

Integrated technology of cadmium phytoextraction for soils of urban ecosystems

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ABSTRACT

The paper seeks to develop an integrated mechanism for designing a technology of heavy metal phytoextraction from soils to enhance the environmental safety of urban ecosystems affected by anthropogenic impact. Drawing from an analysis of existing remediation methods for soils contaminated with heavy metals, a scheme has been proposed as a multipurpose framework for creating an integrated phytoextraction technology. It incorporates various components aimed at increasing the mobility of heavy metals in soil and their translocation into plants. The proposed approach suggests enhancing the rate of heavy metal removal by hyperaccumulator plants through (1) maintaining adequate levels of bioavailable metal forms using phytoextraction effectors, (2) applying plant growth regulators to stimulate root branching, and (3) using nitrogen fertilisers to increase plant biomass, promote soil acidification, and improve pollutant mobility. The efficiency of the proposed technique was verified through vegetation experiments on cadmium (Cd) contamination at a concentration of 10 threshold limit value (TLV) in soils of the Dnipro urban ecosystem. The results confirmed the feasibility of phytoextraction using perennial ryegrass (*Lolium perenne*) in combination with the phytoextraction effector EDTA, the plant growth stimulant *Kornevin*, and the mineral fertiliser ammonium nitrate. This combination achieved the highest rate of Cd²⁺ removal from soil, as evidenced by increased biological absorption factor and tissue coefficient values.

Keywords: phytoextraction, cadmium, heavy metals, phytoextraction effector, EDTA, soil, plant, perennial ryegrass (*Lolium perenne*), plant growth stimulant, urban ecosystems.

INTRODUCTION

Soil contamination with cadmium is primarily caused by anthropogenic activities. These include the combustion of coal, oil, and petroleum products; the extraction and processing of non-ferrous metals and iron; the disposal of solid household waste, especially polyvinyl chloride

(PVC); and the production of batteries, cement, rubber, fertilisers, and other industrial materials (Suhani I. et al., 2021; Krol et al., 2022; Yakovyshyna, 2023; Mokryi, 2023; Bernatska et al., 2023). Currently, local cadmium contamination in soils exceeds the natural background level of <1 mg/kg (Coakley et al., 2019), in some cases by several orders of magnitude (Del Rosario

Delgado-Caballero et al., 2017; Pohrebennyk and Dzhumelia, 2020; Yu et al., 2021).

To mitigate soil contamination with cadmium, it is crucial to use phytoextraction. It involves sowing and growing specially selected plant species in contaminated areas over a defined period (Bhat et al., 2022; Oubohssaine and Dahmani, 2024). When combined with phytoextraction effectors and plant growth regulators, it can facilitate cadmium removal, as well as restore soil quality.

These plants are metal hyperaccumulators, capable of absorbing metals in large quantities and storing them in their biomass (Erakhrumen and Agbontalor, 2007; Mehmood et al., 2022). This process allows restoring the natural environment (structure and functions) of the soil system (Samokhvalova et al., 2013; Yakovyshyna et al., 2011; Yakovyshyna, 2018). As a result, one can observe the notable effects on the full range of biological, physical, and physicochemical soil properties, as well as on migration processes in the soil–plant system (Tangahu et al., 2011; Oubohssaine and Dahmani, 2024). At the same time, the introduction of phytoextraction effectors into the soil and the use of growth regulators can increase the accumulation of heavy metals (Dron' et al., 2005; Alsafran et al., 2023). This technology is simple to implement since it requires no special equipment and does not damage the soil. It is also cost-effective compared to physical and chemical detoxification (Alkorta et al., 2004). Meanwhile, the integration of phytoextraction into urban ecosystems offers aesthetic improvements gained from employing different phytoextractor plants. This technology is environmentally friendly, as it does not involve toxic compounds, disrupt the structure of the soil, or lead to a harmful impact on its properties.

However, some authors (Tangahu et al., 2011; Anoopkumar et al., 2020; Bhat et al., 2022) note certain limitations of the phytoextraction method, particularly regarding the removal of heavy metals from the soil.

Nevertheless, these disadvantages can be eliminated by:

- Intensifying the extraction of heavy metals from soil using effectors (Khanna et al., 2021);
- Identifying the hyperaccumulator plants for each natural and climatic zone.

