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# The phytoextraction power of *Cichorium intybus* L. on metal-contaminated soil: Focus on time- and cultivar-depending accumulation and distribution of cadmium, lead and zinc

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**Title:** The phytoextraction power of *Cichorium intybus* L. on metal-contaminated soil: focus on time- and cultivar-depending accumulation and distribution of cadmium, lead and zinc.

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## 1 **Abstract**

2 This study is focused on the evaluation of the accumulation of Cd, Pb and Zn in five cultivars of  
3 *Cichorium intybus* L. (chicory) which were produced on contaminated agricultural soil. Over a growth  
4 period of 211 days, the roots and leaves were collected in four stages and then analyzed by flame  
5 atomic absorption spectrometry to measure the concentration and distribution of the target metals in  
6 these two chicory organs considering the weather and the nature of the cultivar. For all cultivars, sharp  
7 decreases of Pb (from 165 mg kg<sup>-1</sup> to 3 mg kg<sup>-1</sup>), Cd (from 11 mg kg<sup>-1</sup> to 5 mg kg<sup>-1</sup>) and Zn  
8 concentrations (from 157 mg kg<sup>-1</sup> to 40 mg kg<sup>-1</sup>) in the roots were highlighted over time. The data  
9 collected enabled the calculation of the variation of the bioconcentration factor, the biological  
10 absorption coefficient and the translocation factor for Cd, Pb and Zn. These parameters were then  
11 correlated with the distribution of the fresh biomass of leaves and roots and several indicators such as  
12 chlorophyll content, flavonols, anthocyanin and nitrogen balance index were measured. The study  
13 concludes with the discussion on the ability of chicory to clean up contaminated agricultural soil. The  
14 current investigation has shown: i) a translocation of Cd (and Zn to a lesser extent) from the roots to  
15 the leaves; ii) an increase in the level of anthocyanins with the increase of the metal trace elements  
16 concentration in the leaf, while the content of chlorophyll and the nitrogen balance index decrease,  
17 which could be linked to the phenomenon of senescence; iii) an ability of the chicory to reduce the  
18 bioavailable pool of the three metal trace elements studied, in particular for Cd.

19

20 **Key words:** Metal; Chicory; Bioavailability; Plant pigments; Remediation factor

21

## 22 1. Introduction

23 Soil pollution by metal(loid)s remains a major environmental concern in the whole world. These  
24 contaminants accumulate quickly in living organisms (fauna and flora) and often reach toxic  
25 concentrations that affect the soil functioning, the ecosystem, and the human health due to their long-  
26 term persistence in the environment. Human activities (e.g. mining and smelting of metal ores) are the  
27 main sources that contributed to increase the environmental anthropogenic pollution by metal(loid)s  
28 (Alloway, 1995, 2013). The most famous contaminated area in the Hauts-de-France region (France) is  
29 located in the former coal mining and ore processing sites (Metaleurop Nord and Nyrstar). For more  
30 than a century, the main pollutants released by these two metallurgical plants were lead (Pb), cadmium  
31 (Cd), and zinc (Zn), defined as metal trace elements (MTE) in the current study. The total  
32 concentration of these MTE and their bioavailability in the surrounding agricultural soils is sometimes  
33 problematic since a high proportion of the agricultural crops for foodstuffs are not conform with the  
34 European legislation (Douay et al., 2013; Pruvot et al., 2006).

35 Many *ex-situ* and *in-situ* methods have been developed to manage polluted soils (Gong et al.,  
36 2018) (e.g. encapsulation, soil washing, vitrification...). While these methods allow effective soil  
37 treatment, these technologies are often costly, time consuming and unsuitable for managing the soil of  
38 large polluted sites (Liu et al., 2018). Soil phytoremediation is a much more viable alternative because  
39 of its ease of implementation and the low costs it implies. This technology refers to the use of plants  
40 and amendments and/or microorganisms that can be added to improve the soil quality through several  
41 processes such as the degradation of organic matter, the degradation of pollutants as well as their  
42 extraction or stabilization (Ali et al., 2013). Among these processes, phytoaccumulation consists in  
43 metal(loid)s accumulation in the plant organs after their extraction from the polluted soils. Some of  
44 them namely nickel (Ni), copper (Cu), manganese (Mn) and Zn are considered as essential for the  
45 growth of plants and so, they can accumulate them (Bhargava et al., 2012). Some others like Cd, Pb,  
46 silver (Ag), arsenic (As), antimony (Sb) or mercury (Hg) are not essential and can cause phytotoxic  
47 effects (Finnegan and Weihua, 2012; Sheoran et al., 2016; Shtangeeva et al., 2011). However,  
48 metallophytes are able to concentrate some of these metal(loid)s from contaminated soils within their  
49 organs without necessarily significantly alter their growth and development (Rossini-Oliva et al.,

50 2018). Therefore, organ of these plants can be used through many applications to develop the bio  
51 economy and so ingrate the circular economy concept (Deyris et al., 2019; Hazotte et al., 2017;  
52 Gomes, 2012; Guérin et al., 2021; Hechelski et al., 2018; Janus et al., 2015; Oustrière et al., 2019;  
53 Waterlot et al., 2019).

54 *Cichorium intybus* L. (chicory) adapts to wide temperature ranges, different types of soils and is able  
55 to grow along the roadside, in industrial sites, urban parks and wasteland, even under high level of  
56 contamination (Askoy, 2008). Several studies have shown that chicory is capable, to some extent, of  
57 accumulating MTE (Cd, Pb and Zn) when produced on moderately contaminated soil (Mandzhieva et  
58 al., 2016; Sekara et al., 2005; Zeng et al., 2019). Moreover, Zeng et al. (2019) showed that  
59 translocation of metals to shoots depended on the nature of metals and on seedling and mature periods.

60 The purpose of this work is (i) to assess the dynamic of the MTE accumulation (Pb, Cd and Zn)  
61 by the roots and shoots of various cultivars of chicory produced on severely contaminated agricultural  
62 soils sampled near the former Metaleurop Nord plant, (ii) to examine the variation of several plant  
63 pigments (chlorophyll, anthocyanins, flavonols and nitrogen balance index) and (iii) to evaluate the  
64 ability of chicory in the remediation of contaminated soils by Cd, Pb and Zn.

65

## 66 2. Materials and Methods

### 67 2.1. Soil sampling, experimental set-up, and plants sampling

68 Contaminated soil (300 kg) was sampled from the ploughed layer (0-25 cm) of an agricultural plot  
69 (latitude: 50° 26' 15.9" N; longitude: 3° 01' 04.9" E) located not far away from the former Metaleurop  
70 Nord plant (France) in November 2018. This soil is a clay sandy loam dominated by silt and it is  
71 characterized by the following parameters: pH=7.7, Total N: 1200 mg kg<sup>-1</sup>; Total C: 18.2 g kg<sup>-1</sup>; C/N:  
72 15.2; P<sub>2</sub>O<sub>5</sub>: 160 mg kg<sup>-1</sup>; Organic matter: 45 g kg<sup>-1</sup>; CEC: 15 cmol<sup>+</sup> kg<sup>-1</sup> (Hechelski et al., 2020;  
73 Nsanganwimana et al., 2015). After homogenization, five containers (outside length: 40 cm; outside  
74 width: 30 cm; outside height: 25 cm) were filled with 20 kg of air-dried contaminated soil. The soil  
75 moisture experimental device was maintained at 40% field capacity with tap water in greenhouse at  
76 20-25 °C. In each of containers, 7 seeds of chicory were sown in 2 rows. Five cultivars, providing by  
77 Florimond Desprez company (<https://www.florimond-desprez.com/rep/en/nl/groupe-florimond->

78 desprez-2.html), were considered (C1, C2, C3, C4 and C5) in the current study. Chicories were  
79 samples after 74, 105, 156 and 211 days after sowing, taking one plant out of every two times. Shoots  
80 and roots of chicory were then separated, crushed, and dried at 105 °C, then stored in acid-washed  
81 plastic bottles until digestion.

