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Carbonaceous amendment addition as an alternative to decrease phytotoxicity of sediments from the Matanza-Riachuelo Basin (Argentina)

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ABSTRACT

Sustainable management strategies for highly polluted dredged sediments are crucial in ports and waterways, where dredging activities take place on a regular basis. In the case of Argentina, the lack of national legislation enables the unregulated sediment disposal in marginal areas, exposing low-resource populations to these sources of pollution. In order to decrease the sediment phytotoxicity for the potential revegetation of dredged sediments from the Matanza-Riachuelo River, with high concentrations of heavy metals, the effect of two types of carbonaceous amendments (biochar, BC, and commercial activated carbon, AC) in different proportions (10% and 20%) was studied. With the defined treatments, germination and root elongation tests, and seedling-level tests were carried out to compare the phytotoxicity of the amended sediments with that of the pure sediment. Lettuce (*Lactuca sativa*) was used as an indicator species. Both amendments in the highest dose (AC20% and BC20%) improved germination index. AC20% presented the highest heavy metal accumulation in biomass for all the metals under analysis, but plants did not exhibit negative morphological alteration or phytotoxic symptoms. By contrast, BC treatments did not improve lettuce's morphological variables and heavy metal accumulation significantly. Together with adequate agronomic practices, the appropriate selection and dosage of carbonaceous amendments could be a useful strategy to modify the physicochemical conditions of the sediment conveniently, and promote either heavy metal mobilization or stabilization.

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1. Introduction

Freshwater sediments are considered long-term sinks for many pollutants, including heavy metals (Saleem et al., 2015; Algül and Beyhan, 2020). As a consequence of different human activities to promote specific uses in ports and

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waterways, sediment dredging and relocation is frequent. The unregulated disposal of dredged sediments with high loads of heavy metals on land and in landfills can harm human and environmental health (Tamburini et al., 2020). This is why remediation, sustainable management, and safe disposal of polluted sediments is needed to protect coastal water quality, wildlife, and human health (Di Vaio and Varriale, 2018; Norén et al., 2020).

In a remediation scheme, organic and inorganic soil amendments are frequently used to immobilize heavy metals and reduce their bioavailability in soils and sediments. These amendments can alter metal speciation, reduce heavy metal solubility by changing pH value and redox condition of the substrate, and, eventually, turn them into more geochemically stable and less toxic forms via sorption, precipitation, and complexation (Yan et al., 2020). In addition, amendments can improve soil physical and chemical fertility (Brassard et al., 2019), helping further revegetation steps. Many types of soil amendments have been proposed, namely clay, cement, zeolites, minerals, phosphates, organic composts, biosolids, sawdust, wood ash and microbes (Wuana and Okieikmen, 2011; Lomaglio et al., 2017). Recently, particular emphasis has been placed in cost-effective and environmentally friendly alternatives. Among these, biochar – a low-cost biomass-derived carbon with no further activation process (Thompson et al., 2016) – is a newly emerging soil amendment (Lomaglio et al., 2017; Sultan et al., 2020; Zand et al., 2020). However, few articles deal with biochar's performance in naturally polluted substrates, and few experimental designs study the effect of dosage and type of carbon amendment used (i.e., biochar vs. commercial activated carbon) (Zhang et al., 2021).

The Matanza-Riachuelo River is located in the province of Buenos Aires (Argentina), and it is considered one of the most contaminated rivers in Latin America. Several studies have shown the high load of heavy metals in the lower region, including Zn, Cr, Pb, Cu, Ni and Cd (Bursztyn Fuentes et al., 2018; do Carmo et al., 2021). The application of amendments to those areas is a cost-effective remediation technique that would aid the stabilization of pollutants and further revegetation efforts, considering that wind and water erosion of polluted sites can severely affect the health of the surrounding environment and population (Yan et al., 2020). The aim of this study was to evaluate the effect of the addition of different carbonaceous amendments in a highly polluted sediment from the Matanza-Riachuelo Basin as a strategy to decrease its phytotoxicity, using lettuce as an indicator.

2. Material and methods

2.1. Sediment and amendments

A composed sample of sediment was collected from the top 0–10-cm layer in an urbanized area of the low region of the Matanza-Riachuelo Basin. The sediment sample was air-dried, grounded, sieved (mesh #10, ASTM) and stored. The sediment was fully characterized in a previous work (do Carmo et al., 2021), and heavy metals concentrations were: 404.5 mg kg⁻¹ Pb, 289.3 mg kg⁻¹ Cu, 964.6 mg kg⁻¹ Cr, 48.9 mg kg⁻¹ Ni and 748.9 mg kg⁻¹ Zn. According to the national regulation, Cu and Zn concentrations are considerably higher than the maximum levels allowed for agricultural and urban use of the substrate, and Cr exceeds the industrial use of dredged sediments, which is the least conservative level (HWAA, Federal Hazardous Waste Act of Argentina 24,051, Regulatory Decree No 831/93, Annex II).

