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1 **Health risk assessment via ingestion and inhalation of soil PTE of an urban area**

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11

12 **Abstract**

13 Potentially Toxic Elements (PTE) are common soil contaminants and pose a significant risk to  
14 human health. In this study, ingestion (<150 µm) and inhalation (<10 µm) bioaccessibility and  
15 human health risk due to PTE were investigated in soils of the urban and peri-urban area of  
16 Torino. Lead, Cd, Cu, and Zn were observed to be the most soluble elements in simulated  
17 gastric and lung fluids. Higher bioaccessible concentrations of Pb, Ni, Co and Sb were  
18 observed in the inhalable size fraction (< 10 µm) compared to ingestible one probably  
19 because of the higher concentration in fine soil size fraction. Conversely, the relative  
20 bioaccessibility of Pb, Cu, Cd, Zn and As was lower, due to the different extracting conditions  
21 and to the presumable different elemental speciation. Average values suggested that PTE  
22 would be more bioavailable if ingested than inhaled, particularly in urban areas, where the  
23 bioaccessible percentages were always higher than in peri-urban sites. Health risk assessment  
24 was conducted using bioaccessible concentrations and their corresponding toxicities via  
25 ingestion and inhalation exposures. Unacceptable non-carcinogenic risk (HQ > 1) was found  
26 through ingestion exposure for children in some urban sites and Pb was the most hazardous  
27 elements. Carcinogenic risks were under the threshold levels for every soil (CR < 10<sup>-4</sup>), with  
28 Cr and As being the dominant contributors to risk. Therefore, necessary soil remediation  
29 activities are needed to reduce the risks of human, especially for children, exposure to Pb.

30

31 **Keywords:** Potentially Toxic Elements, urban area, peri-urban area, oral bioaccessibility, lung  
32 bioaccessibility

33

34 **Highlights:**

35 - Gastric and lung bioaccessibility in diverse soil size fractions were investigated

36 - PTE would be more bioavailable if ingested than inhaled

37 - Higher bioaccessibility was visible in urban sites

38 - Pb was, still, the most important element for non-carcinogenic risk

39

40 **1. Introduction**

41 Rapid industrialization and expansion of urban areas lead to the entrance of numerous  
42 Potentially Toxic Elements (PTE) to soil (Kabata Pendias, 2010; Ajmone-Marsan and Biasioli,  
43 2010). As PTE tend to accumulate in soils, in cities people exposure to contaminated soils can  
44 pose significant human health risk, due mainly to the routes connected to oral ingestion and  
45 inhalation (Manjon et al., 2020; Marini et al., 2021). In most cases, health risk assessment has  
46 been conducted considering PTE total concentrations; however, not all the elemental species  
47 are available for adsorption and the use of total or pseudo-total contents may somewhat  
48 overestimate the risk, as already reported from many researchers (Paustenbach, 2000; Han et  
49 al., 2020; Mokhtarzadeh et al., 2020). In recent years, different *in vitro* methods have been  
50 used for estimating the PTE gastrointestinal bioaccessibility, especially the Simple  
51 Bioaccessibility Extraction Test (SBET), which has been widely applied for human health risk  
52 assessment (Oomen et al., 2002; Li et al., 2020).

53 To correctly estimate the risk due to ingestion, in addition to the SBET, or similar extraction  
54 methods, studies need to analyze the bioaccessibility only on the potentially ingestible  
55 fraction of soil (i.e. the fraction of soil <150  $\mu\text{m}$ ) (Li et al., 2021).

56 The second most important route for PTE interaction with urban population is inhalation,  
57 which involves the soil fine size fractions (i.e. particles <10  $\mu\text{m}$ ), as they are easily  
58 resuspended by anthropogenic activities and wind erosion. Thus, PTE in fine particles may  
59 easily enter the nasal cavity and lungs through inhalation (Kastury et al., 2018; Li et al., 2020).  
60 Until now, no unified analytical protocol for the determination of lung bioaccessibility has

61 been adopted, and this poses many challenges for methodologies comparison (Ren et al.,  
62 2020). Recently, a new study (Zhong et al., 2020) obtained a good *in vitro-in vivo* correlation  
63 using optimized Gamble solution (Wragg and Klinck, 2007). The method showed good  
64 performance for the prediction of lung bioaccessible PTE and has been proposed for human  
65 exposure assessment.

66 Turin is the third-largest city in Italy, which has a long industrial history and may represent a  
67 model for cities with historical contaminations, as the industrial activities were concentrated  
68 in the city centre while the peri-urban area was mostly residential and surrounded by  
69 agricultural fields. Previous studies in this area evidenced this difference between the urban  
70 and the peri-urban area (Biasioli et al., 2006; Padoan et al., 2017), however few studies were  
71 carried out to the bioaccessibility of PTE in the particle size-associated fractions (Padoan et  
72 al., 2017; Pelfrêne and Douay, 2018) and to assess the health risk via the combined ingestion  
73 and inhalation pathways, essential to determine the exposure risk. Therefore, the objectives of  
74 this study are: (1) to investigate the concentration and distribution of PTE in soils of the urban  
75 and peri-urban areas; (2) to assess the gastrointestinal and lung bioaccessibility of PTE; (3) to  
76 estimate health hazards due to non-carcinogenic and carcinogenic elements via ingestion and  
77 inhalation exposure based on bioaccessibility data.

78

## 79 **2. Materials and methods**

### 80 2.1 Study area

81 The metropolitan area of Turin (45°04' N; 7°41' E) lies on an alluvial plain in the Piemonte  
82 region, in north-west Italy, and has a population of 1.7 million inhabitants. It features a very  
83 large amount of vehicular traffic and has a long history of industry, primarily  
84 car-manufacturing factories, and metallurgical industries (Padoan et al., 2017).