With rare exceptions, in situations of aerogenic pollution typical of urban ecosystems, contamination normally penetrates beyond a depth

of 0–10 cm, provided there has been no human intervention. In single-family residential areas, it often corresponds to the arable soil layer.

Most phytoremediation methods focus on contaminated but undisturbed soils, which, due to their ecological properties, still can meet plant requirements for nutrients, aeration, and moisture. However, in urban ecosystems, as the concentration of heavy metals increases, the nutrient content of soils decreases (Kovrov and Krasovskiy, 2025). Consequently, managing urban soil toxicity presents a considerable challenge.

Only a few attempts have been made to combine the restoration of natural soil functions with the extraction of heavy metals. One example is a well-known method described by Huang Jianwei et al. (1997), which involves loosening the top fertile layer and applying ammonium nitrate phosphate fertiliser encapsulated with a natural sorbent. In the conditions of urban ecosystems, this approach is rather time-consuming.

Selecting appropriate phytoextractor plants for urban ecosystems involves identifying hyperaccumulators within urban phytocenoses that also exhibit ornamental qualities. Traditionally, the phytoremediation potential of ruderal species has been analysed first. However, their use is not always appropriate in urban environments. For instance, common ragweed (*Ambrosia artemisiifolia* L.) (Ryzhenko et al., 2022) is a hyperaccumulator of Pb^{2+} . This is a strong allergen which can cause hay fever or lead to bronchial asthma. Therefore, it is essential to select plant species from the natural phytocenoses of urban ecosystems that not only meet the requirements for phytoextractors but are also non-allergenic, undemanding in terms of mineral nutrition, and widely distributed across the city. Even though cereals are generally sensitive to the toxic effects of heavy metals, it has been proposed to use their wild relatives, such as grasses. Within this study, perennial ryegrass (*Lolium perenne*) was chosen. This species is traditionally used for establishing grass cover on lawns, sports fields, and similar areas.

At present, sufficient data have been accumulated on phytoextractor plants and the criteria for their selection. However, no comprehensive solution has been developed for the soil–plant system. The influence of soil conditions on heavy metal mobility and plant uptake is often overlooked. Therefore, additional measures have been proposed to enhance phytoextraction efficiency, namely:

- taking into account the functional characteristics of urban ecosystems, including the sufficient content of available forms of heavy metals (Fritioff and Greger, 2003);
- using phytoextraction effectors;
- stimulating plant uptake of chemical elements by applying growth regulators and nitrogen fertilisers to enhance mineral nutrition.

The scientific novelty of the research lies in creating additional conditions to enhance the efficiency of phytoextraction and, based on these, developing a universal integrated phytoextraction technology.

The objective of the study was to design an integrated phytoextraction approach that combines components with different mechanisms of action to increase the mobility of cadmium in soil and their translocation within perennial ryegrass plants (*Lolium perenne*).

MATERIALS AND METHODS

The efficiency of the integrated phytoextraction technology was assessed within the urban ecosystem of Dnipro (Ukraine) under Cd²⁺ anthropogenic contamination of soils at a dose of 30.0 mg/kg, corresponding to a high pollution level. The threshold limit value (TLV) of

cadmium in the soil was exceeded by 10 times. The TLV for the total cadmium content in soil is 3 mg/kg. Excessive amounts of Cd²⁺ cations in the soils of the Dnipro urban ecosystem result from emissions produced by both ferrous and non-ferrous metallurgy enterprises, as well as from municipal solid waste processing and disposal activities (Yakovyshyna 2023). According to the Main Department of Statistics in the Dnipropetrovsk Region, three major polluting enterprises in Dnipro emit a total of 0.508 tonnes of cadmium compounds into the atmosphere each year. This amount corresponds to approximately 0.001 tonnes per square kilometre of the city’s area or 0.0005 kilograms per capita. The total cadmium content in the soil exceeded the natural geochemical background, indicating low to medium levels of contamination. In contrast, the mobile and potentially mobile forms, extracted using an ammonium acetate buffer solution (AAB, pH 4.8) and 1 N HCl, showed medium to high contamination levels according to the Nemerov pollution index (NPI) (Yakovyshyna et al., 2025) (Fig. 1). Taking into account the worst-case scenario associated with the impaired performance of emission treatment systems caused by the war, a cadmium concentration of 30.0 mg/kg was selected for testing the integrated phytoextraction technology. For the control variant, common

