indicate that the four vegetables cannot be consumed by the population of Lubumbashi, as the high quantities of metals found in the leaves exceed the limits set by the FAO/WHO for the daily consumption of vegetables for a person of 60 kg body weight. In addition, the application of organocalcareous amendments influenced the daily consumption index. Treatment D4 proved to be more effective than other treatments with fewer amendments, following the order of accumulation D4 > D3 > D2 > D1 > D0. Our results reveal persistent problems, as the consumption indices exceed the limits set by the FAO/WHO for daily vegetable consumption, particularly about cobalt for vegetables from the Kashamata market garden (Abuzed Sadee & Jameel Ali, 2023; Adefa & Tefera, 2020; Langunu et al., 2023; Tasleem et al., 2023). This phenomenon could be explained by the fact that the soils of Haut-Katanga province in general, and the city of Lubumbashi in particular, have a pedogeochemical background enriched in copper and cobalt. In addition, the poor management of quarries and mines, as well as the discharge of effluents rich in metallic particles and aerosols containing dust, can contribute to the propensity of this environmental scourge (Bogaert et al., 2018; Shengo et al., 2020; Shutcha et al., 2015). The recommended quantities of vegetables (300 g/60 kg of an adult) could prove very dangerous for children whose weight is less than that of adults, given the danger that the city of Lubumbashi presents in terms of copper and cobalt production. On the other hand, if we consider the other metallic trace elements (Cu, Pb, and Cd), the daily vegetable consumption index indicates that these vegetables can be consumed up to three times a week without exceeding the limits set by the FAO/WHO for daily vegetable consumption for a person of 60 kg body weight (Cherfi et al., 2016;

Zhuang et al., 2009). According to the International Soil Classification, Lubumbashi soils belong to the category of ferralitic soils characterized by the presence of over 20% clay in soil profiles A-C and A-B-C, mainly composed of Kaolinite, as well as iron and aluminum oxides (G. Chen et al., 2019). However, the clay component is mainly composed of kaolinite and is mixed with significant amounts of free oxides, resulting in a $SiO_2/Al2O_3$ ratio less than or equal to 2. Applying organocalcic soil improvers to ferralitic soils contaminated with trace metal elements improves soil fertility and offers a high capacity for immobilizing trace metal elements in the soil. This is due to the high reactivity of dissolved and colloidal iron in ferralsols, mixed with other elements such as Si, Ca, Mg, Na, and K introduced by the application of organo-calcium amendments on metal-contaminated soils, destabilizing kaolinite and allowing the formation of 2:1 clay mineral. These minerals then reduce the bioavailability of metals to plants (G. Chen et al., 2019; Mohamed et al., 2010).

Involvement in the production of quality vegetables, and choice of urban market gardens in Lubumbashi

In agro-environmental applications, the use of organocalcareous soil improvers has been suggested as a remediation technique for soils contaminated by heavy metals. However, few studies have been carried out in Lubumbashi to confirm or refute these techniques. These techniques are applied to moderately contaminated soils, and their effectiveness depends on the plant species used, and the types and quantities of organic amendments applied to the soil. Our results show that the majority of Lubumbashi's urban gardens are contaminated by heavy metals, mainly copper and cobalt, and that the vegetables produced there are of poor sanitary quality for human health Studies carried out by (Mununga Katebe et al., 2023) showed that the level of contamination, pollution and enrichment of each market garden was not the same, as the majority of gardens were contaminated. We, therefore, recommend that urban market gardens in Lubumbashi with extremely high levels of contamination, as well as those with exceptionally high levels of pollution, use soilless production techniques such as conventional hydroponics or bioponics to guarantee the quality of the vegetables produced in their gardens to safeguard human health (Dhawi, 2023; Gartmann et al., 2023; Magwaza et al., 2020; Mai et al., 2023). The Congolese government must ensure that planning for urban agriculture in the country takes into account the implications of pollution and high levels of contamination on the potential risk posed by market gardens. To produce in quantity and quality, gardens with very severe levels of pollution and/or contamination should be prioritized for the adoption of new soilless production techniques such as bioponics or conventional hydroponics. Bioponics is a method of growing plants in an aquatic environment, where the roots are immersed in a nutrient solution derived from animal manure or plant waste, to promote both the quantity and quality of plant growth (Ezziddine et al., 2021; Bergstrand et al., 2020; Resh, 2013). In developing countries, where obtaining agricultural inputs is becoming increasingly difficult and expensive, adopting bioponics could prove a sustainable solution for Lubumbashi's poor urban farmers. These farmers need to adopt new techniques to grow vegetables, enabling them to reduce production costs to increase producer profits (Nsele et al., 2022).

Conclusion

Mining activities contaminate agricultural soils, water, and air, as well as plants, due to the large quantities of metals they release into the environment, posing a danger to human health. This study aimed to assess the effectiveness of organo-lime amendments applied to soils in reducing the transfer of metals from the soil to plants. Increasing doses of organic soil improvers (chicken droppings and sawdust) and agricultural lime were applied to the soils of three market gardens. Soil samples were taken from three urban market gardens in Lubumbashi, according to the level of copper contamination (high, medium, and low copper contamination). The study showed that soils heavily and moderately contaminated with copper are unable to produce quality vegetables for human consumption. On the other hand, soils with low levels of contamination (e.g., 204 Cu mg/kg) can produce vegetables that are not contaminated with copper. Organocalcareous soil improvers were incorporated at different concentrations. However, none of the tested concentrations improved germination and plant survival in soils with high and medium levels of TME contamination. The garden with low copper contamination shows that the application of organocalcareous amendments reduced the transfer of metals from soil to plants, and consequently, the vegetables produced pose no risk for consumption concerning Cu, Cd, and Pb. Plants of *B. chinensis* and *B. carinata* can be grown on soils from gardens with low levels of trace metal contamination to prove quality plants. Vegetables grown on these soils have not absorbed large quantities of metals. This underscores the importance of determining the mechanisms of metal absorption by plants to propose appropriate remediation techniques. For example, the daily vegetable consumption index obtained for the element cobalt in the low TME-contaminated garden (Kashamata) ranged from (0.029 to 0.465 mg/60 kg/day), i.e. from 0.5 to 8.45 times higher than the FAO/WHO limit, in contrast to the other trace metals (Cu, Cd and Pb) where the daily consumption index found was below the FAO/WHO limit. Organocalcareous soil improvers can only be applied to soils with low levels of TME contamination, but for garden soils with medium to high levels of contamination, it is necessary to test other types of organic soil improvers and other plant species, as well as test new soilless production techniques such as hydroponics and bioponics.

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Data availability No datasets were generated or analysed during the current study.

Declarations

I hereby declare that the contents of this manuscript are original and have not been published elsewhere in whole or in part. The corresponding author has received permission from all authors to submit this manuscript.

Ethical approval All authors have read and understood the declaration on « the ethical responsibilities of authors» and have complied where appropriate with the declaration on « the ethical responsibilities of authors» indicated in the instructions to authors.

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