The two carbonaceous amendments used were: a commercial activated carbon (Biopack, analytical grade) and a homemade biochar obtained from eucalyptus pruning (Bursztyn Fuentes et al., 2020), named AC and BC, respectively. BC is an inexpensive material produced locally: Eucalyptus wood residues are an abundant waste material from the wood industry (Mopoung and Dejang, 2021), including Argentina. Therefore, this feedstock is a feasible option to produce activated carbon. This material has exhibited promising results in other applications, such as pollutant removal from aqueous phase (Bursztyn Fuentes et al., 2020, 2021). AC has been chemically activated with H₃PO₄ and it was used herein as a reference material: it is a certified product with standardized physicochemical properties and it can be purchased from local suppliers.

Both carbonaceous amendments were physically and chemically characterized, including pH with a pH-meter HANNA[®] HI 9827 (ratio sediment/water 1:2.5) (McLean, 1982), electrical conductivity with an EC-meter HANNA[®] HI 98304 (Rhoades, 1982a), nitrogen by Kjeldahl method (AOAC, 1975) and extractable phosphorous (Bray and Kurtz, 1945). Exchangeable cations (Ca, Mg, Na, K) were determined by the method with ammonium acetate at pH = 7 (Rhoades, 1982b). Surface area was calculated from N₂ sorption isotherms using BET equation with an automatic equipment (Micromeritics ASAP 2020) at 77 K. Samples were previously outgassed in vacuum at 200 °C overnight. Morphology and surface chemical composition were studied with SEM-EDS (JEOL JCM-6000 Neo Scope). To assess crystalline composition, X-ray diffraction (XRD) patterns were collected using a diffractometer with CuK α radiation (Philips PW 1710), operated at 40 kV and 30 mA, with counting time 10 s/step and 0.02° (2 θ) step size. The main reflections were defined and contrasted with reference patterns.

2.2. Experimental design

Two bioassays were performed to study the toxicity of the sediment and the effect of the carbonaceous amendment addition: seed germination and root elongation test, and a greenhouse experiment. For both essays, a completely randomized design was performed where four treatments were applied together with a positive control (pure sediment – SED 100%). To prepare the treatments for the essays, the sediment was mixed with the carbonaceous amendment (AC and

BC) with particle size <125 μm (mesh 120, ASTM) at two different doses (10% and 20% v/v), resulting in four treatments: activated carbon 10% (AC10%), activated carbon 20% (AC20%), biochar 10% (BC10%) and biochar 20% (BC20%). 200 mL of deionized water were incorporated to each batch, and the mixtures were kept at 80% of the field capacity for 15 days for stabilization. The mixtures were characterized concerning nutrient availability: Kjeldahl nitrogen, extractable P and exchangeable cations (K^+ , Ca^{2+} and Mg^{2+}), following the methodology presented in Section 2.1.

2.3. Seed germination and root elongation test

To assess the integrated effect of soil and sediment pollutants, seed germination and root elongation tests with *Lactuca sativa* are among the simplest and cheapest short-term options. Lettuce is commonly used as an indicator because it is a fast-growing, easy-to-handle species that is highly sensitive to toxic compounds, and it has been recommended by renowned institutions such as USEPA (Ahmad et al., 2012). Seedlings are rather uniform and standardized protocols are easily available (OECD, 2006). Hence, a 120-h static acute toxicity test was conducted to evaluate the effect of aqueous extracts of the different treatments on lettuce seed germination and root elongation. The bioassay was performed according to the methodology proposed by Sobrero and Ronco (2004).

Aqueous extracts of the stabilized mixtures were prepared in proportion 1:2 (1 part of the mixture, 2 parts of distilled water). Suspensions were mechanically stirred for 3 h at 700 rpm and then filtered. 12 seeds of *Lactuca sativa* (90% of germinating power) were placed in each sample unit which consisted of a 100 mm-diameter polyethylene container filled with filter paper (Whatman[®] No. 3) as the support. Afterwards, 4 mL of the different aqueous extracts were poured in and the containers were covered. A negative control with distilled water was performed and for each treatment there were five replicates. All the sample units were kept under controlled temperature ($22\text{ }^\circ\text{C} \pm 2$) for 5 days. For each one, the number of germinated seeds was counted, and the root elongation was registered using graph paper. 0.5 cm was the minimum length taken as a criterion to define germinated seeds. Relative root elongation (RRE) and relative seed germination (RSG) were calculated according to Eqs. (1) and (2), respectively.

$$\text{RRE (\%)} = \frac{L_1}{L_0} * 100 \quad (1)$$

Where L_1 is the mean root length for each treatment and L_0 is the mean root length of the control treatment with distilled water.

$$\text{RSG (\%)} = \frac{N_1}{N_0} * 100 \quad (2)$$

Where N_1 is the mean number of germinated seeds for each treatment and N_0 is the mean number of germinated seeds of the control treatment with distilled water.