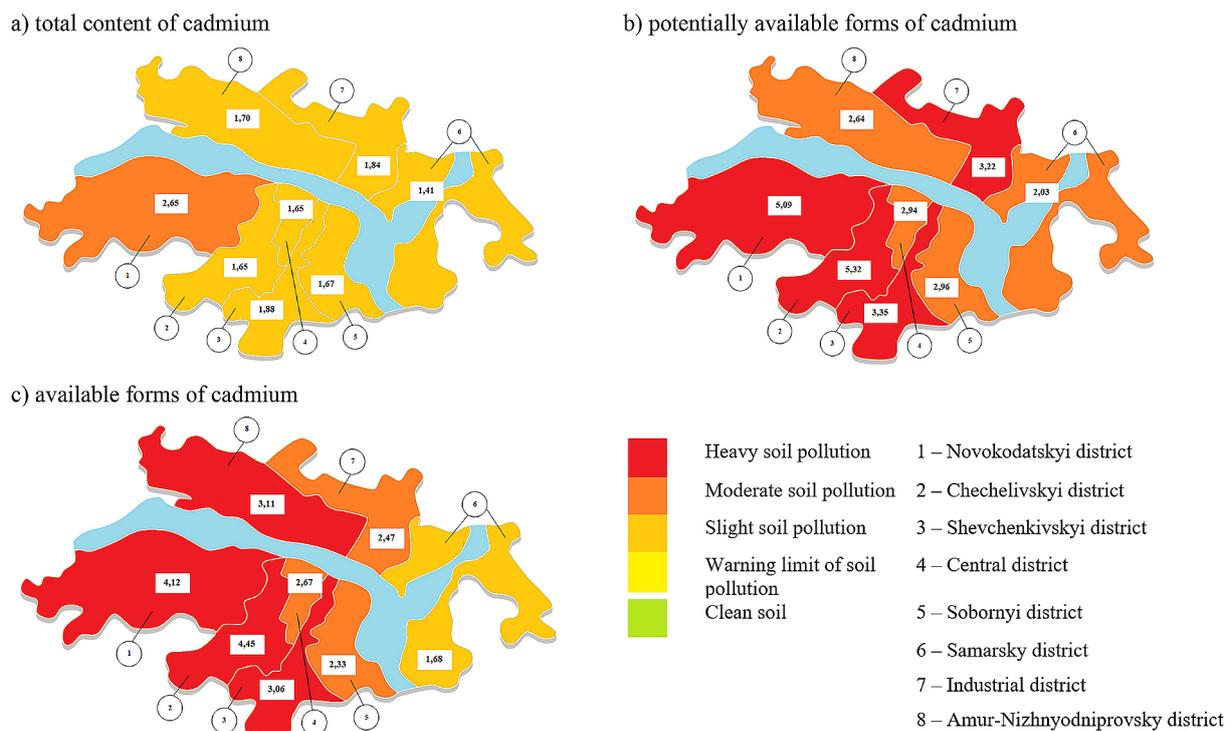


Figure 1. Intensity of soil pollution by cadmium according to NPI

low-humus heavy-loam black soil (chernozem) was used. This soil type has a high buffering capacity, enabling it to fix heavy metal cations and maintain a low level of their mobility. The total cadmium content in the chernozem was 0.39 mg/kg, while the content of available forms (AAB, pH 4.8) amounted to 0.10 mg/kg.

The efficiency of the integrated phytoextraction technology components was evaluated on urban soil from the Dnipro urban area. This soil, derived from zonal chernozem, had undergone significant anthropogenic disturbance and exhibited high cadmium mobility.

EDTA was used as a phytoextraction effector in combination with the *Kornevin* growth stimulant and ammonium nitrate mineral fertiliser to enhance the phytoremediation potential of perennial ryegrass (*Lolium perenne*).