85 Soil sampling sites were selected along a main road across the city, on a South-North  
86 directory, beginning and ending in the peri-urban area (Figure 1). Sites in the peri-urban area  
87 (n=10) were surrounded by agricultural fields and sites in the urban area sites (n=20) were  
88 distributed on roadsides and parks.

89

90 2.2 Soil sampling

91 Samples collection was conducted in January and May 2020, a total of 30 topsoil samples  
92 were collected from the study area. Each sample was taken at a 0-10 cm depth and a  
93 composite soil sample at each site was obtained by mixing three sub-samples at a distance of  
94 1 m away from each other. The collected samples were put in plastic bags and homogenized.  
95 All samples were air dried in laboratory at room temperature and sieved through a 2 mm  
96 plastic sieve to remove stones, plant, and anthropic fragments (plastic, glass, metallic, etc.)  
97 before further analyses.

98

99 2.3 Sample characterization

100 The pH of soil samples was measured in 1:2.5 soil/water suspensions by using a pH meter  
101 with a combined glass electrode, total carbon (TC) and total nitrogen (TN) were measured by  
102 an element analyser (CE Instruments, NA2100 Elemental Analyzer, ISO 10694), carbonates  
103 were analysed by volumetric method (ISO 10693). Particle size distribution and fraction  
104 below 10 µm were measured and collected via the hydrometer method (Padoan et al., 2017).  
105 Soil digestion and measurement of pseudo-total PTE were carried out according to  
106 Ajmone-Marsan et al. (2019). A portion of each sample was crushed to pass through 0.15 mm  
107 sieves, 1.00 g soil sample was weighed and microwave-digested with *aqua regia* (HCl/HNO<sub>3</sub>,  
108 3:1 v/v, Milestone Ethos D, ISO 11466)) and then determined by inductively coupled plasma  
109 mass spectrometry (ICP-MS, Perkin Elmer NexION® 350D). All the determinations were  
110 carried out in triplicate. Accuracy was checked against a certified reference material for *aqua*  
111 *regia* extractable elements in calcareous soil (CRM 141R).

112 Along with concentrations in bulk soil (<2 mm), pseudo-total PTE concentrations were  
113 analysed in the <10 µm and in the <150 µm fraction using the same procedure.

114

115 2.4 *In vitro* gastric and lung bioaccessibility

116 The gastric bioaccessibility of the elements was determined using the SBET method (Ruby et  
117 al., 1999; Oomen et al., 2002). In brief, soil samples sieved at 0.15 mm were used; 0.5 g of

118 sample was weighed and mixed with 50 mL of a 0.4 M glycine solution with pH adjusted to  
119 1.5 by concentrated HCl. The mixture was shaken at 150 rpm, incubated at 37°C for 1 h and  
120 then centrifuged at 3000 rpm for 10 minutes, the supernatant was taken and filtered through a  
121 0.45 µm cellulose filter prior to the analysis.

122 The lung bioaccessibility test was performed using the optimized Gamble Solution (the  
123 chemical composition of the solution presented in Table S1). Briefly, <10 µm soil samples  
124 were weighed accurately into labelled 50 mL tubes and mixed with solution at a solid:solution  
125 ratio of 1:1000; the mixture was then shaken at 37°C for 24h. After oscillation, the extracts  
126 were centrifuged at 3000 rpm for 10 minutes; the supernatant was taken and filtered through a  
127 0.45 µm cellulose filter. All extraction solutions were freshly prepared, and all the  
128 determinations were carried out in triplicate, the extractant was analysed by ICP-MS.

129 The bioaccessibility was calculated as follows (Du et al., 2020):

130 
$$\text{Bioaccessibility (\%)} = (C_{\text{in vitro}}/C_{\text{total}}) \times 100$$

131 Where  $C_{\text{in vitro}}$  is the bioaccessible concentration of PTE as determined using the *in vitro*  
132 extraction, and  $C_{\text{total}}$  is the *aqua regia* concentration in the considered soil fraction.