Then, the germination index (GI) was calculated:

$$\text{GI (\%)} = \frac{\text{RRE} * \text{RSG}}{100}$$

RSG and RRE are relative terms calculated on the basis of the control treatment. Hence, if a treatment exceeds the control in either germination or root elongation, the RSG and RRE values will be greater than 100%, correspondingly.

2.4. Greenhouse experiment

A pot experiment was conducted to further study the phytotoxicity of the sediments and the effect of the carbons in lettuce seedlings. The bioassay was carried out during Autumn in a greenhouse with no light or temperature manipulation. According to the National Meteorological Service, during that period the average temperature was $12\text{ }^\circ\text{C}$ (max: $16\text{ }^\circ\text{C}$, min: $8\text{ }^\circ\text{C}$) and the average photoperiod was 10 h. As described in Section 2.2, four treatments with amendments were applied (AC10%, AC20%, BC10%, BC20%) with five replicates per treatment. A control treatment with pure sediment was added (SED100%). Seeds were grown in an inert substrate (50% peat and 50% perlite) and transplanted (one plant per pot) after 15 days to plastic pots containing 500 g (dry weight basis) of the stabilized mixtures. Pots were watered daily with tap water to 80% of field capacity. After 30 days of growth, several morphological variables were measured: plant height, root length, number of leaves, stem diameter and dry weight. For the latter, plants were harvested, shoot and roots were separated and cautiously washed, dried in an oven at $70\text{ }^\circ\text{C}$ for 48 h, and then dry weights were recorded. Afterwards, the dried material was ground and digested following the methodology EPA 3050B (EPA, 1996). The concentrations of Cu, Cr, Pb, and Zn in the plant digests were determined by air-acetylene flame atomic absorption spectrometry (AAS, Perkin Elmer Model AAnalyst 200), using external standards prepared from stock solutions of the metals (1000 mg kg^{-1} , Merck).

2.5. Statistical analysis

The data presented in this study were the mean values obtained from the corresponding replicates of each treatment. Statistical analysis was performed with InfoStat software. Germination index and morphological variables were analyzed using an analysis of variance (ANOVA), and the means were compared using Tukey Test ($\alpha = 0.05$). Data were checked for normality and homogeneity of variances and no data transformation was applied. When the set of data did not meet the normality and/or homoscedasticity assumptions, the statistical analysis was performed using Kruskal–Wallis test.

Table 1
Physicochemical characterization of the commercial activated carbon (AC) and the home-made eucalyptus-derived biochar (BC).

Parameters	AC	BC
pH	2.4	9.6
EC (dS m ⁻¹)	5.5	0.8
Extractable P (mg kg ⁻¹)	8171	0.71
N (%)	0.33	0.30
Ca ²⁺ (mg kg ⁻¹)	214.8	11352
Mg ²⁺ (mg kg ⁻¹)	140.7	799.7
K ⁺ (mg kg ⁻¹)	174.3	2500
Na ⁺ (mg kg ⁻¹)	99.6	524.8
Surface area (m ² g ⁻¹)	900	392

EC: electrical conductivity.

Table 2
Reference Germination Index (GI) adapted from Emino and Warman (2004).

GI	Category
< 50%	High phytotoxicity
50%–80%	Moderate phytotoxicity
> 80%	No phytotoxicity

3. Results and discussion

3.1. Characterization of the carbonaceous amendments

Table 1 presents the physicochemical characteristics of the amendments used.

The two amendments have contrasting physicochemical properties. Purchased AC has been chemically treated with H₃PO₄, a widely used industrial activating agent. By contrast, BC is a raw biochar with no further activation process. This is evident in the pH and the nutrient content of the amendments. AC has a low pH (2.4) and a very high extractable P concentration, probably residual from activation process, while BC has an alkaline pH (9.6) and high concentrations of alkaline and alkaline earth metals (Ca, Mg, K and Na), associated with the enhanced ash content of these type of raw wood-derived biochars (Taraqqi-A-Kamal et al., 2021; Zhang et al., 2021). Differences in pH and nutrient contents in carbons are greatly determined by feedstock source and temperature of pyrolysis, together with the type of activation process applied (Ding et al., 2016). Contrasting physicochemical differences between activated carbons and biochars have already been reported (Sultan et al., 2020).