82

## 83 **2.2. Digestion of plant and soil**

### 84 **2.2.1. Soil digestion and extractable-MTE in soils**

85 300 mg of soil were digested by a mixture of 37% HCl (4.5 mL) and 70% HNO<sub>3</sub> (1.5 mL). The  
86 suspension was heated at 120 °C for 90 min in a hot-block digester (**HotBlock™ Environmental**  
87 **Express®SC100, Charleston, USA**). Ultra-pure water was then added until reaching 25 mL and the  
88 mixture was filtered over an acetate Millipore membrane (0.45 µm porosity). The resulting solutions  
89 were stored in acid-washed plastic bottles at 4 °C prior to analysis. Calcium chloride (0.01 M) and a  
90 mixture of Low Molecular Weight Organic Acids (LMWOAs) were used to evaluate the labile pool  
91 MTE in soils, the bioavailable MTE in short and long run ([Waterlot et al., 2017](#); [Waterlot and](#)  
92 [Hechelski, 2019](#)).

### 93 **2.2.2. Plant digestion**

94 300 mg of dry plant sample (roots or leaves) were added to 5 mL of 70% HNO<sub>3</sub>. The resulting  
95 suspension was heated at 95 °C for 90 min using the hot-block digester. After heating, 5 mL of H<sub>2</sub>O<sub>2</sub>  
96 (30%) were slowly added in the cooled solution and the mixture was heated at 90±5 °C for 180 min.  
97 Ultra-pure water was then added until reaching a total volume of 25 mL, the mixture was filtered over  
98 an acetate Millipore membrane (0.45 µm porosity) and stored at 4 °C prior to analysis.

### 99 **2.2.3. Chemical and statistical analyses**

100 The concentration of MTE (Pb, Cd and Zn) in soil and plant digests were determined by flame or  
101 electrothermal atomic absorption spectrometry (**AA-6800, Shimadzu, Tokyo, Japan**) following the  
102 recommendations described in the literature ([Waterlot et Douay, 2009](#); [Savio et al., 2010](#)). **The limit of**  
103 **detection was 2.1 µg Cd L<sup>-1</sup>, 41 µg Pb L<sup>-1</sup>, 1.5 µg Zn L<sup>-1</sup> using flame as atomizer and 0.06 µg Pb L<sup>-1</sup>**  
104 **using graphite furnace as atomizer** ([Waterlot et al., 2013](#); [Waterlot and Hechelski, 2019](#)). **INCTL-**  
105 **OBTL-5 (Virginia tobacco leaves n=3)** was used as reference material for the quality control. The

106 digestion and analysis procedures yielded good average recovery values of 90-108 %, depending on  
107 MTE (Obtained concentrations: [Cd] = 2.36±0.12 mg kg<sup>-1</sup>; [Pb] = 2.11±0.21 mg kg<sup>-1</sup>; [Zn] = 56.2±2.2  
108 mg kg<sup>-1</sup>; Certified concentrations: [Cd] = 2.64±0.14 mg kg<sup>-1</sup>; [Pb] = 2.01±0.31 mg kg<sup>-1</sup>; [Zn] =  
109 52.4±1.8 mg kg<sup>-1</sup>).

110 Chlorophyll content (µg cm<sup>-2</sup>), Flavonols Index (relative units) and Anthocyanins Index (relative  
111 units) and were measured using a plant pigment content meter (Dualux® Scientific+, Force-A, Orsay,  
112 France) on green leaves at the base of the rosette. Moreover, the Dualux device provided a Nitrogen  
113 Balance Index (NBI) as reported in Rusinowski et al. (2019). Data collected were compared with those  
114 obtained from chicories grown in the same conditions on a control unpolluted soil considered as a  
115 reference soil (R). From the data set (n<sub>1</sub> = 120; n<sub>1</sub> = 6n with n=20), analyses were performed using the  
116 software program XLSTAT 2021 (Addinsoft, Paris, France). Significant differences between reference  
117 and/or cultivars were determined using a one-way ANOVA. Normality and homoscedasticity of  
118 residuals were met for all tests. When significant differences occurred between reference and/or  
119 cultivars, multiple comparisons of mean values were made using post-hoc Tukey HSD tests.  
120 Differences were considered statistically significant at p<0.05.

121

## 122 **2.3. Indices calculation**

### 123 **2.3.1. Bioconcentration factor (BCF)**

124 The BCF is the ability of plants to accumulate MTE with respect to their concentration in soils  
125 (Wang et al., 2019). In the current study, the BCF is the ratio of MTE concentration in the roots to  
126 those in the soil substrate (Eq. 1; Mirzaei et al., 2021):

$$127 \quad BCF = \frac{C_{MTERP}}{C_{MTE S}} \quad (1)$$

128 where C<sub>MTERP</sub> is the MTE concentration in the root of plants and C<sub>MTE S</sub> is the MTE concentration of  
129 in soils.

### 130 **2.3.2. Biological absorption coefficient (BAC)**

131 The BAC is related to the bioaccumulation of MTE in the aerial part of plants. This index is  
132 defined as the ratio between the MTE concentrations in the shoots and the soil substrate (Eq. 2, [Zehra  
133 et al., 2020](#)).

$$134 \quad BAC = \frac{C_{MTESP}}{C_{MTE S}} \quad (2)$$

135 where  $C_{MTESP}$  is the MTE concentration in the shoot of plants and  $C_{MTE S}$  is the MTE concentration in  
136 soils.

### 137 2.3.3. Translocation factor (TF)

138 The TF indicate the ability of plants to translocate MTE from roots to leaves ([Zehra et al., 2020](#))  
139 and is defined as follows (eq 3):

$$140 \quad TF = \frac{C_{MTE L}}{C_{MTE R}} \quad (\text{eq 3})$$

141 where  $C_{MTE L}$  is the concentration of MTE in leaves and  $C_{MTE R}$  is the concentration of MTE in roots.

142

## 143 3. Results and discussion

### 144 3.1. Metal concentration in soil-chicory system

145 The concentrations of Pb, Cd and Zn in the studied agricultural soil were  $757.1 \pm 35.4 \text{ mg kg}^{-1}$ ,  
146  $10.7 \pm 0.5 \text{ mg kg}^{-1}$ ,  $857.4 \pm 74.0 \text{ mg kg}^{-1}$  ( $n = 9$ ), respectively. On average, these concentrations are  
147 20-fold, 25-fold and 12-fold higher than those in the loessic reference soils ([Sterckeman et al., 2002](#)).  
148 Compared to the ploughed horizons of cultivated plots around Noyelles-Godault plants, Pb and Zn  
149 concentrations in the studied agricultural soil were the highest (45% and 33%, respectively) whereas  
150 Cd was quite similar ( $10.7$  vs  $9.8$ ; [Sterckeman et al., 2002](#)). The  $0.01\text{M CaCl}_2$ -extractable  
151 concentrations were  $0.04 \pm 0.01 \text{ mg Pb kg}^{-1}$ ,  $0.28 \pm 0.07 \text{ mg Cd kg}^{-1}$  and  $0.56 \pm 0.11 \text{ mg Zn kg}^{-1}$  ( $n =$   
152  $9$ ). The extractable-MTE concentrations measured in the mixture of LMWOAs were  $5.34 \pm 1.07 \text{ mg}$   
153  $\text{Pb kg}^{-1}$ ,  $1.83 \pm 0.12 \text{ mg Cd kg}^{-1}$  and  $172 \pm 13 \text{ mg Zn kg}^{-1}$  ( $n = 9$ ). These results highlight the poor  
154 labile pool of these MTE. The bioavailable fraction of MTE in short run was below 0.1%. In long run,  
155 it was 0.7% for Pb, 17% for Cd and 20% for Zn. This means that a potential decrease of the total Cd  
156 and Zn will be done, but obviously it will take time.