133

134

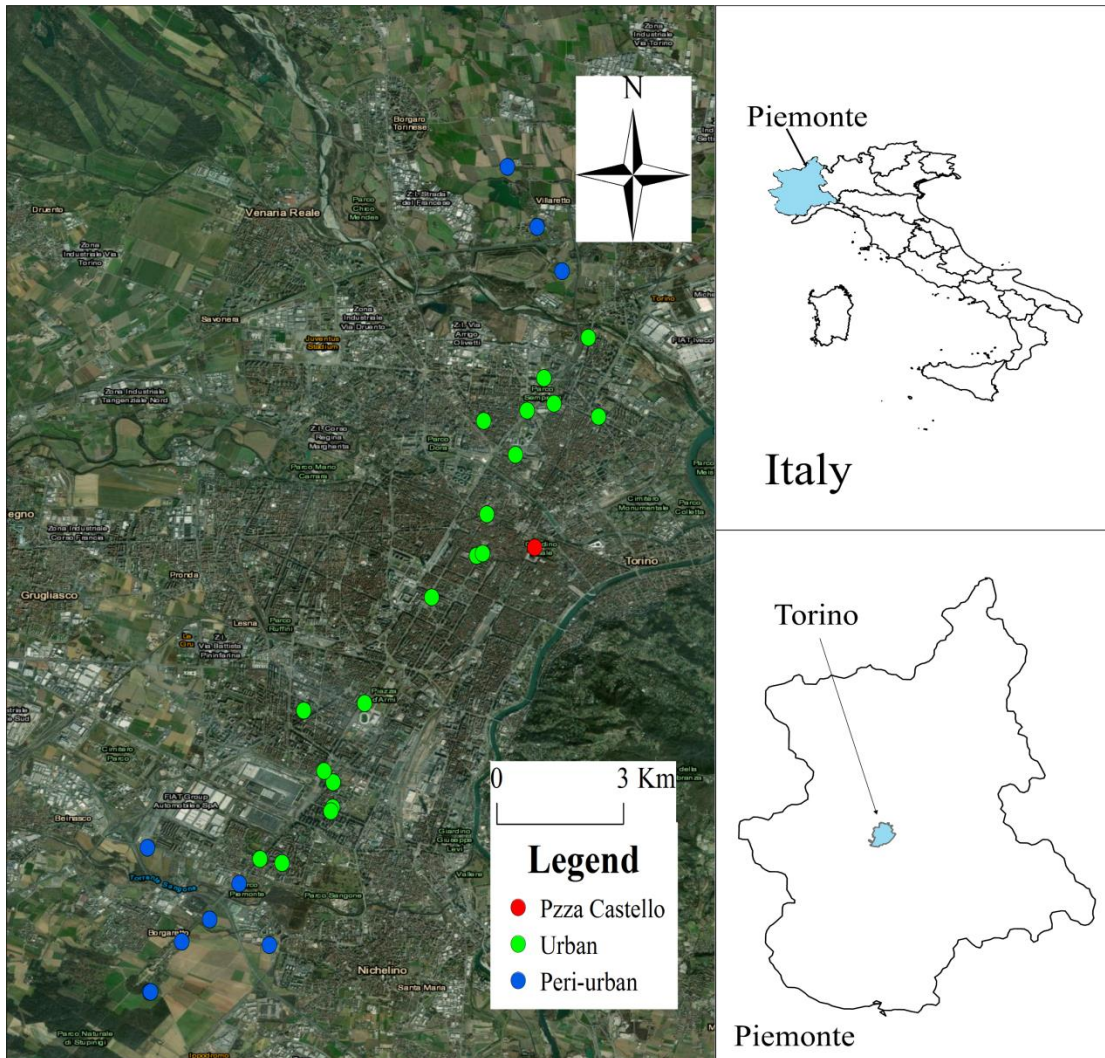


Figure 1. Sampling sites and map of the study area in Turin, Italy.

135

136

137

### 138 2.5 Human health risk assessment

139 The non-carcinogenic risk (hazard quotients; HQ) and carcinogenic risk (CR) which proposed  
 140 by US Environmental Protection Agency (USEPA, 2004) have been widely used to quantify  
 141 the risk of people exposure to PTE contaminated soil. Exposure of humans to PTE in soils can  
 142 be categorized into three pathways: inadvertent oral ingestion, dermal contact, and inhalation  
 143 (Paustenbach, 2000). Based on the guidelines and Exposure Factors Handbook (USEPA,  
 144 1989, 1997, 2002), chemical daily intake (ADD, mg/kg/day) of PTE through different  
 145 pathways from soil were calculated using the following equations (1) - (2).

146

$$ADD_{ing} = C_{(Gastric)} \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (1)$$

147 
$$ADD_{inh} = C_{(Pulmonary)} \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT} \quad (2)$$

148 Where  $ADD_{ing}$ ,  $ADD_{inh}$  are the daily amount of elemental intake via ingestion and inhalation.  
 149  $C_{(Gastric)}$  and  $C_{(Pulmonary)}$  are the bioaccessible concentration (mg/kg) in simulated gastric and  
 150 lung fluids. Other parameters are given in Table 1.

151 The hazard quotients (HQ, Eq. (3)) and the hazard index (HI, Eq. (4)) were used to  
 152 characterize the non-carcinogenic hazard.

153 
$$HQ_i = \frac{ADD_i}{RfD_i} \quad (3)$$

154 
$$HI = \sum HQ_i = \sum \frac{ADD_i}{RfD_i} \quad (4)$$

155 Where RfDi is the reference dose of the specific element (mg/kg/day). When HQ or HI < 1, it  
 156 indicates that no potential non-carcinogenic risk for humans, and HQ > 1 or HI > 1 indicates  
 157 adverse health effects (USEPA, 2011).

158 Carcinogenic risk (CR) was calculated using the dose of PTE multiply the corresponding  
 159 slope factor (Eq. (5)) and it was assumed that all the element risks were additive (Li et al.,  
 160 2012; Luo et al., 2012).

161 
$$CR = ADD_i \times SF_i \quad (5)$$

162 
$$TCR = \sum CR \quad (6)$$

163 Where SF is the slope factor of carcinogenicity (mg/kg/day). When  $10^{-6} < CR < 10^{-4}$  is  
 164 considered acceptable (USEPA, 2011), while  $CR > 10^{-4}$  means a carcinogenic risk to human  
 165 health (Li et al., 2014; Guney et al., 2010; USEPA, 1989). The values of RfD and SF for  
 166 different PTE are shown in Table 2.