Soil phytoextraction experiment variants are the following:

1. Control: Uncontaminated climatophytic soil (common low-humus, heavy-loam black soil);
2. Urban soil contaminated with Cd at a dose of 30.0 mg/kg;
3. Urban soil contaminated with Cd at a dose of 30.0 mg/kg + EDTA;
4. Urban soil contaminated with Cd at a dose of 30.0 mg/kg + EDTA + *Kornevin* growth stimulant;
5. Urban soil contaminated with Cd at a dose of 30.0 mg/kg + EDTA + *Kornevin* growth stimulant + ammonium nitrate.

According to the exchange reaction, the required amount of EDTA was calculated and then increased 1.5 times to account for the adsorption capacity of the soil-adsorbing complex (SAC). The final EDTA dose was 77.90 mg/kg of contaminated soil. It was applied in the form of an aqueous solution before sowing the seeds, followed by thorough mixing of the soil. According to the suggested recommendations, the *Kornevin* product was applied by dusting the seeds before sowing, as well as in the form of a solution for root feeding every two weeks. For the climatophytic soil in Ukraine's Northern Steppe, the most optimal application of ammonium nitrate was determined to be 60 kg/ha of active material. Perennial ryegrass (*Lolium perenne*) was used as a phytoextractor. This herbaceous flowering plant, from the *Lolium* genus of the grass family (*Poaceae*), is quite susceptible to higher concentrations of heavy metals in the soil due to its biological properties and can

accumulate large amounts of heavy metals in its biomass. The plants were grown in 5-litre polyethylene containers filled with 4.5 kg of air-dry soil.

Cadmium content was determined by atomic absorption analysis after wet ashing of plant material and acid treatment of soil samples. The efficiency of the proposed technique, based on the phytoextraction potential of the studied plants, was evaluated using the bioconcentration factor (BCF) for aerial parts and roots (Brooks, 1998; Buscaroli, 2017; Chandra and Kumar, 2018) (Equation 1) and the translocation factor (TC) (Buscaroli, 2017) (Equation 2):

$$BCF = \frac{Cp_i}{Cs_i} \quad (1)$$

$$TC = \frac{Caer.p_i}{Cf.end_i} \quad (2)$$

where: Cp_i – content of metal cations in the plant or its part, mg/kg; Cs_i – content of metal cations in the soil after acid treatment, mg/kg; $Caer.p_i$ – content of metal cations in the aerial part of the plant, mg/kg; $Cf.end_i$ – content of metal cations in the underground part of the plant, mg/kg.

The technology was considered successful under conditions of high phytoextraction potential of perennial ryegrass (*Lolium perenne*) when the values of TC and BCF exceeded one (Fitz and Wenzel, 2002).

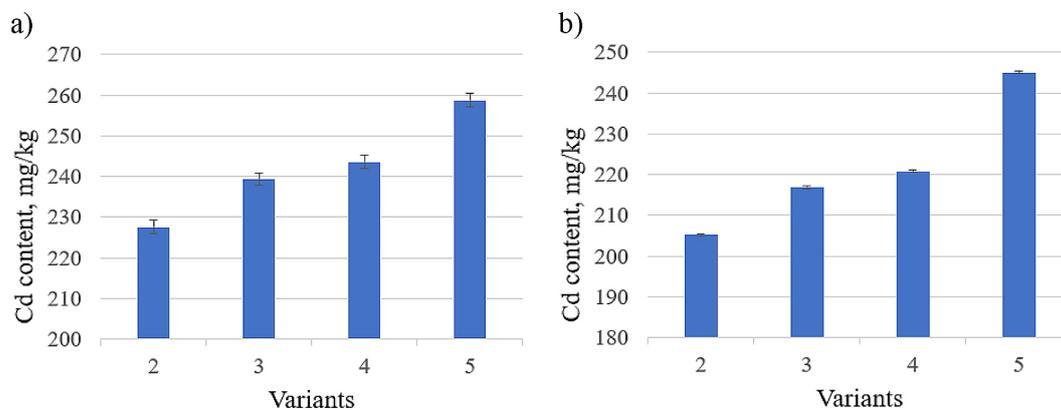
RESULTS

In the control plants grown in zonal soil, the cadmium content was 0.043 mg/kg in the above-ground parts and 0.094 mg/kg in the roots. Both values were within the TLV. The TLV for cadmium in plant biomass is 0.3 mg/kg. Under uncontaminated conditions, BCF and TC values below one (Table 1) indicated the functioning of protective mechanisms that block the transfer of cadmium to the above-ground biomass (Eben et al., 2024).