157 [Figure 1](#) shows the mean of MTE concentrations in the roots and shoot of chicory over time. Pb-  
158 concentrations in the roots of chicory at the first sampling (74 days) ranged from 101 to 165 mg.kg<sup>-1</sup>,  
159 depending on cultivars. These concentrations were 10-fold higher than those measured in the shoots of  
160 cultivars C1, C2 and C5 and 6-fold higher for C4. From the second sampling up to the sampling at the  
161 end of the experiment, the concentration measured in the roots of chicory drastically decreased (from  
162 60% to 85%) to reach a plateau, ranging from 3.21 to 9.07 mg Pb kg<sup>-1</sup> for the two last samplings,  
163 which depends on cultivars. In the same time, slight modifications in the Pb concentrations measured  
164 in the shoots of chicory may be noted but without any relations with the decrease of Pb concentrations  
165 in the roots. These results are not surprising knowing that Pb is a non-phytoavailable MTE and  
166 suggests a dilution of Pb in the roots over the growing period. **Indeed, the ratio of roots biomass**  
167 **between the second and the first samplings (105 and 74 days, respectively) is approximately 14.**  
168 However, these results are somewhat at odds with those described in Zeng et al. (2019). The mean Pb  
169 concentrations measured by the authors in the roots and shoots of chicory were around 50 and 25 mg  
170 kg<sup>-1</sup>, although the Pb concentration in their soil were 10-fold lower at least than in the current study.  
171 This result means that the labile pool of Pb is a crucial parameter to consider. The extractable-MTE  
172 concentration using the mixture of LMWOAs and 0.01 M CaCl<sub>2</sub> represented 1% and 0.01% of the  
173 total Pb concentration, respectively, as reported in previous studies (Hechelski et al., 2020;  
174 Nsanganwimana et al., 2015). These data correlated well with the fact that the Pb concentrations in  
175 both studied chicory' organs are low despite the high total Pb concentrations in the soil substrate.

176 Variations in Cd and Zn concentrations in roots and shoots of chicory over time are presented in  
177 [Figures 1B and 1C](#). The concentrations of Cd and Zn in the roots of chicory decreased over time (from  
178 50 to 60% and 64 to 78%, respectively) and slightly increased at the fourth sampling (211 days). In  
179 contrast, concentration of the two metals increased over the growth period, from 25 to 147% for Cd  
180 and from 5.5 to 43% for Zn. As shown on [Figures 1B and 1C](#), the Cd and Zn accumulations in plant  
181 organs at the end of the experiments were higher in shoots than in roots whatever the cultivars are. 211  
182 days after sowing, the Cd and Zn concentrations in the shoots of chicory were up to 50 mg kg<sup>-1</sup> DW  
183 and 172 mg kg<sup>-1</sup> DW, respectively. These concentrations were, respectively, 7-fold and 3.4-fold higher  
184 than those in chicory' roots. These results correlated well with those obtained for Zn by Zeng et al.

185 (2019) but are quite different for Cd. No significant difference was highlighted by the authors between  
186 the Cd concentrations measured in shoots and in roots in seedling and mature periods. It has been  
187 reported in previous studies that the MTE accumulation capacities are affected by interspecific  
188 differences, environment conditions (Grant et al. 2008; Shi and Cai 2009) and the available Cd and the  
189 total Cd concentration, which was 8-fold higher in the current study than in Zeng et al. (2019).

190

### 191 **3.2. Bioaccumulation factor, biological absorption coefficient and translocation factor**

192 MTE-accumulation, MTE-translocation, and MTE-distribution in the upper and underground  
193 parts of plants were studied by means of three indices named bioconcentration factor (BCF: root-to-  
194 soil metal concentration ratio), biological adsorption coefficient (BAC: plant leaves-to-soil metal  
195 concentration ratio) and translocation factor (TF: leaves-to-root metal concentration ratio). The  
196 utilization of these indexes was recommended to define the ability of plant models in the  
197 phytoextraction and phytostabilization of MTE (Zhou et al., 2020). According to Alagić et al. (2015),  
198 a value of BCF greater than 1 ( $BCF > 1$ ) indicates a good bioaccumulation of MTE in the roots of  
199 plants and if these plants have BAC values greater than 1 ( $BAC > 1$ ), they are a suitable option for  
200 bioaccumulation of MTE in their shoots. Moreover, if  $TF > 1$ , the good ability of plants to translocate  
201 MTE from their roots to their aboveground parts make them as suitable for phytoextraction purpose  
202 (Vamelari et al., 2010). In contrast, for  $BCF > 1$  and  $TF < 1$ , the potential of plants to be MTE-tolerant  
203 is great and so, they have potential for introducing as phytostabilization purpose (Vamelari et al.,  
204 2010). The three parameters were reported in Table 1 for each sample. The Pb-BCF values were low,  
205 ranging from 0.13 to 0.22 at the first sampling, and then, decreased sharply to reach 0.01 from the  
206 third sampling up to the last one. This trend was not cultivar-dependent. As shown in Table 1, the Pb-  
207 BAC values are very low over time (ranging from 0.01 to 0.03) whatever the cultivar meaning that  
208 chicories should not be suitable for Pb-phytoaccumulation. However, depending on time, the Pb-TF  
209 values were higher than 1 and were cultivar-dependent (from 1.44 to 3.53 at 156 days and from 0.86 to  
210 1.34 at 211 days). These trends correlated well with the fact that the Pb-concentration remained quite  
211 constant from the second harvest to the end of the experiment. Caution should be taken when  
212 interpreting the results related to Pb-BAC and Pb-TF. Thus, we do not want to conclude on the

213 capacity of chicory to phytostabilize and phytoextract Pb. However, it is worth mentioning that  
214 chicories were described in other studies as Pb-phytoextractor (Vamelari et al., 2010) and Pb-  
215 accumulator (Baker et al., 1981).

216 As reported in Sêkara et al. (2005), Mandzhieva et al. (2016) and Zeng et al. (2019), the data for  
217 Cd distribution suggest that chicories are characteristic of good accumulators since BAC and TF were  
218 higher than 1. These two indicators increased over the growth period to reach values higher than 4 and  
219 8, respectively corroborating the decrease of the BCF values over the same period. Unfortunately, due  
220 to the size of containers, the growth of plants was limited between 156 days and 211 days, potentially  
221 leading to a bias in the data collected. This result is even more pertinent as 60% of the total Cd-  
222 concentration was found in the acido-soluble fraction of the fourth-step sequential extraction  
223 procedure (Pelfrêne et al., 2015). Thus, by removing the shoots of chicory from the field, this plant  
224 should be able to be used for the removal of the bioavailable pool of Cd from the soil. Although Cd  
225 and Zn have similar chemical properties, the Zn-BAC and Zn-BCF were lower than 1 from the first  
226 harvest to the last one. However, Zn-BAC decreases whereas Zn-BCF increases over the growth  
227 period meaning that Zn-TF increases. As shown in Table 1, this indicator increases in time up to 156  
228 days and was higher than 3 at 211 days meaning that chicories are able to extract Zn from soil.  
229 Recently, Wolf and Paulino (2020) pointed out the potential toxicity effects of Zn when chicories were  
230 produced on Zn-contaminated soils. In fact, the authors spiked their soils with zinc sulfate to obtain  
231 concentrations of 1200 mg Zn kg<sup>-1</sup> and 2400 mg Zn kg<sup>-1</sup>. They highlighted a decrease of leaf  
232 biomasses 45 days after seedling and chlorosis effects. In the current study, no visual symptoms were  
233 noticed.

234

### 235 ***3.3. Plant uptake and foresight***

236 The total harvested-plant biomass was expressed as leaf and root fresh-biomass distribution  
237 (Figure 2). As reported on it, the absolute mass distribution of these two plant-parts depends on  
238 cultivars. Leaf and root biomasses were in the same order of magnitude for the first two cultivars  
239 whereas they were different for the last three cultivars. For those, biomasses of roots ranged from  
240 58.6% to 59.5% and so, were higher than in leaves. Based on the total mass of sampled roots and

241 leaves, exported metals from the soil to the chicories were calculated and presented in [Table 2](#). The  
242 total metal uptake in leaves and roots were slightly dependent on cultivars and were highly metal-  
243 dependent. The ascending order of metals mass in the leaves of chicories was Zn>Cd>Pb whereas it  
244 was Zn>Pb>Cd in roots. Whatever the results, the data highlighted that if chicories are produced on  
245 contaminated soils, collections of leaf are required to avoid the recycling of leaf-bound MTE before  
246 the root harvest. As shown in [Figure 3](#), chlorophyll contents in the reference (R), and the cultivars C3  
247 and C5 were statistically the same. This result corroborates with the fact that the exported MTE by  
248 these two cultivars were the lowest. On the contrary, statistical differences were highlighted between  
249 the chlorophyll contents in R and the cultivars C1, C2 and C4, for which the exported MTE were the  
250 greatest. This means that higher the exported MTE is, lower the concentration of chlorophyll in the  
251 leaves of chicory is. Indeed, among the survival mechanisms of plants are MTE-translocation to leaves  
252 and decreasing chlorophyll ([Uzu et al., 2010](#)). Moreover, the decrease of chlorophyll may be linked to  
253 the senescence ([Wojciechowska et al., 2018](#)).