167 Table 1. Definition and reference value of some parameters for health risk assessment of PTE  
 168 in soils.

Parameters	Definition	Units	Values		Reference
			Adult	Child	
IngR	Soil ingestion rate	mg/day	100	200	US DOE (2011)



EF	Exposure frequency	day/year	350	350	US EPA (2002)
ED	Exposure duration	year	24	6	US DOE (2011)
BW	Body weight	kg	70	15	US EPA (2002)
AT	Average time	day	$\frac{365 \times ED}{(non-carcinogen) / 365 \times 70 (carcinogen)}$		US EPA (2002)
InhR	Soil inhalation rate	m <sup>3</sup> /day	20	7.5	US DOE (2011)
PEF	Soil to air particulate emission factor	m <sup>3</sup> /kg	1.36×10 <sup>9</sup>	1.36×10 <sup>9</sup>	US EPA (2002)

169

170 Table 2. Summary of reference does (RfD) and slope factor (SF) of different PTE.

Metals	RfD (mg/kg/day)		SF (mg/kg•day)	
	Ingestion	Inhalation	Ingestion	Inhalation
Cd	1.0·10 <sup>-03</sup>	1.0·10 <sup>-02</sup>		6.3
Cr	3.0·10 <sup>-03a</sup>	2.86·10 <sup>-05</sup>	5.01·10 <sup>-01</sup>	4.2·10 <sup>-01</sup>
Ni	2.0·10 <sup>-02</sup>	2.0·10 <sup>-02</sup>		
Zn	3.0·10 <sup>-01</sup>	3.0·10 <sup>-01</sup>		
Cu	4.0·10 <sup>-02</sup>	4.0·10 <sup>-02</sup>		
Pb	3.5·10 <sup>-03b</sup>	3.5·10 <sup>-02</sup>	8.5·10 <sup>-03</sup>	4.2·10 <sup>-02c</sup>
As	3.0·10 <sup>-02</sup>	3.0·10 <sup>-03</sup>	1.5	4.3·10 <sup>-03</sup>
References	USDOE, 2011	USDOE, 2011	Adimalla, 2020	Adimalla, 2020

171 a USEPA (2002)

172 b WHO (1993)

173 c Wang et al. (2020)

174

## 175 2.5 Statistical analysis

176 Data processing and statistical analysis were conducted with Microsoft Excel 2010 and Origin

177 8.0.

178

## 179 3. Results and discussion

### 180 3.1 Physicochemical properties of soils

181 In Table 3, the mean values of the soil physicochemical properties in the urban and peri-urban

182 area are presented. Soils pH in the peri-urban area (agricultural soils) were slightly acidic,

183 however, urban soils were neutral to alkaline, consistently with previous studies highlighting  
184 this difference, which may be due to the historical inclusion of extraneous materials (Biasioli  
185 et al., 2006). The sand content (50  $\mu\text{m}$  - 2 mm) was almost constant in all samples, with a  
186 mean value of 65%. Total carbon (TC) and carbonates content in the urban area were, on  
187 average, higher than in peri-urban areas, with carbonate content in line with differences in pH.  
188 The higher TC was probably due to the sampling areas, as most of the urban area soils were  
189 covered by grass or trees, with a possible variable but low contribution from exogenous  
190 organic pollutants such as hydrocarbons or plastics.

191 The descriptive statistics summary of PTE concentrations in samples is presented in Table 4.  
192 The mean and median concentrations of all the elements (except As) were higher in the urban  
193 area than in peri-urban locations. The concentration of all the elements were higher than the  
194 average values of European and world soils (Kabata-Pendias 2010) in both peri-urban and  
195 urban areas. Compared to a previous study (Padoan et al., 2017), peri-urban concentrations  
196 were lower, while some elements in urban area, such as Cd and Ni, were a little higher.

197 Little can be said about the spatial trends within the city, as the variability of the distribution  
198 of PTE within an urban area is exceedingly high (Ajmone and Biasioli 2010).

199 Considering only the transect, PTE presented a higher pollution degree in the middle of the  
200 city, near the historical centre, and lower concentrations at the edge of the city, in the  
201 peri-urban area (Figure S1). High concentration of Ni was documented in a roadside park,  
202 while Cr presented no obvious polluting sources, confirming that Cr and Ni concentrations in  
203 soils were primarily controlled by parent materials (Ajmone-Marsan et al., 2008).

204 Copper and Zn had similar spatial distributions, indicating that they may originate from the  
205 same source. The highest concentrations were found in the central and northern part of the  
206 city, coherently with previous studies indicating Cu and Zn as mainly originating from vehicle  
207 factories and traffic (Grigoratos and Martini, 2015). Two Pb hotspots were located in the  
208 north of the study area, near two gas stations, and in trafficked sites; thus, the high  
209 concentrations may derive from fuel leakage or diffuse contamination. Antimony, also, was  
210 concentrated in the northern part of the city, which is the oldest industrialized area (Figure  
211 S2).

212 These few hints, together with the results of previous studies (Biasioli et al., 2006), suggest  
 213 the use of distance patterns (e.g. from the city centre) in place of a systematic sampling to  
 214 evaluate the effects of a city on the transportation and disposal of pollutants within its  
 215 boundaries giving the heterogeneity of human activities contribution to the content of PTE in  
 216 urban soils.

217

218 Table 3. Descriptive statistics of the peri-urban and urban area soil properties.

219

	pH	TN %	TC %	Carbonates %	Particle size distribution (mass %)				
					< 2 $\mu\text{m}$	2-20 $\mu\text{m}$	20-50 $\mu\text{m}$	50-200 $\mu\text{m}$	> 200 $\mu\text{m}$
<u>Peri-urban area</u>									
Mean	6.53	0.35	3.10	0.76	4.3	19.2	13.2	43.5	19.9
Median	6.27	0.39	3.41	0.65	3.9	19.8	13.5	45.4	21.0
Max	8.00	0.59	5.39	1.77	7.9	26.5	16.8	51.7	31.5
Min	5.70	0.10	0.75	0.33	1.2	11.7	8.9	32.2	7.9
Std.Dev	0.72	0.17	1.54	0.39	2.3	4.7	2.3	5.5	7.3
<u>Urban Area</u>									
Mean	7.42	0.37	4.02	1.05	4.8	18.3	12.1	34.5	30.3
Median	7.46	0.34	3.56	1.01	4.7	17.8	12.0	31.4	28.6
Max	7.91	0.64	6.36	2.29	8.9	27.8	20.8	58.9	54.9
Min	6.53	0.21	2.16	0.32	0.2	5.7	7.5	21.5	17.5
Std.Dev	0.31	0.12	1.44	0.58	2.0	6.5	3.2	9.9	11.2

220

221 Table 4. Summary statistics of PTE (mg/kg) in the peri-urban and urban area. (significant  
 222 differences ( $p < 0.05$ ) between the two areas are represented from different lower-case letters  
 223 in the same column).