XRD analysis also confirmed the differences between the amendments used (Fig. 1a). While AC did not display crystalline phases, BC displayed the characteristic peaks of crystalline calcite (PDF: 00-047-1743): 23.04° (012), 29.32° (104), 35.92° (110), 39.36° (113), 43.08° (202), 47.24° (024 and 018) and 48.40° (116). This is a common compound found in other eucalyptus-derived biochars (Khanna et al., 1994). Both amendments exhibited a broad peak at 2θ = 22.7°, which corresponds to the amorphous structure of cellulose after pyrolysis (Regmi et al., 2012). In addition, the specific surface area was higher for AC, which agrees with the fact that it underwent activation (Fig. 1b).

3.2. Seed germination and root elongation test

Acute toxicity assays with *Lactuca sativa* seeds are conducted to assess phytotoxic effects of pure compounds or complex mixtures in the process of seed germination and development of seedlings, a crucial stage in plants life cycle (Bowers et al., 1997; Chan-Keb et al., 2018). Fig. 2a displays the germination indexes obtained in this study for the different treatments. Soil amendments significantly affected lettuce relative seed germination and relative root elongation (Table S1, Supplementary material) and, hence, germination index (Fig. 2a). For both amendments at the higher doses (AC20% and BC20%), germination index significantly improved in comparison to the control treatment (pure sediment, SED100%). The lower doses (AC10% and BC10%) did not differ significantly from the control treatment.

According to phytotoxicity references (Table 2), SED100% displays a high phytotoxicity with a germination index of 34.3%. Treatment BC10% was characterized as highly phytotoxic too. However, treatments BC20%, AC10% and AC20% showed moderate phytotoxicity. Positive effect of biochar in both seed germination and root elongation in polluted soils has already been reported (Ahmad et al., 2012).

3.3. Lettuce biomass and morphological variables

Fig. 2b shows that the addition of BC did not improve significantly neither shoot dry biomass nor root dry biomass in comparison to the SED100%. With AC, only with the higher dose the shoot dry weight was significantly improved.