The Cd^{2+} content in plant biomass exceeded TLV values in contaminated variants of the experiment. Cadmium accumulation increased by up to 19.4% in the above-ground part and 13.7% in the roots when measures were applied to enhance its mobility in the soil and stimulate plant uptake. These effects were observed in variants 3–5 compared to variant 2 (Figure 2).

Table 1. Phytoremediation potential of perennial ryegrass (*Lolium perenne*)

Variant	BCF		TC
	Aerial part	Roots	
1. Control (uncontaminated soil)	0.11	0.24	0.46
2. Contaminated soil at a Cd dose of 30.0 mg/kg + perennial ryegrass (<i>Lolium perenne</i>) (phytoextractor);	6.84	7.59	0.90
3. Contaminated soil at a Cd dose of 30.0 mg/kg + perennial ryegrass (<i>Lolium perenne</i>) (phytoextractor) + EDTA (phytoextraction effector)	7.23	7.98	0.91
4. Contaminated soil at a Cd dose of 30.0 mg/kg + perennial ryegrass (<i>Lolium perenne</i>) (phytoextractor) + EDTA (phytoextraction effector) + Kornevin (growth stimulant)	7.36	8.12	0.91
5. Contaminated soil at a Cd dose of 30.0 mg/kg + perennial ryegrass (<i>Lolium perenne</i>) (phytoextractor) + EDTA (phytoextraction effector) + Kornevin (growth stimulant) + ammonium nitrate (mineral fertiliser)	8.17	8.56	0.95

**Figure 2.** Cd content in the dry biomass of perennial ryegrass (*Lolium perenne*), mg/kg

The highest cadmium accumulation in ryegrass occurred in variant 5, reaching 245.1 mg/kg in the above-ground part and 258.8 mg/kg in the roots. Cadmium accumulation was higher in the roots than in the aerial parts, indicating, firstly, an acropetal distribution within the plant organs and, secondly, the activation of internal protective mechanisms, which is consistent with the results of other studies (Lou, et al., 2013; Eben et al., 2024) However, when the soil contained a high level of available Cd forms, including mobile compounds, the difference between roots and aerial parts was partially reduced, as indicated by the translocation coefficient (TC) of 0.95 in variant 5.

The increased content of available Cd in the soil caused toxic effects on perennial ryegrass plants, including inhibition of morphological and biological parameters (plant height, average number of leaves per plant, average leaf length, panicle height, etc.), paler leaf colour, and marginal necrosis. A high level of mineral nitrogen supply under cadmium nitrate

pollution not only promoted intensive green biomass growth but also led to plant lodging (variant 5). However, mowing the plants 3–4 times during the vegetation period does not reduce the efficiency of the developed phytoextraction technology. Under Cd contamination at 30.0 mg/kg (10 TLV), the above-ground biomass of plants increased by 8–14% when a plant growth regulator and nitrogen fertiliser were applied. The efficiency of phytoextraction was evident from the accumulation of Cd²⁺ in plant organs and the whole plant, as indicated by BCF and TC coefficients (Table 1). If either coefficient exceeds one, the developed technology can be considered effective. In this study, the use of a growth stimulant and fertiliser proved beneficial. Maintaining a high level of available Cd in the soil, combined with a branched root system and stimulation of intensive element uptake by the phytoextractor plants, resulted in the highest BCF values exceeding one ($BCF_{\text{Aerial part}} = 8.17$, $BCF_{\text{Roots}} = 8.56$) and TC values approaching one (TC = 0.95).

DISCUSSION

Most phytoextraction technologies typically involve a maximum of two components:

- Plant extractor;
- Phytoextraction effector (Puschenreiter et al., 2001; Prasad and De Oliveira Freitas, 2003).

However, when the available forms of heavy metals in contaminated soil are in excess (ammonium acetate extract, pH 4.8), their active absorption by plants requires additional measures. First, the formation of a branched root system is necessary (Bhat et al., 2022). Second, intensive cadmium uptake and biomass growth should be promoted, which can be supported by the application of plant growth stimulants and nitrogen fertilisers. The effectiveness of such integrated measures was confirmed by the high values of BCF and TC coefficients observed in variant 5.