254 Although there is no statistical difference in the concentration of flavonols between the reference  
255 and the five cultivars studied, it is worth mentioning the relationship between the results obtained with  
256 chlorophyll and anthocyanins. No statistical difference was highlighted between anthocyanins in R and  
257 C3 and C5, whereas anthocyanin concentrations in R were statistically different from those in C1, C2  
258 and C4. As shown in [Figure 3](#), concentrations of anthocyanin were the highest in these three cultivars.  
259 This corroborates with previous studies in which it was well established that one of the role of  
260 anthocyanin is the protection of plants from several abiotic and biotic stress ([Chalker-Scott,](#)  
261 [1999](#); [Ahmed et al., 2014](#)), which may provide them a better adaptation to contamination level. Acting  
262 as antioxidant, anthocyanins are able to bind with MTE reducing consequently their toxicity ([Dai et](#)  
263 [al., 2012](#); [Akbari et al., 2013](#)). It is worth mentioning that the formation of anthocyanin-MTE  
264 complexes is pH-dependent since it affects the protonation/deprotonation of anthocyanins and  
265 consequently their reactivity towards heavy metals.

266 As for chlorophyll concentrations, the NBI indices ([Figure 3](#)) were the lowest for C1, C2 and C4  
267 and statistically different from that of R. In addition, no statistical difference was highlighted between  
268 the reference and the cultivars C3 and C5. Defined as an indicator of C:N allocation changes ([Cerovic](#)

269 [et al., 2012](#)), the NBI could be a simple valuable tool for preventing the rate of senescence of chicory  
270 leaves in addition to the chlorophyll measure, and so the premature leaf fall of chicories produced in  
271 contaminated soils. This highlight has been suggested in several studies about miscanthus ([Mos et al.,](#)  
272 [2013](#); [Rusinowski et al., 2019](#)).

273 **Despite** the short time-experimentation (211 days) and the limited-size of the containers, the  
274 exported metal from soil ranged from 0.83 mg to 1.59 mg Pb, 1.44 to 2.03 mg Cd and 6.94 to 10.87  
275 mg Zn. Based on the dataset, a remediation factor (RF) was calculated according to the definition  
276 described in [Sabir et al. \(2015\)](#). **Briefly, this factor was defined as the ratio of the mass of metal in the**  
277 **set of plants cultivated in each container to soil as follows** (Eq. 4):

$$278 \quad RF = \frac{MTE \text{ concentration in plant} \times \text{plant dry biomass}}{MTE \text{ concentration in soil} \times \text{mass of air-dried contaminated soil}} \times 100 \text{ (eq 4)}$$

279 It was clearly demonstrated that the mechanism uptake of MTE depended on several parameters  
280 like the root zone, the environmental conditions, the soil parameters, the plant species, the speciation  
281 of MTE ([Tangahu et al., 2011](#)) and so, the bioavailability of MTE. Thus, two remediation factor  
282 indexes, named  $RF_{LMWOAs}$  and  $RF_{CaCl_2}$  were calculated considering the extractable MTE concentrations  
283 measured in the mixture of organic acids (LMWOAs) and in the 0.01 M calcium chloride solution.  
284 The results are summarized in [Table 3](#). Although it was demonstrated that Pb, Cd and Zn were poorly  
285 phytoavailable using miscanthus as plant model ([Nsanganwimana et al., 2015](#); [2021](#)), the RF-Cd  
286 values were in the range 0.67-0.95 %, depending on the cultivars. Even if the maturity of chicories has  
287 not been reached, this result is interesting since the RF values tend to increase with time ([Saraswat and](#)  
288 [Rai, 2011](#)). According to our knowledge, no study reported similar data using chicory cultivars. In  
289 contrast, some RF-Cd values were reported in literature using various plant models in  
290 anthropogenically or artificially contaminated soils ([Hu et al., 2014](#); [Chhajro et al., 2018](#); [Moemeri](#)  
291 [and Khalaki, 2019](#)). **Chhairo et al. (2018) revealed RF-Cd values of 0.39 without any amendment and**  
292 **up to 1 using chelators (EDTA, NTA, citrate) and castor bean (*Ricinus communis*) whereas Rf-Cd**  
293 **values below 0.7 was highlighted whatever the treatments (EDTA, EGTA, citrate; [Sun et al., 2011](#); [Hu](#)**  
294 **[et al., 2014](#)).** However, RF-Cd values between 1.0 and 4.0 using *Secale montanum* and *Leucaena*  
295 *leucocephala* were reported under a phytoextraction context ([Saraswast and Rai, 2009, 2011](#); [Moameri](#)

296 and Khalaki, 2019) As shown in Table 3, the RF-Pb values are very low, from 0.006 to 0.01. They are  
297 in the same order of magnitude as those reported in Moameri and Khalaki, (2019) and Sun et al.  
298 (2011). Nevertheless, depending on the ability of shrub and tree species to phytoextract Pb, some  
299 authors highlighted medium and high RF-Pb values (from 0.5 to 13.5; Aman et al., 2018; Singh et al.,  
300 2020). The RF-Zn values were ten-fold higher than those of RF-Pb although the total concentrations of  
301 these MTE in the soil studied were quite similar. Even if similar RF-Zn values were reported in Sun et  
302 al. (2001) as those obtained in the current study, it is worth noting that RF-Zn values are between 0.3  
303 to 2.1, depending on plant species and soil characteristics (Aman et al., 2018; Sarawat and Rai, 2011;  
304 Sabir et al., 2015).

305 In the Gentle soil Remediation Options (GRO) the common goal is to decrease the labile pool of  
306 MTE because it represents the most available pool of MTE. This pool is a part of the total metal  
307 concentration and is commonly named bioavailable. In this concept, phytoextraction and  
308 phytoremediation are both strategies that can be used to achieve this objective if this plant-based soil-  
309 management is integrated in the bioeconomy concept. From these global considerations, we defined  
310 the  $RF_{LMWOAs}$  and  $RF_{CaCl_2}$  described above. Values of these two remediation factors were higher than  
311 those of RF since there were defined from the extractable-MTE concentrations. As indicated in Table  
312 3, the  $RF_{LMWOAs-Cd}$  is higher than 4 meaning that chicories can be used as phytoextractor for  
313 bioavailable-Cd in long run. This result correlated with the conclusion described previously from the  
314 BAC, BCF and TF values. In contrast, the results remain less evident for Pb and Zn since their  
315 respective  $RF_{LMWOAs}$  values were generally below 1. Anyway, chicories are able to decrease the pool  
316 of the bioavailable-MTE in short time as shown by the  $RF_{CaCl_2}$  values for the three MTE studied.

317 Although the growth period was limited in time due to the size of containers, this new approach  
318 and the whole of results obtained from container-experiments should provide new insights into the  
319 potential of chicories in lowering the environmental risks after a large-scale chicory production on  
320 contaminated agricultural soils. However, it is worth mentioning that further studies need to be  
321 conduct due to (i) the restriction of the root size in the current study and not for field studies and (ii) a  
322 potential lateral and vertical gradient of metal(loid)s contamination levels in real contaminated sites.

323

324

#### 325 **4. Conclusion**

326 This study, carried out over a period of 211 days, was conducted to determine the concentration  
327 and time distribution of Cd, Pb and Zn in five cultivars of chicory which have been produced on an  
328 agricultural contaminated soil. Leaves and roots analysis at 4 time points during experimentation (at  
329 74, 105, 156 and 211 days, respectively) revealed that the Cd and Zn concentration in plants organs at  
330 the end of the experiments were higher in shoots than in roots (up to 7-fold and 3.4-fold higher,  
331 respectively) whatever the cultivars were, while no significant differences were observed for Pb.  
332 Indeed, Cd-BAC and Cd-TF increase during the growing period to reach values above 4 and 7,  
333 highlighting the ability of chicory to reduce the Cd content of the soil. This reasoning is also valid for  
334 Zn, but to a lesser extent since the Zn-TF reaches values higher than 3 at 211 days. The Zn-BAC  
335 values are lower than 1 from the first harvest to the last one. In addition, MTE concentrations in shoots  
336 have been related to the content of chlorophyll, anthocyanins and nitrogen balance index. It appears  
337 that an increase of the MTE concentration in the leave induces i) an increase of the anthocyanin  
338 content, which may provide to the chicory a better adaptation to contamination level ii) a decrease of  
339 the content of chlorophyll and nitrogen balance index, which could be related to the senescence  
340 phenomenon. Finally, the phytoextracting power of chicory has been discussed regarding the  
341 bioavailable part of the total MTE concentration and has been identified as a good phytoextractor,  
342 particularly for Cd. These news results thus highlight the interest of harvesting the aerial parts of  
343 chicory thus limiting the deposition of MTE after large-scale chicory production on contaminated  
344 agricultural soils.