	Cr	Ni	Cu	Zn	Pb	Co	Cd	Sb	As
<u>Peri-urban area</u>									
Mean	265	<b>187 b</b>	<b>47 b</b>	<b>145 b</b>	<b>66 b</b>	20	1.0	<b>1.2 b</b>	7.9

Median	206	162	43	130	54	20	0.6	1.0	7.7
Max	461	289	94	322	196	25	4.6	2.5	12.1
Min	158	125	26	72	24	14	0.4	0.7	5.3
Std.Dev	121	56	19	66	48	3.5	1.3	0.5	1.7
Urban area									
Mean	270	<b>240 a</b>	<b>90 a</b>	<b>216 a</b>	<b>220 a</b>	23	1.3	<b>4.1 a</b>	7.5
Median	236	222	69	167	86	22	0.6	2.8	6.8
Max	665	632	257	551	1174	37	7.9	19.1	11.7
Min	117	104	31	89	27	15	0.3	0.9	0.7
Std.Dev	128	113	56	139	319	5	1.7	4.1	2.8
Previous study <sup>1</sup>	405	254	128	286	319		0.6	5.4	
European soils <sup>2</sup>	59.5	37	38.9	68.1	32				11.6
Worldwide soils <sup>2</sup>	94.8	29	17.3	70	27	10			6.8
Legislative limit <sup>3</sup>	150	120	120	150	100 ab	11	2	10	

224 <sup>1</sup> Padoan et al., 2017

225 <sup>2</sup> Kabata-Pendias, 2010

226 <sup>3</sup> Metha et al., 2020

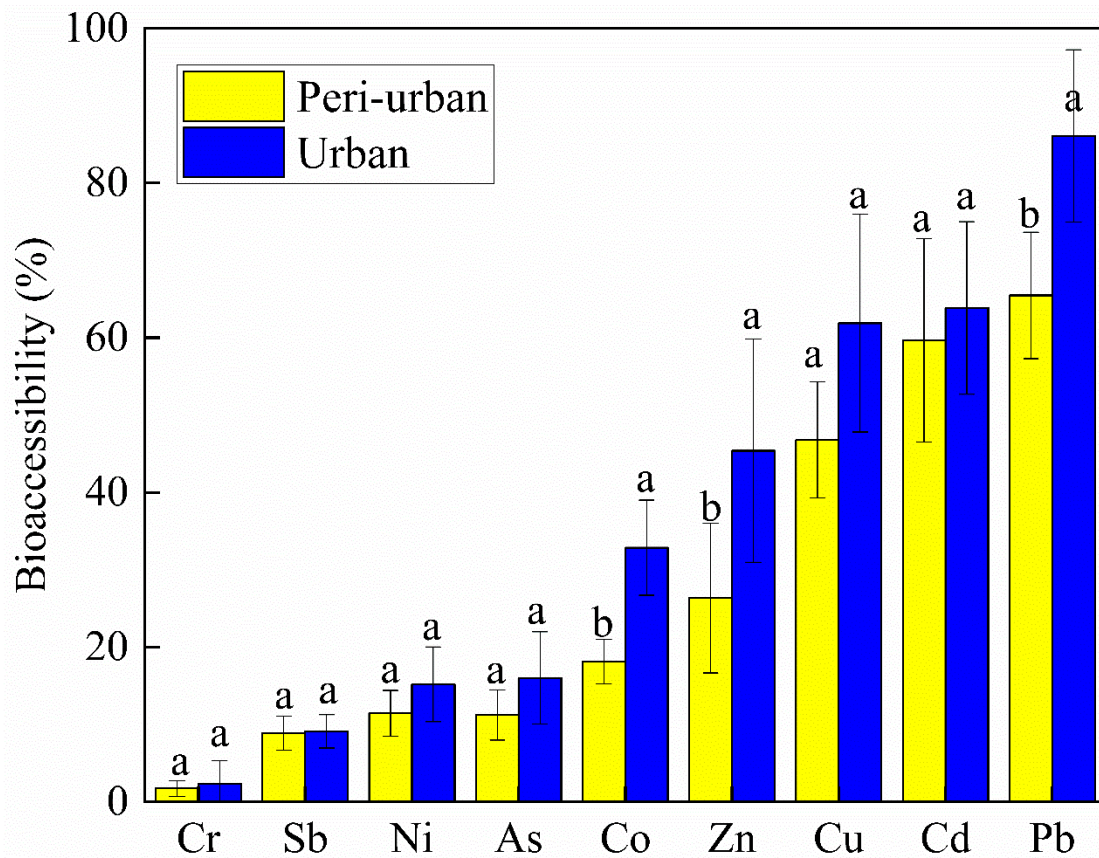
227

228 3.2 *In vitro* bioaccessibility of PTE in urban and peri-urban areas

229 3.2.1 *Oral bioaccessibility*

230 Bioaccessible percentages and relative concentrations for the studied PTE are presented in  
231 Figure 2 and Table 5 for the urban and peri-urban areas. The data showed that the  
232 bioaccessibility of Pb, Zn and Co ( $p < 0.05$ ) in the urban area was significantly higher than in  
233 the peri-urban area, although all the elements were more bioaccessible in the urban area. The  
234 bioaccessibility trend between elements was similar in both areas; i.e. Pb > Cd, Cu > Zn > Co >  
235 As, Ni, Sb > Cr. Moderate to weak correlations between total concentrations and  
236 bioaccessibility were observed for Cu ( $R^2=0.67$ ), Zn ( $R^2=0.54$ ), Pb ( $R^2=0.43$ ), and Ni  
237 ( $R^2=0.33$ ), while there was no clear connection in the case of Cr and Cd ( $R^2<0.10$ , Fig. S3).  
238 These observations corroborated previous studies where PTE bioaccessibility in soils varied