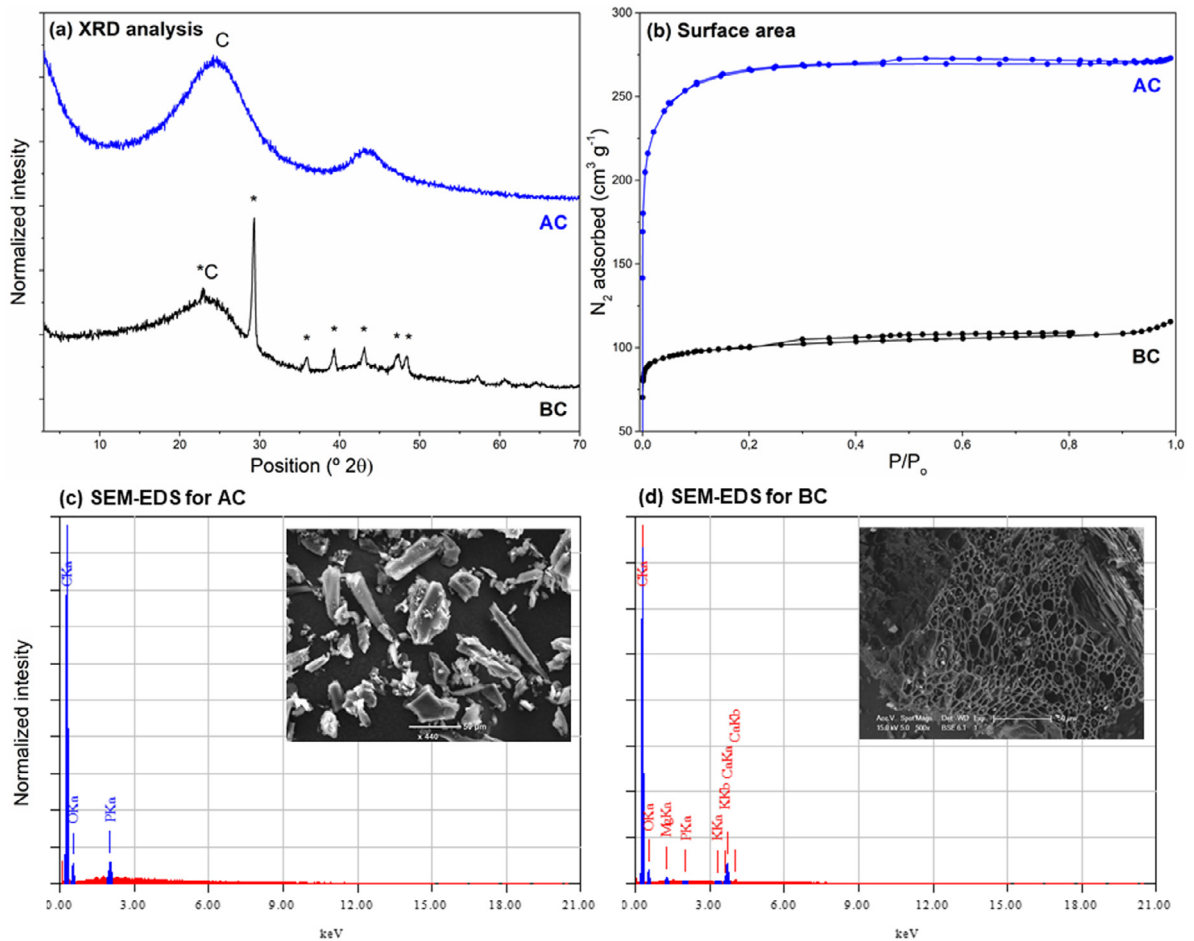


Fig. 1. XRD patterns (a), N_2 sorption isotherms (b), SEM images and SEM-EDS elemental analysis (c and d) for AC and BC. References: calcite (*) and cellulose (C).

Fig. 2c shows that AC, in both doses, had a mean plant height that differed significantly from SED100%. On the contrary, both treatments including BC did not differ from the control treatment. Root length and number of leaves are the other variables that displayed a similar tendency to the one detailed above (Fig. 2d and e): treatments AC10% and AC20% differed significantly from the SED100%. But, in addition, BC20% also presented significant differences with the control treatment. As regards stem diameter, this behavior was only significant in AC20% (Fig. 2f).

Overall, results from the greenhouse experiment demonstrated the importance of carbonaceous amendments addition to plant growth. However, the two amendments had different effects on lettuce morphological variables. The activated carbon seemed to be more effective than the biochar, being AC20% the best treatment concerning all the morphological variables under study, even with no visual symptoms of chlorosis or necrosis (Figure S1, Supplementary material).

Carbonaceous amendments can influence all physical, chemical, and biological properties of soils and sediments (Ding et al., 2016; Zhang et al., 2021). Carbon improves soil physical properties, including the increase of porosity, water storage capacity and the decrease of bulk density. Carbon may also be used to modify soil chemical properties such as nutrient content and availability (soluble based cations), cation exchange capacity and pH. In this way, biochars could alternatively assist plant growth via enhanced soil fertility (Chaturika et al., 2016; Ding et al., 2016; Gascó et al., 2019). Phosphorus dynamics in soils can also be altered by, for instance, directly supplying P (Bolan et al., 2003; Li et al., 2019). Additionally, the amounts of the extractable nutrient elements (e.g., K, Ca, and Mg) could increase after amendment's application, even by pH changes or mediated by microbial transformation (He et al., 2019). Table 3 shows the nutrient content of the mixtures.

Indeed, with the addition of AC there is an important increase in extractable P content in the mixtures, which may have boosted plant growth. Sultan et al. (2020) also reported that the application of acid-activated carbon was more effective than biochar in the improvement of soil fertility and plant status.