345

#### 346 **Declaration of Competing Interest**

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

349

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355

## 356 **References**

357 Ahmed, N.U., Park, J.I., Jung, H.J., Yang, T.J., Hur, Y., Nou, I.S., 2014. Characterization of  
358 dihydroflavonol 4-reductase (DFR) genes and their association with cold and freezing stress in  
359 *Brassica rapa*. *Gene* 550, 46–55. <https://doi.org/10.1016/j.gene.2014.08.013>

360 Akbari, R., Hatamzadeh, A., Sariri, R., Bakhshi, D., 2013. Relationship of flower color parameters and  
361 metal ions of petal tissue in fully opened flowers of *Gerbera*. *J. Plant Stud.* 2, 89–96.  
362 <https://dx.doi.org/10.5539/jps.v2n1p89>

363 Aksoy, A., 2008. Chicory (*Cichorium Intybus* L.): A possible biomonitor of metal pollution. *Pak. J.*  
364 *Bot.* 40, 791–797. <https://doi.org/10.1.1.681.4091>

365 Alagić, S.Č., Tošić, S.B., Dimitrijević, M.D., Antonijević, M.M., Nujkić, M.M., 2015. Assessment of  
366 the quality of polluted areas based on the content of heavy metals in different organs of the grapevine  
367 (*Vitis vinifera*) cv Tamjanika. *Environ. Sci. Pollut. Res.* 22, 7155–7175.  
368 <https://doi.org/10.1007/s11356-014-3933-1>

369 Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—Concepts and applications.  
370 *Chemosphere* 91, 869–881. <https://doi.org/10.1016/j.chemosphere.2013.01.075>

371 Alloway, B.J., 2013. Sources of Heavy Metals and Metalloids in Soils, in: Alloway, B.J. (Ed.), *Heavy*  
372 *Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability*, Environmental  
373 Pollution. Springer Netherlands, Dordrecht, pp. 11–50. [https://doi.org/10.1007/978-94-007-4470-7\\_2](https://doi.org/10.1007/978-94-007-4470-7_2)

374 Alloway, B.J. (Ed.), 1995. *Heavy Metals in Soils*, 2nd ed. Springer Netherlands.

375 Aman, M.S., Jafari, M., Reihan, M.K., Motesharezadeh, Babak., 2018. Assessing some shrub species  
376 for phytoremediation of soils contaminated with lead and zinc. *Environ. Earth. Sci.* 77, 1–  
377 10. <https://doi.org/10.1007/s12665-018-7256-2>



378 Baker A.J., 1981. Accumulators and excluders — strategies in the response of plants to heavy metals.  
379 J. Plant Nutr. 3, 643–654. <https://doi.org/10.1080/01904168109362867>

380 Bhargava, A., Carmona, F.F., Bhargava, M., Srivastava, S., 2012. Approaches for enhanced  
381 phytoextraction of heavy metals. J. Environ. Manage. 105, 103–120.  
382 <https://doi.org/10.1016/j.jenvman.2012.04.002>

383 Cerovic, Z.G., Masdoumier, G., Ghazlen, N.B., Latouche, G., 2012. A new optical leaf-clip meter for  
384 simultaneous non-destructive assessment of leaf chlorophyll and epidermal flavonoids. Physiol. Plant.  
385 146, 251–260. <https://doi.org/10.1111/j.1399-3054.2012.01639.x>

386 Chalker-Scott, L., 1999. Environmental significance of anthocyanins in plant stress responses.  
387 Photochem. Photobiol. 70, 1–9. <https://doi.org/10.1111/j.1751-1097.1999.tb01944.x>

388 Chhajro, M.A., Rizwan, M.S., Huang, G., Zhu, J., Kubar, K.A., Hu, Hongqing., 2016. Enhanced  
389 accumulation of Cd in castor (*Ricinus communis* L.) by soil-applied chelators. Intern. J. Phytoremed.  
390 18, 664–670. <https://doi.org/10.1080/15226514.2015.1115965>

391 Dai, L.-P., Dong, X.-J., Ma, H.-H., 2012. Antioxidative and chelating properties of anthocyanins in  
392 *Azolla imbricata* induced by cadmium. Pol. J. Environ. Stud. 21, 837–844.

393 Deyris, P.-A., Adler, P., Petit, E., Legrand, Y.-M., Grison, C., 2019. Woody species: a new bio-based  
394 material for dual Ca/Mg catalysis with remarkable Lewis acidity properties. Green Chem. 21, 3133–  
395 3142. <https://doi.org/10.1039/C9GC00770A>

396 Douay, F., Pelfrène, A., Planque, J., Fourier, H., Richard, A., Roussel, H., Girondelot, B., 2013.  
397 Assessment of potential health risk for inhabitants living near a former lead smelter. Part 1: metal  
398 concentrations in soils, agricultural crops, and homegrown vegetables. Environ. Monit. Assess. 185,  
399 3665–3680. <https://doi.org/10.1007/s10661-012-2818-3>

400 Finnegan, P., Chen, W., 2012. Arsenic Toxicity: The Effects on Plant Metabolism. Front Physiol. 3,  
401 182–190. <https://doi.org/10.3389/fphys.2012.00182>

402 Grant, C.A., Clarke J.M., Duguid, S., Chaney, R.L., 2008. Selection and breeding of plant cultivars to  
403 minimize cadmium accumulation. Sci. Total Environ. 390, 301–310.  
404 <https://doi.org/10.1016/j.scitotenv.2007.10.038>

405 Gomes, H.I., 2012. Phytoremediation for bioenergy: challenges and opportunities. *Environ. Technol.*  
406 *Rev.* 1, 59–66. <https://doi.org/10.1080/09593330.2012.696715>

407 Gong, Y., Zhao, D., Wang, Q., 2018. An overview of field-scale studies on remediation of soil  
408 contaminated with heavy metals and metalloids: Technical progress over the last decade. *Water Res.*  
409 147, 440–460. <https://doi.org/10.1016/j.watres.2018.10.024>

410 Guérin, T., Ghinet, A., Waterlot, C., 2020. Toward a New Way for the Valorization of Miscanthus  
411 Biomass Produced on Metal-Contaminated Soils Part 2: Miscanthus-Based Biosourced Catalyst:  
412 Design, Preparation, and Catalytic Efficiency in the Synthesis of Moclobemide. *Sustainability* 13, 34.  
413 <https://doi.org/10.3390/su13010034>

414 Hazotte, C., Laubie, B., Rees, F., Morel, J.L., Simonnot, M.-O., 2017. A novel process to recover  
415 cadmium and zinc from the hyperaccumulator plant *Noccaea caerulea*. *Hydrometallurgy* 174, 56–  
416 65. <https://doi.org/10.1016/j.hydromet.2017.09.012>

417 Hechelski, M., Ghinet, A., Louvel, B., Dufrénoy, P., Rigo, B., Daïch, A., Waterlot, C., 2018. From  
418 Conventional Lewis Acids to Heterogeneous Montmorillonite K10: Eco-Friendly Plant-Based  
419 Catalysts Used as Green Lewis Acids. *ChemSusChem* 11, 1249–1277.  
420 <https://doi.org/10.1002/cssc.201702435>

421 Hechelski, M., Louvel, B., Dufrénoy, P., Ghinet, A., Waterlot, C., 2020. Toward a New Way for the  
422 Valorization of Miscanthus Biomass Produced on Metal-Contaminated Soils Part 1: Mesocosm and  
423 Field Experiments. *Sustainability* 12, 9370. <https://doi.org/10.3390/su12229370>