239 significantly between sampling sites and elements (Wu et al., 2017; Ai et al., 2019). Many  
240 factors contribute to the disparity in bioaccessibility values, which one of the most important  
241 is the presence of different sources of elements (Kelepertzis, 2014; Liu et al., 2019) whose  
242 possibly include diverse fractions of PTE with different bioaccessibilities (Liu et al., 2019).  
243 High bioaccessibility of Pb, Zn, and Cu has been linked to a higher level of anthropogenic  
244 pollution (Liu et al., 2017; Padoan et al., 2017), since elements from anthropogenic sources  
245 are generally more soluble in the gastrointestinal environment and thereby more bioaccessible  
246 (Luo et al., 2019; Hernandez-Pellon et al., 2018). Huang et al. (2018) also reported that PTE  
247 originated in a residential area were more bioaccessible than ones originated in commercial  
248 and industrial areas. Furthermore, the PTE speciation need to be considered; the low  
249 bioaccessibility of Cr, for example, may be due to the high geogenic contribution of refractory  
250 chromium-containing minerals from serpentinites, which cannot be easily solubilized (Sialelli  
251 et al., 2011; Biasioli et al., 2006). A very high bioaccessibility of Cd was observed during *in*  
252 *vitro* digestion, as found also in different areas (Luo et al., 2012; Francova et al., 2020) and  
253 the results may be associated with the low pH in simulated extraction solutions (Li et al.,  
254 2016).



255  
 256 Figure 2. Gastric bioaccessibility of PTE in the urban and peri-urban area. Lower-case letters  
 257 show significant difference ( $p < 0.05$ ) of different element bioaccessibility between areas.  
 258

259 *3.2.2 Lung bioaccessibility*

260 Elements associated with fine soil size fraction ( $<10 \mu\text{m}$ ) may pose potential health risks  
 261 because they can directly enter into the lung then to the blood system via inhalation. The  
 262 results of the total and bioaccessible concentrations, and inhalation bioaccessibility in soils  
 263 ( $<10 \mu\text{m}$ ) were displayed in Table 5 and Figure 3. Bioaccessible PTE concentrations (Co, Ni,  
 264 Sb and Pb) through inhalation were higher than ones through ingestion ( $p < 0.05$ ), posing  
 265 concerns to their possible harm. However, the relative bioaccessibility was lower (Fig. 4)  
 266 because of the high total concentrations in the  $<10 \mu\text{m}$  fraction, higher than in coarser  
 267 fractions. The higher concentrations has already been reported from many articles and is due  
 268 to different phenomenon, such as, in some case, to the increase of sorption due to the higher  
 269 specific surface of fine particles, according to what was already been reported  
 270 (Ajmone-Marsan et al., 2008; Ma et al., 2019).

271 The differences in bioaccessibility may be due also to the different components of the  
272 extracting solutions and to pH values of the *in vitro* methods (Hu et al., 2019; Monneron et al.,  
273 2020). Many researchers found that pH has a substantial impact on PTE bioaccessibility (Liu  
274 et al., 2018). In opposition with these results, PTE bioaccessibility generally decrease with a  
275 higher pH (Basta et al., 1993; Li et al., 2020), however, the complexity of Gamble's solution  
276 could probably have resulted in a different behaviour as, for example, the presence of  
277 chlorides in its formula could lead in the formation of metal-chloride complexes which are  
278 readily solubilized (Bourliva et al., 2020).