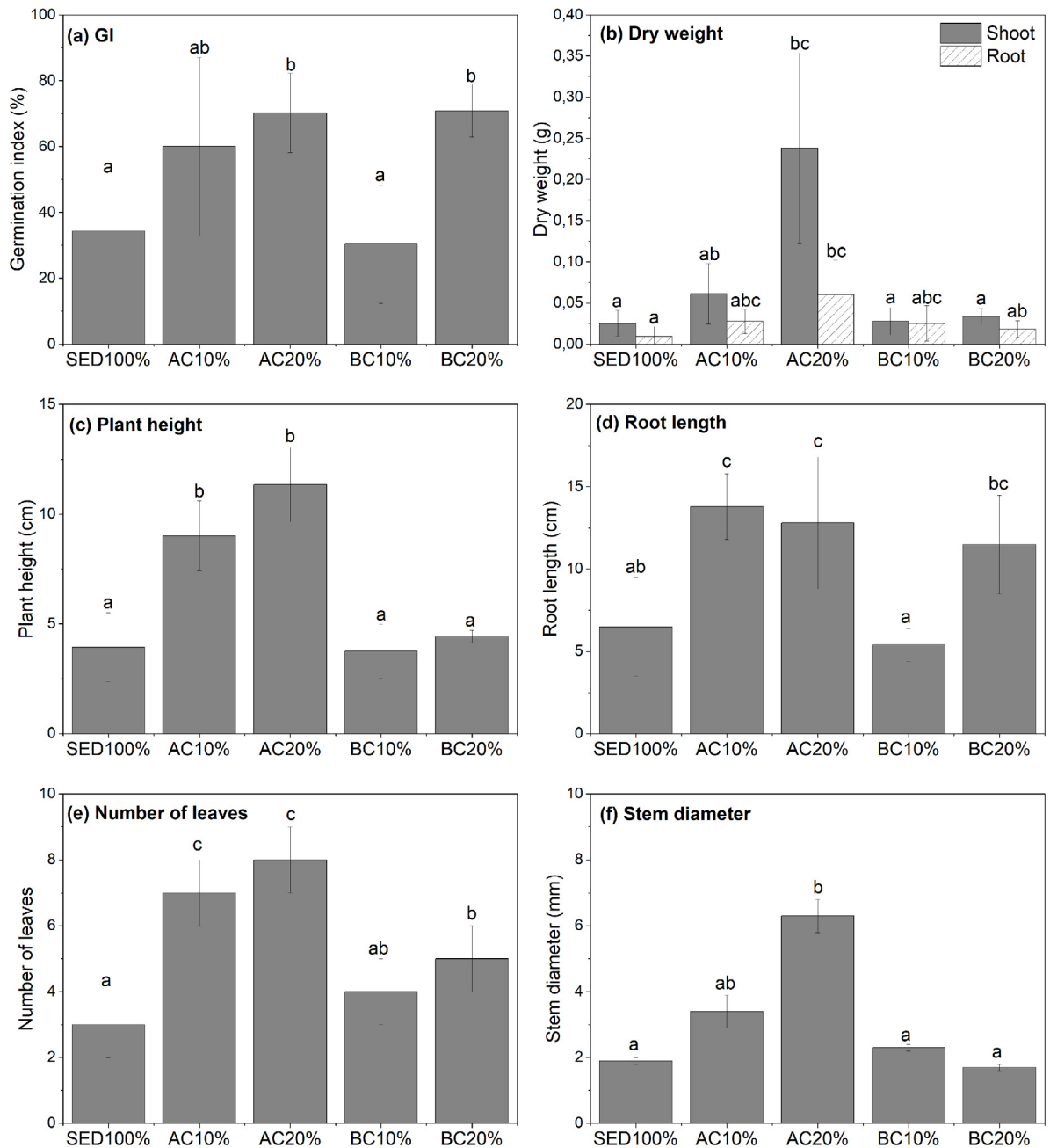


Fig. 2. Germination index (a) and growth parameters for lettuce under the different treatments: dry weight (b), plant height (c), root length (d), number of leaves (e) and stem diameter (f). Different letters indicate significant differences between treatments ($n = 5$).