The components of integrated phytoextraction technology are examined in light of current scientific advances.

The studied perennial ryegrass (*Lolium perenne*) meets nearly all the criteria established for effective phytoextractors (Barth, 1990; Alkorta et al., 2004), including:

- Tolerance to environmentally hazardous metal compounds without showing phytotoxic effects such as discolouration, abnormal pigmentation, necrosis, or inhibited growth and development.
- High growth rate and substantial aerial biomass production, requiring no specialised cultivation techniques. The species is also resistant to diseases and pests and is unattractive to animals and humans, which reduces the risk of poisoning.

The exception is the root system, which does not penetrate very deeply. However, under conditions of intensive aerogenic soil contamination in the Dnipro urban ecosystem, where a non-leaching water regime prevails and heavy metals remain concentrated at a depth of around 10 cm rather than being flushed into groundwater, ryegrass is suitable because most of its roots develop within the 0–30 cm soil layer.

The effectiveness of perennial ryegrass (*Lolium perenne*) for cadmium phytoextraction from soil has been confirmed by several researchers (Masotla et al., 2023). This species can grow on soils with high cadmium contamination (Li et al., 2021). Bai et al. (2024) found cadmium

concentrations in the roots of perennial ryegrass ranging from 370.0 to 828.0 mg/kg when the soil contained 100 mg/kg of the metal. However, without additional components in the phytoextraction technology, the plant's potential is not fully realised. In contrast, the proposed integrated approach maximises its efficiency.

To enhance the extraction of heavy metals from soil, it is recommended to use phytoextraction effectors, primarily represented by polyaminopolyacetic acid complexones (Tangahu et al., 2011), namely:

- Ethylenediaminetetraacetic acid [EDTA];
- Dihydroxyethylethylenediamineacetic acid [DDA];
- Diethylenetriaminepentaacetic acid [DTPA];
- Ethylenebis (oxyethylenetriamine) tetraacetic acid [ETTA];
- Ethylenediamine dihydroxyphenylacetic acid [EDPA];
- Cyclohexane-trans-1,2–diaminetetraacetic acid [CDTA].

These substances form stable, water-soluble intracomplex compounds (chelates) with many heavy metals. This increases the solubility and mobility of metals in the soil, leading to their increased absorption by the root system and further accumulation in aerial biomass (Holbein et al., 2021; Alsafran et al., 2023). According to Huang Jianwei et al. (1997), the chelates rank in efficiency as follows: EDTA > DDA > DTPA > EGTA > EDPA.

EDTA was specifically included as a component of the proposed technology. It is the most effective substance among the phytoextraction effectors due to its properties. Research indicates that its application promotes overall plant growth and increases root biomass (US, 1998; Tangahu et al., 2011). It also increases enzymatic activity and enhances the availability of macro- and microelements necessary for plant development. EDTA ($C_{10}H_{16}N_2O_8$) forms stable complexes in a wide pH range, even in a strongly acidic environment.

EDTA plays an important role in the proposed integrated technology for cadmium phytoextraction from soil using perennial ryegrass (*Lolium perenne*). In the role of a phytoextraction effector, EDTA contributes to preventing heavy metal cations from being fixed in SAC and, thus, maintains a high level of migration ability (Kamal et al., 2023). In this study, the rate of cadmium

availability reached approximately 70% of the total soil content. Therefore, the root system of the plant can effectively absorb the created metal chelates. Israila et al. (2023) found that EDTA is an effective soil enhancer. It promotes the desorption of heavy metals, including cadmium, and increases their accumulation in plants such as *Vetiveria zizanioides*, *Cymbopogon citratus*, and *Helianthus annuus* when the translocation factor (TF) is greater than 1.

Using EDTA increased cadmium content in the above-ground parts and roots of perennial ryegrass (*Lolium perenne*) by 5.7% and 5.1%, respectively, compared to variant 2, which did not include the phytoextraction effector. However, the TF values, which reflect cadmium distribution between shoots and roots, were slightly below one.