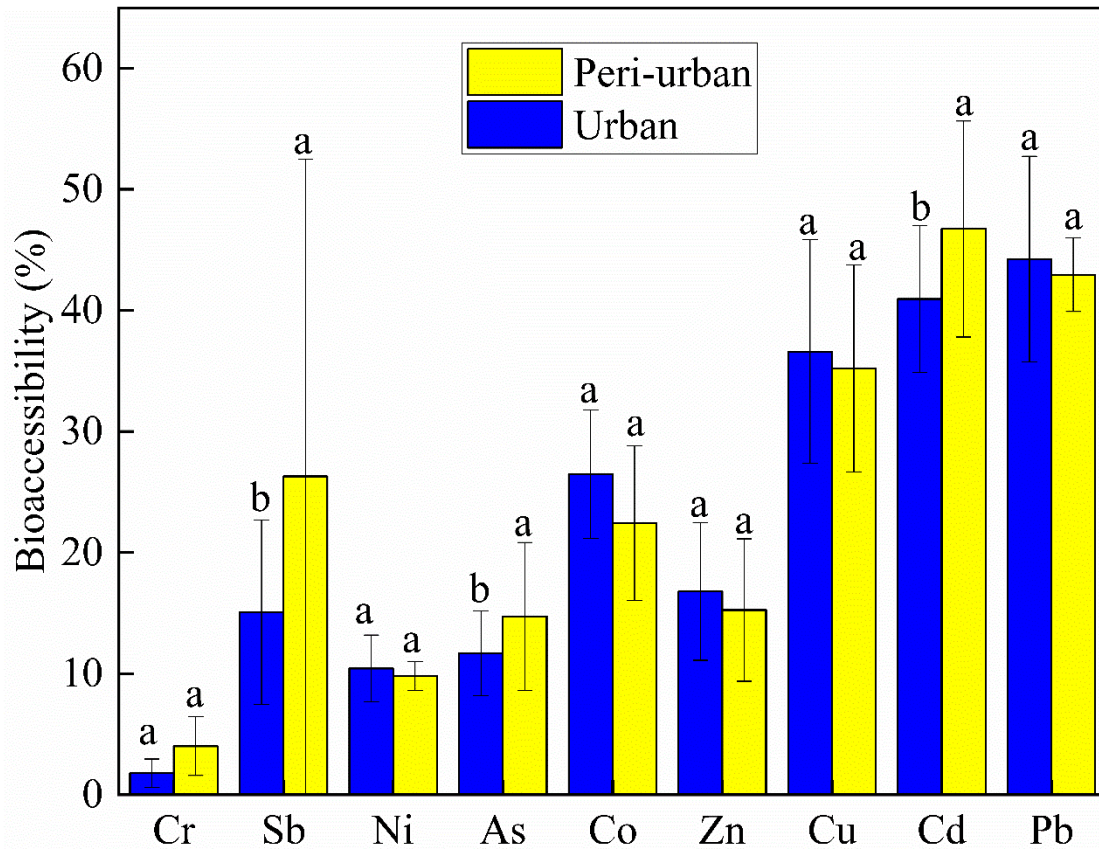
279 The lung bioaccessibility varied widely among different elements because of the different  
280 chemical forms in which the elements could be present in the urban setting. Lead, Cd, Cu, and  
281 Co had the highest bioaccessibility, followed by Sb, Zn, As, Ni and Cr. The relatively high  
282 bioaccessibility of Cu and Zn may be due to the presence of cysteine in the extraction solution,  
283 which provides thiol groups that strongly coordinated with Zn and Cu (Huang et al., 2014).

284 The high bioaccessibility of Cd is also interesting. According to a previous study (Pelfrêne  
285 and Douay, 2018), between the major forms of the elements present in the environment, Cd  
286 oxide and Cd chloride are easily dissolved in the lung, however, Cd sulfide not.

287 Lead, Cu, Zn, Ni, and Co had a higher bioaccessibility in the urban than in the peri-urban area,  
288 although not statistically significant, while Cr, As, Sb and Cd where more bioaccessible in the  
289 peri-urban area. This variability highlighted that PTE release could be influenced by the  
290 geological origins and by different anthropogenic processes.

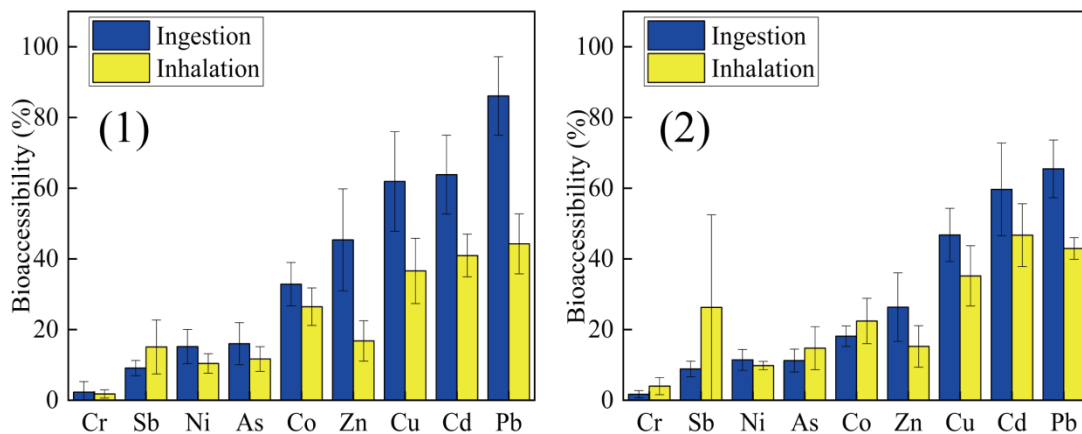
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293

294 Figure 3. Lung bioaccessibility of PTE in the urban and peri-urban area. Lower-case letters  
 295 show significant difference ( $p < 0.05$ ) of different element bioaccessibility between areas.



296

297 Figure 4. Comparison of PTE oral and lung bioaccessibility in urban (1) and peri-urban (2)  
 298 area.

299

300 Table 5. Total ( $< 10\mu\text{m}$ ) and bioaccessible ( $<150\mu\text{m}$ ,  $<10\mu\text{m}$ ) PTE concentrations (mg/kg) in  
 301 the urban and peri-urban area. Ranges, Median (Med), Averages (Avg) and Standard  
 302 Deviations (SD). Upper-case letters show significant differences ( $p < 0.05$ ) between ingestion



303 and inhalation in the urban area, while lower-case letters indicate significant differences ( $p <$   
304  $0.05$ ) in the peri-urban area.