424 Hu, Y., Nan, Z., Su, J., Wang, Shengli., 2014. Chelant-Assisted Uptake and Accumulation of Cd by  
425 Poplar from Calcareous Arable Soils Around Baiyin Nonferrous Metal Smelters, Northern China. *Arid*  
426 *Land Res. Manag.* 28, 340–354. <https://doi.org/10.1080/15324982.2013.841305>

427 Janus, A., Pelfrène, A., Heymans, S., Deboffe, C., Douay, F., Waterlot, C., 2015. Elaboration,  
428 characteristics and advantages of biochars for the management of contaminated soils with a specific  
429 overview on Miscanthus biochars. *J. Environ. Manage.* 162, 275–289.  
430 <https://doi.org/10.1016/j.jenvman.2015.07.056>

431 Liu, L., Li, W., Song, W., Guo, M., 2018. Remediation techniques for heavy metal-contaminated soils:  
432 Principles and applicability. *Sci. Total Environ.* 633, 206–219.  
433 <https://doi.org/10.1016/j.scitotenv.2018.03.161>

434 Mandzhieva, S.S., Minkina, T.M., Chaplygin, V.A., Motuzova, G.V., Sushkova, S.N., Bauer, T.V.,  
435 Nevidomskaya, D.G., 2016. Plant contamination by heavy metals in the impact zone of  
436 Novocherkassk Power Station in the south of Russia. *J. Soil. Sediment.* 16, 1383–1391.  
437 <https://doi.org/10.1007/s11368-015-1098-2>

438 Mirzaei, M., Verrelst, J., Bakhtiari, A.R., Marofi, S., 2021. Potential use of grapevine cv Askari for  
439 heavy metal phytoremediation purposes at greenhouse scale. *Environ. Sci. Pollut. Res.* 28, 12447–  
440 12458. <https://doi.org/10.1007/s11356-020-11129-9>

441 Moameri, M., Abbasi Khalaki, Masoomeh., 2019. Capability of *Secale montanum* trusted for  
442 phytoremediation of lead and cadmium in soils amended with nano-silica and municipal solid waste  
443 compost. *Environ. Sci. Pollut. Res.* 26, 24315–24322. <https://doi.org/10.1007/s11356-017-0544-7>

444 Mos, M., Banks, S.W., Nowakowski, D.J., Robson, P.R.H., Bridgwater, A.V., Donnison, I.S., 2013.  
445 Impact of *Miscanthus x giganteus* senescence times on fast pyrolysis bio-oil quality. *Bioresour.*  
446 *Technol.* 129, 335–342. <https://doi.org/10.1016/j.biortech.2012.11.069>

447 Nsanganwimana, F., Pourrut, B., Waterlot, C., Louvel, B., Bidar, G., Labidi, S., Fontaine, J.,  
448 Muchembled, J., Lounès-Hadj Sahraoui, A., Fourier, H., Douay, F., 2015. Metal accumulation and  
449 shoot yield of *Miscanthus x giganteus* growing in contaminated agricultural soils: Insights into  
450 agronomic practices. *Agric. Ecosyst. Environ.* 213, 61–71. <https://doi.org/10.1016/j.agee.2015.07.023>

451 Nsanganwimana, F., Al Souki, K.S., Waterlot, C., Douay, F., Pelfrêne, A., Rodöšková, A., Louvel, B.,  
452 Pourrut, B., 2021. Potentials of *Miscanthus x giganteus* for phytostabilization of trace element-  
453 contaminated soils: *Ex situ* experiment. *Ecotoxicol. Environ. Safe.* 214, 112125.  
454 <https://doi.org/10.1016/j.ecoenv.2021.112125>

455 Oustriere, N., Marchand, L., Lizama-Allende, K., Roulet, E., Rousset, C., Bordas, F., Mench, M.,  
456 2019. Selection of macrophytes with Cu-enriched root biomass intended for ecocatalyst production.  
457 *Ecol. Eng.* 138, 88–96. <https://doi.org/10.1016/j.ecoleng.2019.07.001>

458 Pelfrêne, A., Kleckerová, A., Pourrut, B., Nsanganwimana, F., Douay, F., Waterlot, C., 2015. Effect of  
459 miscanthus cultivation bioaccessibility in metal-contaminated soils: comparison between greenhouse  
460 and field experiments. *Environ. Sci. Pollut. Res.* 22, 3043–3054. <https://doi.org/10.1007/s11356-014->  
461 3585-1

462 Pruvot, C., Douay, F., Hervé, F., Waterlot, C., 2006. Heavy Metals in Soil, Crops and Grass as a  
463 Source of Human Exposure in the Former Mining Areas. *J. Soil. Sediment.* 6, 215–220.  
464 <https://doi.org/10.1065/jss2006.10.186>

465 Rossini-Oliva, S., Abreu, M.M., Leidi, E.O., 2018. A review of hazardous elements tolerance in a  
466 metallophyte model species: *Erica andevalensis*. *Geoderma* 319, 43–51.  
467 <https://doi.org/10.1016/j.geoderma.2017.12.035>

468 Rusinowski, S., Krzyzak, J., Clifton-Brown, J., Jensen, E., Mos, M., Webster, R., Sitko, K., Pogrzeba,  
469 M., 2019. New Miscanthus hybrids cultivated at a polish metal-contaminated site demonstrate high  
470 stomatal regulation and reduced shoot Pb and Cd concentrations. *Environ. Pollut.* 252, 1377–1387.  
471 <http://creativecommons.org/licenses/by-nc-nd/4.0/>

472 Sabir, M., Ali, A., Zia-Ur-rehman, M., Hakeem, K.R., 2015. Contrasting Effects of Farmyard Manure  
473 (FYM) and Compost for Remediation of Metal Contaminated Soil. *Int. J. Phytorem.* 17, 613–21.  
474 <https://doi.org/10.1080/15226514.2014.898019>

475 Saraswat, S., Rai, J.P.N., 2011. Prospective Application of *Leucaena Leucocephala* for  
476 Phytoextraction of Cd and Zn and Nitrogen Fixation in Metal Polluted Soils. *Int. J. Phytorem.* 13,  
477 271–288. <https://doi.org/10.1080/15226514.2010.483259>

478 Saraswat, S., Rai, J.P.N., 2009. Phytoextraction potential of six plant species grown in multimetal  
479 contaminated soil. *Chem; Ecol.* 25, 1–11. <https://doi.org/10.1080/02757540802657185>

480 Savio, M., Cerutti, S., Martinez, L.D., Smichowski, P., Gil, R.A., 2010. Study of matrix effects and  
481 spectral interferences in the determination of lead in sediments, sludges and soils by SR-ETAAS using  
482 slurry sampling. *Talanta* 82, 523–527. <https://doi.org/10.1016/j.talanta.2010.05.017>

483 Sêkara, A., Poniedzia, M., 2005. Cadmium and Lead Accumulation and Distribution in the Organs of  
484 Nine Crops: Implications for Phytoremediation. *Pol. J. Environ. Stud.* 14, 509–516.

485 Sheoran, V., Sheoran, A.S., Poonia, P., 2016. Factors Affecting Phytoextraction: A Review.  
486 *Pedosphere* 26, 148–166. [https://doi.org/10.1016/S1002-0160\(15\)60032-7](https://doi.org/10.1016/S1002-0160(15)60032-7)

487 Shi, G.R., Su, G., Lu, Z., Liu, C.F., Wang, X., 2014 Relationship between biomass, seed components  
488 and seed cd concentration in various peanut (*Arachis hypogaea* L.) cultivars grown on Cd-  
489 contaminated soils. *Ecotoxicol. Environ. Saf.* 110, 174–181.  
490 <https://doi.org/10.1016/j.ecoenv.2014.09.003>

491 Shtangeeva, I., Bali, R., Harris, A., 2011. Bioavailability and toxicity of antimony. *J. Geochem.*  
492 *Explor.* 110, 40–45. <https://doi.org/10.1016/j.gexplo.2010.07.003>

493 Sterckeman, T., Douay, F., Proix, N., Fourrier, H., Perdrix, E., 2002. Assessment of the contamination  
494 of cultivated soils by eighteen trace elements around smelters in the north of France. *Water Air Soil*  
495 *Pollut.* 135, 173-194. <https://doi.org/10.1023/A:1014758811194>

496 Singh, B., Kaur, B., Singh, D., 2020. Assessment of different multipurpose tree species for  
497 phytoextraction of lead from lead-contaminated soils. *Biorem. J.* 24, 215–  
498 230. <https://doi.org/10.1080/10889868.2020.1811634>