The root system of perennial ryegrass (*Lolium perenne*) does not penetrate very deeply. To address this, the auxin-based growth stimulant *Kornevin* was proposed for inclusion in the phytoextraction technology to promote a more branched root system. Auxins have also been shown to enhance metal ion phytoextraction from contaminated soil, as demonstrated in sunflower (*Helianthus annuus* L.) (Liphadzi et al., 2006). The rooting process is greatly facilitated by the use of auxin-group growth regulators. They ensure the formation of roots from stem cells and enhance the development of the root system in vegetative plants (Hu et al., 2021; Chen et al., 2023). The active substance in the *Kornevin* product, 4-(indol-3-yl) butyric acid, is gradually converted into heteroauxin phytohormones within plants, which produces the optimal effect at the lowest doses compared to other auxins. Moreover, the convenient preparative form of *Kornevin* (powder) allows activating the active substance penetration into plant cells due to high adhesion (sticking) to the surface of seeds or petioles. In turn, this significantly increases the efficiency and simplifies the product application. The use of *Kornevin* accelerates the development of roots by 14–18 days earlier compared to untreated plants. As a result, a well-branched root system is formed. This extensive root network in the contaminated soil layer increases contact between root hairs and the toxic environment, thereby enhancing and accelerating the uptake of heavy metals. The application of *Kornevin* increased cadmium content in the roots by 7.0% and in the above-ground parts by

7.6% compared to variant 3, which did not receive this treatment.

Cadmium removal from the soil in the proposed technology was further enhanced through the active promotion of plant biomass. This effect was supported by the application of ammonium nitrate. Ammonium nitrate is characterised by a high content of mineral nitrogen (34%) and an optimal combination of nitrate and ammonium forms. It acts quickly, is easy to transport and apply, has low surface volatilisation, and is effective even in soils with insufficient moisture, reducing the need for digging in. On degraded or nutrient-depleted urban soils, it provides an essential macronutrient for plants, whose deficiency can inhibit growth and development, reduce chlorophyll content, and lower photosynthetic activity. Findings suggest that the use of ammonium nitrate as a fertiliser increases plant biomass by up to 30% (Samokhvalova, 2014). Moreover, the acidification of the soil's reaction enables heavy metals to migrate significantly within it (Prasad and De Oliveira Freitas, 2003), both directly and indirectly by increasing the efficiency of the phytoextraction effector EDTA and, thus, improving metal accessibility to plant roots. The application of ammonium nitrate, which promotes a higher concentration of available heavy metals in soil and their substantial absorption with nutrients, enhances the accumulation of metals within phytoextractor plant biomass. Cadmium content in *Panicum maximum* (Tanzania variety) increased when nitrogen-containing compounds were applied (Leite and Monteiro, 2019). The inclusion of ammonium nitrate in the integrated phytoextraction technology further enhanced cadmium accumulation in perennial ryegrass (*Lolium perenne*). It also increased BCF values for both the above-ground parts and roots and brought the TF closer to one.

These results demonstrate that a comprehensive approach, combining multiple components in the cadmium phytoextraction technology, substantially improves its efficiency compared to using the components individually. In particular, BCF for the aerial parts rose from 6.85 to 8.17, and BCF for the roots from 7.59 to 8.56, while the TF approached one.

The generalisation of research findings has made it possible to design an integrated scheme for developing such technologies, taking into account a specific heavy metal pollutant, the degree of anthropogenic impact relative to