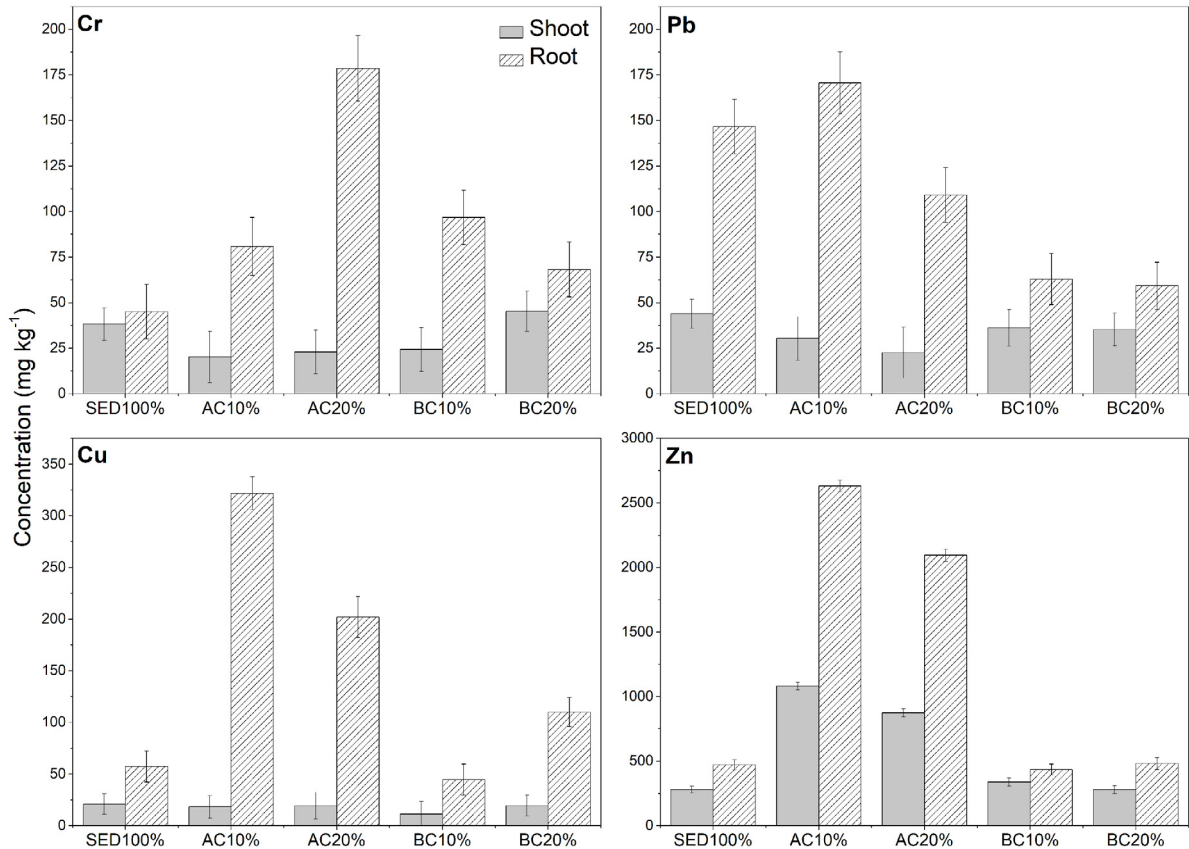
3.4. Heavy metals in biomass

Fig. 3 presents heavy metal concentrations in lettuce. For all the heavy metals under study, AC treatments presented higher accumulation than BC and the pure sediment, both in shoots and roots.

The vast majority of researchers have reported that the application of carbonaceous amendments decreases heavy metal solubilization and phytoavailability in soils (Wang et al., 2020). Carbon textual properties often account for this effect (Oliveira et al., 2017; Ranguin et al., 2020). While BC had an average surface area of $392 \text{ m}^2 \text{ g}^{-1}$ (Bursztyn Fuentes et al., 2020), commercial activated carbons range from $800\text{--}1200 \text{ m}^2 \text{ g}^{-1}$. Thus, AC was expected to immobilize more heavy metals and, hence, have a better performance than biochar BC, as reported by other authors (Ranguin et al., 2020).

Table 3PH, electrical conductivity (EC) and nutrient content in the sediment and mixtures after stabilization (mean \pm standard deviation).

	SED100%	AC10%	AC20%	BC10%	BC20%
pH	6.8 \pm 0.1	6.2 \pm 0.2	5.5 \pm 0.2	7.5 \pm 0.1	7.6 \pm 0.1
EC (dS m ⁻¹)	2708 \pm 95	3000 \pm 80	3130 \pm 100	2683 \pm 53	2915 \pm 30
N (%)	0.18 \pm 0.05	0.17 \pm 0.06	0.19 \pm 0.05	0.17 \pm 0.05	0.12 \pm 0.04
Extractable P (mg kg ⁻¹)	13.6 \pm 0.3	91.1 \pm 0.5	231.4 \pm 0.7	13.0 \pm 0.3	13.1 \pm 0.5
K ⁺ (mg kg ⁻¹)	400 \pm 10	399 \pm 12	424 \pm 15	449 \pm 11	499 \pm 12
Ca ²⁺ (mg kg ⁻¹)	7194 \pm 69	6054 \pm 97	5855 \pm 80	7611 \pm 99	8387 \pm 107
Mg ²⁺ (mg kg ⁻¹)	967 \pm 55	841 \pm 68	918 \pm 73	863 \pm 91	841 \pm 89

**Fig. 3.** Heavy metal concentrations in lettuce for the different treatments under analysis.

However, in this study, carbonaceous amendments did not immobilize heavy metals. Indeed, for all the metals under study, uptake by root tissues of plants grown in AC treatments was higher than that of plants grown in pure sediment. This could be attributed to the nature of the amendment. H₃PO₄-activated carbon (AC) could have lowered pH in the rhizosphere, increasing heavy metal solubilization and plant uptake. The pH in AC20% was 5.5 while in BC20% it was 7.6 pH units (Table 3). The origin of the activated carbon, its granulometry and the activating agent used are important factors to take into account when choosing activated carbon as an amendment for phytostabilization experiments, since they can modify the characteristics of the soil or sediment to be amended, providing undesired characteristic to the mixtures. Then, the resulting pH in the sediment to be amended is a key aspect to consider, since metal sorption is highly dependent on this parameter. Kim et al. (2012) found that lowering the pH by adding acidic activated carbon to polluted sediments inhibited heavy metal sorption onto the sediment.