499 Sun, Y.B., Sun, G.H., Zhou, Q.X., Xu, Y.M., Wang, L., Liang, X.F., Sun, Y., Qing, X., 2011.  
500 Induced-phytoextraction of heavy metals from contaminated soil irrigated by industrial wastewater  
501 with Marvel of Peru (*Mirabilis jalapa* L.). *Plant Soil Environ.* 57, 364–  
502 371. <https://doi.org/10.17221/148/2011-PSE>

503 Tangahu, B.J., Abdullah, S.R.S., Basri, H., Idris, M., Anuar, N., Mukhlisin, M., 2011. A review on  
504 heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of*  
505 *Chem. Eng.* 1–31. <https://doi.org/10.1155/2011/939161>

506 Uzu, G., Sobanska, S., Sarret, G., Muñoz, M., & Dumat, C. 2010. Foliar Lead uptake by lettuce  
507 exposed to atmospheric fallouts. *Environ. Sci. Technol.*, 44, 1036–1042.  
508 <https://doi.org/10.1021/es902190u>

509 Vamerali, T., Bandiera, M., Mosca, G., 2010. Field crops for phytoremediation of metal-contaminated  
510 land. A review. *Environ. Chem. Lett.* 8, 1–17. <https://doi.org/10.1007/s10311-009-0268-0>

511 Waterlot, C., Bidar, G., Pelfrène, A., Roussel, H., Fourrier, H., Douay, F., 2023. Contamination,  
512 fractionation and availability of metals in urban soils in the vicinity of former lead and zinc smelters,  
513 France. *Pedosphere* 23, 143–159. [https://doi.org/10.1016/S1002-0160\(13\)60002-8](https://doi.org/10.1016/S1002-0160(13)60002-8)

514 Waterlot, C., Douay, F., 2009. The problem of arsenic interference in the analysis of Cd to evaluate its  
515 extractability in soils contaminated by arsenic. *Talanta* 80, 716–722.  
516 <https://doi.org/10.1016/j.talanta.2009.07.053>

517 Waterlot, C., Dufrénoy, P., Hechelski, M., Louvel, B., Daïch, A., Ghinet, A., 2019. Benefits of  
518 Ryegrass on Multicontaminated Soils Part 2: A Green Process to Provide Idrocilamide. *Sustainability*  
519 11, 6685. <https://doi.org/10.3390/su11236685>

520 Waterlot, C., Hechelski, M., 2019. Benefits of Ryegrass on Multicontaminated Soils Part 1: Effects of  
521 fertilizers on bioavailability and accumulation of metals. *Sustainability* 11, 5093.  
522 <https://doi.org/10.3390/su11185093>

523 Waterlot, C., Pruvot, C., Marot, F., Douay, F., 2017. Impact of a phosphate amendment on the  
524 environmental availability and phytoavailability of Cd ad Pb in moderetaly and highly carbonated  
525 kitchen garden soils. *Pedosphere* 27, 588–605. [https://doi.org/10.1016/S1002-0160\(17\)60354-0](https://doi.org/10.1016/S1002-0160(17)60354-0)

526 Wang, Z., Liu, X., Qin, H., 2019. Bioconcentration and translocation of heavy metals in the soil-plants  
527 system in Machangqing copper mine, Yunnan Province, China. *J. Geochem. Explor.* 200, 159–166.  
528 <https://doi.org/10.1016/j.gexplo.2019.02.005>

529 Wojciechowska, N., Sobieszczuk-Nowiccka, E., Bagniewska-Zadworna, A., 2018. Plant Organ  
530 senescence – regulation by manifold pathways. *Plant Biol.* 20, 167–181. <http://doi:10.1111/plb.12672>

531 Wolf, M., Paulino, A.T., 2020. Phytotoxicity increase induces by zinc accumulation in *Cichorium*  
532 *intybus*. *Bull. Environ. Contam. Toxicol.* 105, 405–410. <https://doi.org/10.1007/s00128-020-02960-4>

533 Zeng, H., Chen, L., Zhou, X., Zeng, Q., 2019. Cadmium accumulation in winter crops and the  
534 assessment of paddy soil phytoremediation in southern China. *Environ. Sci. Pollut. Res.* 26, 17173–  
535 17182. <https://doi.org/10.1007/s11356-019-05054-9>

536 Zehra, A., Sahito, Z.A., Tong, W., Tang, L., Hamid, Y., Wang, Q., Cao, X., Khan, M.B., Hussain, B.,  
537 Jatoi, S.A., He, Z., 2020. Identification of high cadmium-accumulating oilseed sunflower (*Helianthus*

538 *annuus*) cultivars for phytoremediation of an Oxisol and an Inceptisol. *Ecotoxicol. Environ. Saf.* 187,  
539 109857. <http://doi:10.1016/j.ecoenv.2019.109857>

540 Zhou, Z., Guo, Y., Hu, L., He, L., Xu, B., Huang, Z., Wang, G., Chen, Y., 2020. Potential use of king  
541 grass (*Pennisetum purpureum* Schumach. × *Pennisetum glaucum* (L.) R.Br.) for phytoextraction of  
542 cadmium from fields. *Environ. Sci. Pollut. Res.* 27, 35249–35260. [https://doi.org/10.1007/s11356-](https://doi.org/10.1007/s11356-020-09844-4)  
543 020-09844-4

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**Table 1** Mean values of bioaccumulation factor (BAC), bioconcentration factor (BCF) and translocation factor (TF)

Cultivar	Time (days)	BAC			BCF			TF		
		Pb	Cd	Zn	Pb	Cd	Zn	Pb	Cd	Zn
C1	74	0.01	2.06	0.15	0.13	1.05	0.16	0.11	1.97	0.95
	105	0.02	2.14	0.13	0.02	0.44	0.05	0.81	4.91	2.54
	156	0.01	2.45	0.17	0.01	0.39	0.03	1.44	6.31	5.37
	211	0.01	3.29	0.21	0.01	0.57	0.05	0.89	5.80	4.47
C2	74	0.02	1.93	0.15	0.17	1.09	0.20	0.10	1.77	0.75
	105	0.03	1.77	0.11	0.07	0.44	0.04	0.42	4.06	2.62
	156	0.02	2.89	0.15	0.01	0.33	0.04	3.36	8.70	4.22
	211	0.01	3.22	0.20	0.01	0.62	0.05	1.04	5.17	3.63
C3	74	-	-	-	-	-	-	-	-	-
	105	0.02	2.03	0.12	0.05	0.60	0.09	0.45	3.38	1.40
	156	0.02	2.28	0.14	0.01	0.31	0.03	2.48	7.45	4.10
	211	0.02	2.55	0.16	0.01	0.56	0.05	1.34	4.57	3.33
C4	74	0.04	1.90	0.14	0.22	1.15	0.18	0.16	1.65	0.77
	105	0.02	2.23	0.11	0.03	0.57	0.07	0.66	3.90	1.73
	156	0.01	2.73	0.15	0.00	0.09	0.05	3.53	28.82	2.90
	211	0.01	4.69	0.20	0.01	0.70	0.06	0.89	6.65	3.38
C5	74	0.01	2.06	0.14	0.13	1.14	0.18	0.10	1.81	0.78
	105	0.01	1.57	0.11	0.03	0.50	0.06	0.44	3.12	1.90
	156	0.02	2.26	0.13	0.01	0.30	0.03	2.02	7.49	4.05
	211	0.01	3.58	0.15	0.01	0.49	0.05	0.86	7.38	2.97