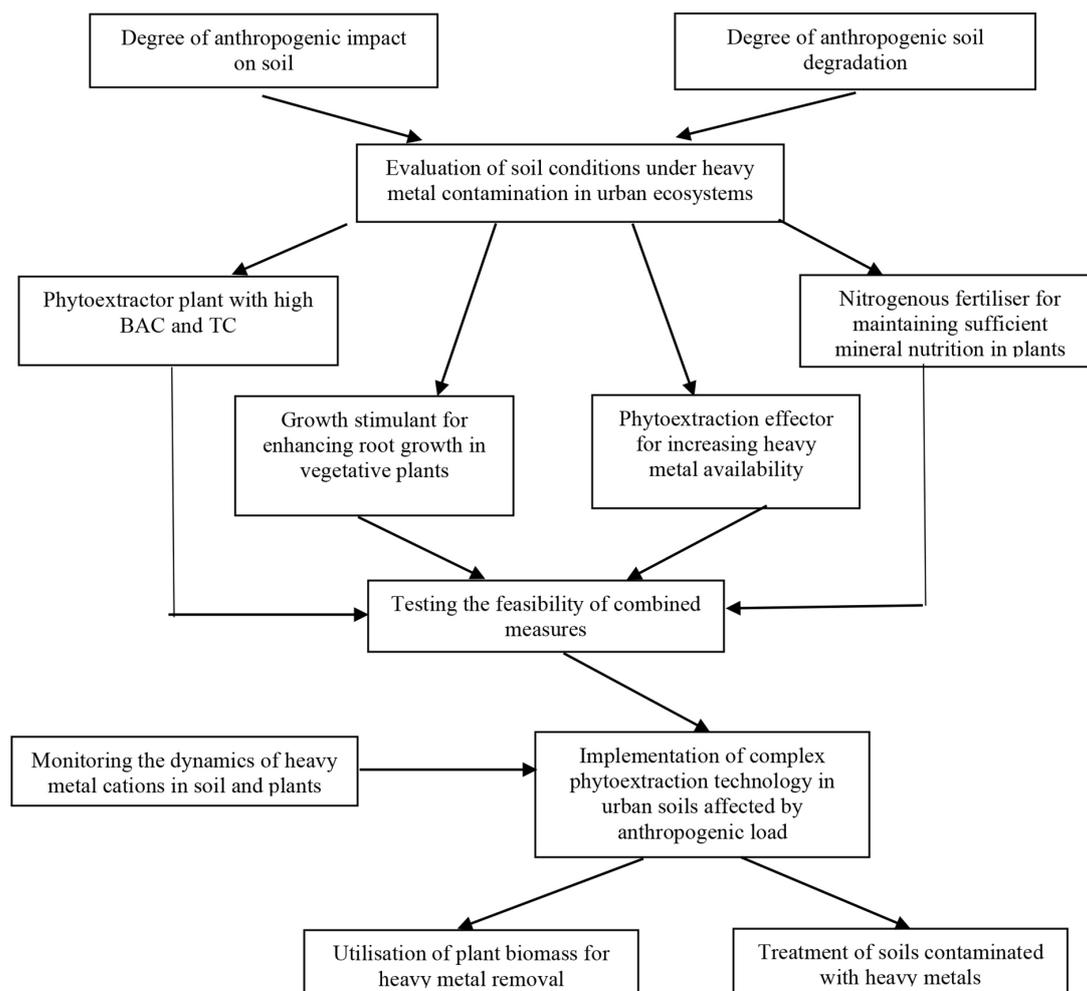


Figure 3. Phytoextraction scheme

TLV, and soil conditions (Figure 3). For a given metal pollutant, the appropriate phytoextraction effector is selected to maintain adequate levels of bioavailable metal forms in the soil. Next, a suitable hyperaccumulator plant is chosen, and a growth stimulant and nitrogenous fertiliser are applied according to the requirements of the selected plant. After evaluating the combined efficiency of these measures, they are implemented under the specific conditions of an urban ecosystem affected by anthropogenic impact, with careful monitoring of pollutant translocation from soil to plants.

CONCLUSIONS

The article proves that current technologies for phytoextraction of heavy metals from soils are, to some extent, limited in their effective application within urban ecosystems. An

integrated approach to cadmium phytoextraction is proposed, combining the cultivation of hyperaccumulator plants with the use of phytoextraction effectors, plant growth regulators, and nitrogenous fertilisers, taking into account the current state of the urban ecosystem and relevant influencing factors. A scheme has been developed as a multipurpose framework for designing integrated phytoextraction technologies. This builds on considerable experience with individual components, which can be combined according to specific soil, climatic, and anthropogenic conditions. In particular, the use of phytoextraction with perennial ryegrass (*Lolium perenne*) as the phytoextractor, in combination with EDTA as a phytoextraction effector, the plant growth stimulant *Kornevin*, and ammonium nitrate fertiliser, is recommended for soils of the Dnipro urban ecosystem subject to high levels of cadmium contamination.

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