Interestingly, Wang et al. (2020) reviewed several cases where neutral, negative, or inconsistent results from the addition of carbonaceous amendments have also been reported, both in heavy metal immobilization and plant uptake (Namgay et al., 2010; Uchimiya et al., 2010; Beesley et al., 2010; Park et al., 2011; Gregory et al., 2014; Lucchini et al., 2014; Yin et al., 2016; Abbas et al., 2018; Yang et al., 2018). Lomaglio et al. (2017) also detected enhanced metal mobility with the amendment's application, and identified that pH changes were a relevant factor to explain metal solubilization. However, the final pH achieved greatly depends on the type of amendment and the physicochemical properties of the

substrate under analysis. In addition, [El-Naggar et al. \(2021\)](#) reported that carbonaceous amendments (namely, different types of biochars) did not reduce the mobilization of Cd and Zn, whereas they simultaneously exhibited disparate effects on As and Pb mobilization.

The effectiveness of the amendments on heavy metal adsorption also depends on the characteristics of the sediment (e.g. pH, texture, organic matter content) that determine the partitioning of sediment-bound metals. The heavy metals in the sediment under study are mostly bound to less available fractions (Fe and Mn oxides and organic matter) except for Zn ([Mosso, 2013](#); [Bursztyn Fuentes, 2015](#)). Hence, acidification is necessary to produce the desorption of sediment-bound metals and their subsequent adsorption onto carbons. The addition of AC20% to the sediment substantially decreased the pH of the mixtures, while the addition of BC increased the pH with respect to the pure sediment. This result could explain the absence of differences in the absorption of metals by plants between the pure sediment and its mixtures with biochar ([Fig. 3](#)).

Besides the effect of changes in soil pH, as abovementioned, several authors propose that dissolved organic matter (DOM) released from carbonaceous amendments forms complexes with metals such as Cu, enhancing their mobility ([Meng et al., 2018](#); [Wang et al., 2018](#)).

Another possible hypothesis is that solubilized heavy metals may have adsorbed externally onto root cells, and not absorbed by plant tissues, leading to an overestimation of the quantified heavy metal concentrations in roots. It is known that there are mechanisms, such as those of metal-tolerant plant species, that immobilize heavy metals belowground: phytoestabilization can involve heavy metal precipitation and reduction in the rhizosphere, or adsorption onto root cell walls ([Yan et al., 2020](#)). Interestingly, AC20% had the highest root dry weight and, together with AC10%, the highest root length. This enhanced root development could have enabled better substrate exploration, with more contact surface for heavy metal sorption. Then, washing roots with DTPA could be an interesting strategy/necessary step to study mechanisms in future essays.

Then, the increased root uptake observed in this study for AC treatments did not impact negatively in the plants' morphological variables given that AC also substantially enhanced soil fertility, compensating phytotoxic effects. These are interesting results given that lowering phytotoxicity of sediment can promote plant growth and revegetation on dredged heavy metal polluted sediments. These can decrease health risks of the population living nearby: the established vegetation cover can prevent soil particles containing heavy metal from being dispersed by wind and inhaled or ingested by people ([Yan et al., 2020](#)).

4. Conclusions

The addition of carbonaceous amendments modified the phytotoxicity of the sediment under analysis, but the effect varied depending on the type and dose of the amendment. While BC20% treatment improved germination index but did not improve lettuce growth, AC20% significantly enhanced lettuce germination and morphological variables, despite the fact that they accumulated the highest amounts of heavy metals. Interestingly, the activation process and the enhanced textural properties of AC were not important in reducing heavy metal uptake, but in determining fertility which could compensate for phytotoxic effects. These are interesting results in a remediation scheme of an urban polluted site given that the appropriate selection and dosage of carbonaceous amendments, together with adequate agronomic practices (i.e. fertilization), could be a useful strategy to modify the physicochemical conditions of the sediment, and promote either heavy metal mobilization or stabilization conveniently.

However, in awareness of the current popularity of urban gardens, it must be highlighted that ornamental plant species should be used in revegetation schemes to avoid the consumption of heavy metal-polluted vegetables, which only functioned as an indicator species in this study.

CRedit authorship contribution statement

Amalia Lara Bursztyn Fuentes: Conceptualization, Investigation, Visualization, Writing – original draft. **Luis Ignacio do Carmo:** Conceptualization, Investigation, Formal analysis. **Anna Balaguer Grimaldo:** Investigation. **Cristian Weigandt:** Investigation. **Alejandra de los Ríos:** Supervision. **Alicia Fabrizio de Iorio:** Resources, Funding acquisition. **Alicia Elena Rendina:** Supervision, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.eti.2022.102687>.

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