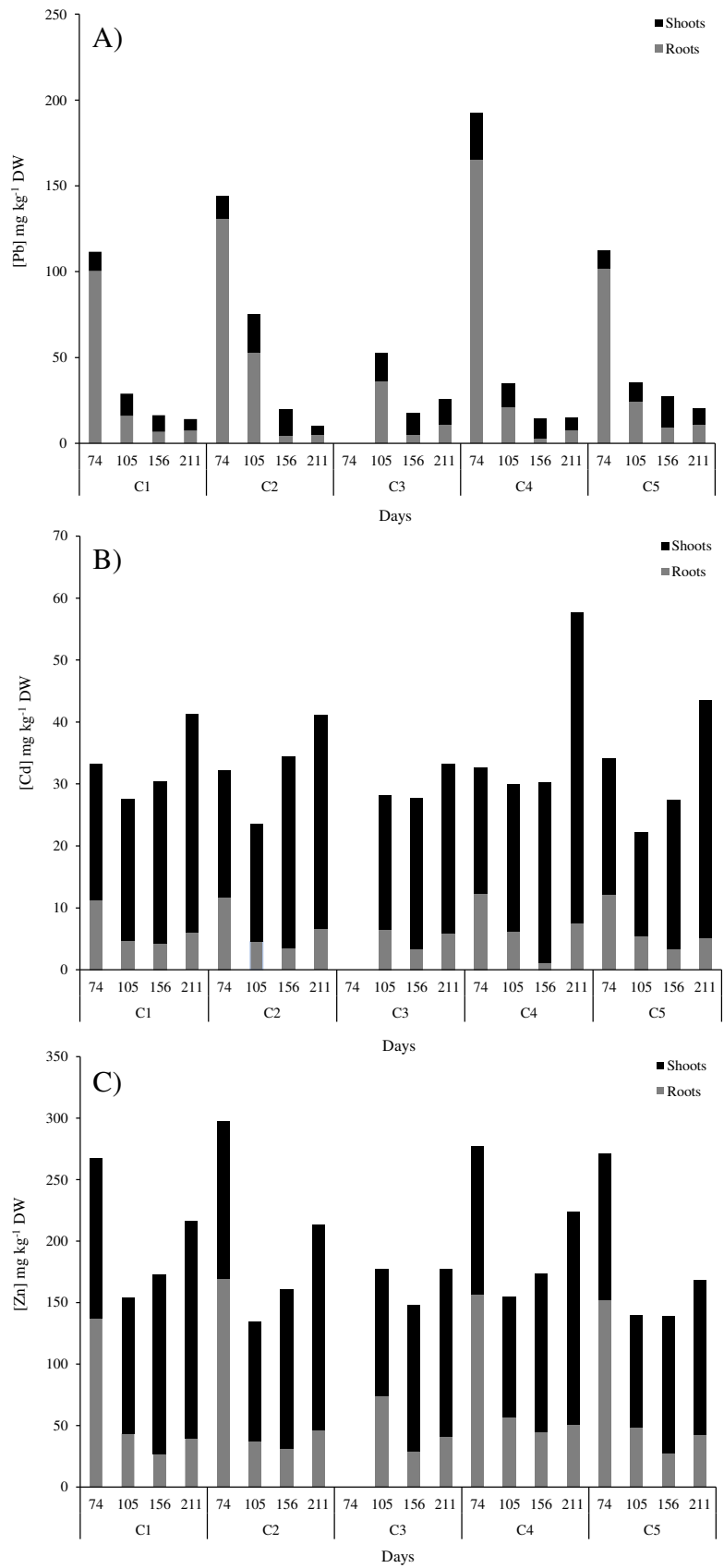
**Table 2** Leaf accumulation and root uptake of MTE by chicories

cultivar	MTE accumulation in leaves			MTE uptake by roots			MTE uptake by chicories		
	Cd (mg)	Pb (mg)	Zn (mg)	Cd (mg)	Pb (mg)	Zn (mg)	Cd (mg)	Pb (mg)	Zn (mg)
C1	1.18	0.28	6.23	0.41	0.56	2.72	1.59	0.83	8.96
C2	1.42	0.33	6.65	0.51	0.51	4.21	1.93	0.84	10.87
C3	1.02	0.54	4.94	0.57	1.05	3.91	1.58	1.59	8.86
C4	1.44	0.39	5.04	0.59	0.67	4.51	2.03	1.06	9.56
C5	1.01	0.30	3.40	0.43	0.93	3.54	1.44	1.23	6.94

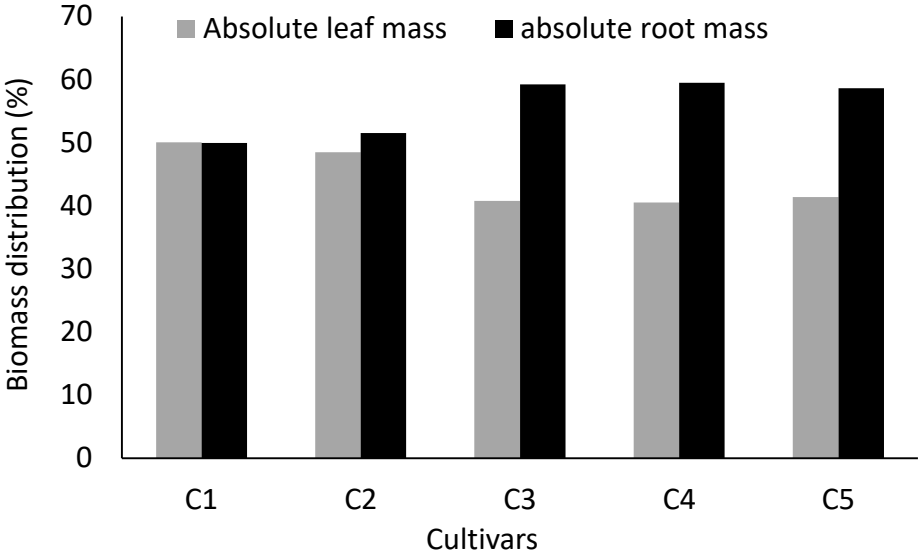
**Table 3** Remediation factors (RF)

cultivar	RF			RF <sub>LMWOAs</sub>			RF <sub>CaCl<sub>2</sub></sub>		
	Cd	Pb	Zn	Cd	Pb	Zn	Cd	Pb	Zn
C1	0.74	0.006	0.05	4.42	0.79	0.26	28.4	119.2	80.5
C2	0.90	0.006	0.06	5.37	0.79	0.32	34.5	119.6	97.7
C3	0.74	0.010	0.05	4.40	1.50	0.26	28.3	227.0	79.6
C4	0.95	0.007	0.06	5.65	1.00	0.28	36.3	152.0	85.9
C5	0.67	0.008	0.04	4.00	1.16	0.20	25.7	175.8	62.4

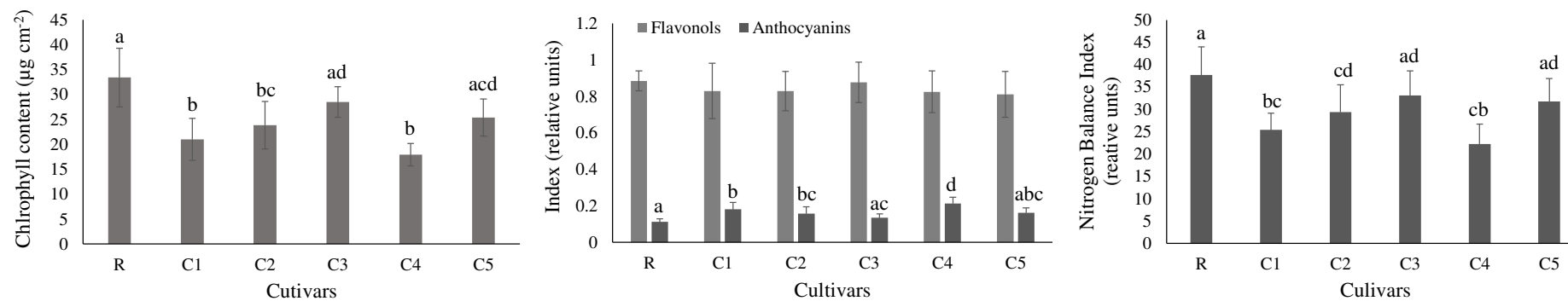
**Fig. 1.** Pb, Cd and Zn accumulation (A,B,C) in the roots and shoots depending on the growing time and cultivars



**Fig. 2.** Distribution (%) of leaf and root biomass for the five cultivars studied



**Fig. 3. Chlorophyll content, Flavonols index, Anthocyanins index and Nitrogen Balance Index measured in leaves of chicories (reference and cultivars)**



Letters (a, b, c, d, e) refer to significant differences ( $p < 0.05$ ) between reference and the five cultivars studied. Values are means  $\pm$  standard deviation ( $n=20$ ).

# Root chicory as selective MTE phytoextractor and high root-leaf translocation of Cd