	Total concentration (< 10µm)						Urban Area						Peri-urban Area					
	Urban			Peri-urban			Bioaccessible concentration (< 150 µm)			Bioaccessible concentration (< 10 µm)			Bioaccessible concentration (< 150 µm)			Bioaccessible concentration (< 10 µm)		
	Range	M	Ave±SD	Range	M	Ave±SD	Range	Med	Ave±SD	Range	Med	Ave±SD	Range	Med	Ave±SD	Range	Med	Ave±SD
		ed	SD	e	ed	SD							e					
Cr	179-850	358	425±192	249-927	368	479±263	1-64	3.4	7±14 A	2-34	5.2	7.6±7.3 A	1.7-20	3.3	4.8±5.5 b	1.9-90	12.4	25±28 a
Co	27-74	42	45±12	22-57	45	40±12	4-13	7	7.3±2.1 B	6-19	12.2	12±3 A	2.1-5	4	3.8±1 b	3.3-15.8	9	8.9±3.6 a
Ni	186-932	408	466±207	247-669	357	410±164	13-164	31	40±35 B	15-140	38.8	50±31 A	12-41	17	21±9 b	25-60	35	40±14 a
Cu	80-467	147	187±111	68-222	103	114±43	15-231	39	63±39 A	28-232	47.9	73±59 A	13-66	19	26±16 b	24-93	47.9	39±21 a
Zn	192-1720	396	510±382	230-559	254	309±113	20-334	66	112±66 A	21-371	65.5	94±90 B	12-135	35	47±38 a	15-106	38.3	48±32 a
As	13-23	18	18±3	7-25	19.9	18±6	0.6-4.1	1.2	1.3±0.8 A	1.3-3.7	2	2.1±0.7 A	0.3-1.5	0.9	0.9±0.4 b	1.3-3.5	2.3	2.4±0.8 a

C	0.7-11.	1.	2.4±2	0.8-6	1.	1.7±1						1.1±1.4						
d	9	3	.7	.4	2	.7	0.2-7	0.5	0.9±1.5 A	0.2-6.1	0.6	A	0.2-4	0.3	0.7±1.2 a	0.4-3.7	0.51	0.9±1 a
Sb	2-30	5.	7.9±7	1.5-5	2.	3.1±1	0.1-1.					1.1±0.9	0.1-0.					0.7±0.4
		6	.7	.8	9	.3	8	0.3	0.4±0.4 B	0.2-3.9	0.8	A	3	0.1	0.1±0.1 b	0.3-1.5	0.6	a
Pb	88-342	28	636±	90-6	12	200±	19-11			35-166	123.	301±486	16-21					
	6	6	938	53	8	174	71	69	209±69 B	9	7	A	0	36	60±63 b	38-300	55	87±81 a

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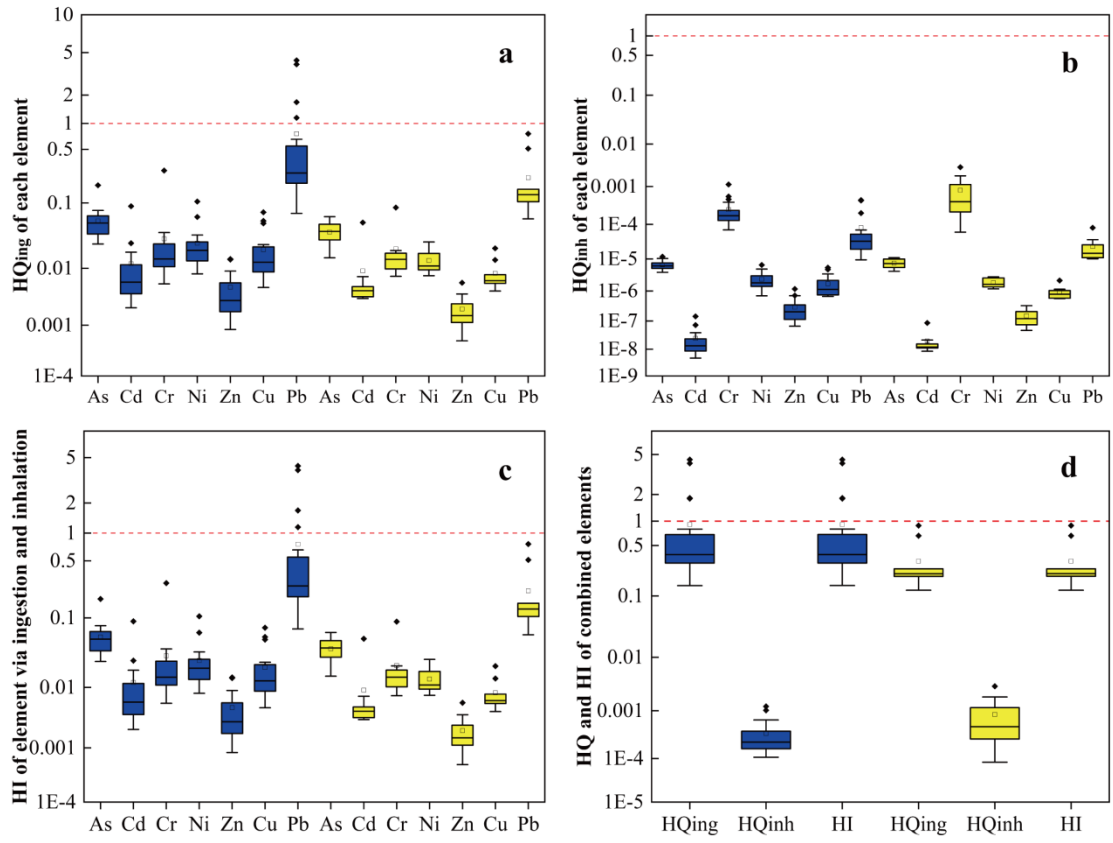
### 307 3.4 Human health risk assessment

308 The non-carcinogenic and carcinogenic risks due to soil PTE via the ingestion and inhalation  
309 exposure pathways are presented in Figures 5 and 6. The mean and median values of HI in  
310 this study were lower than 1, suggesting an acceptable average non-carcinogenic risk for the  
311 studied soils. However, some sample sites in urban area, children exposure to Pb  
312 contaminated soil may have adverse health effects (Fig.5a).

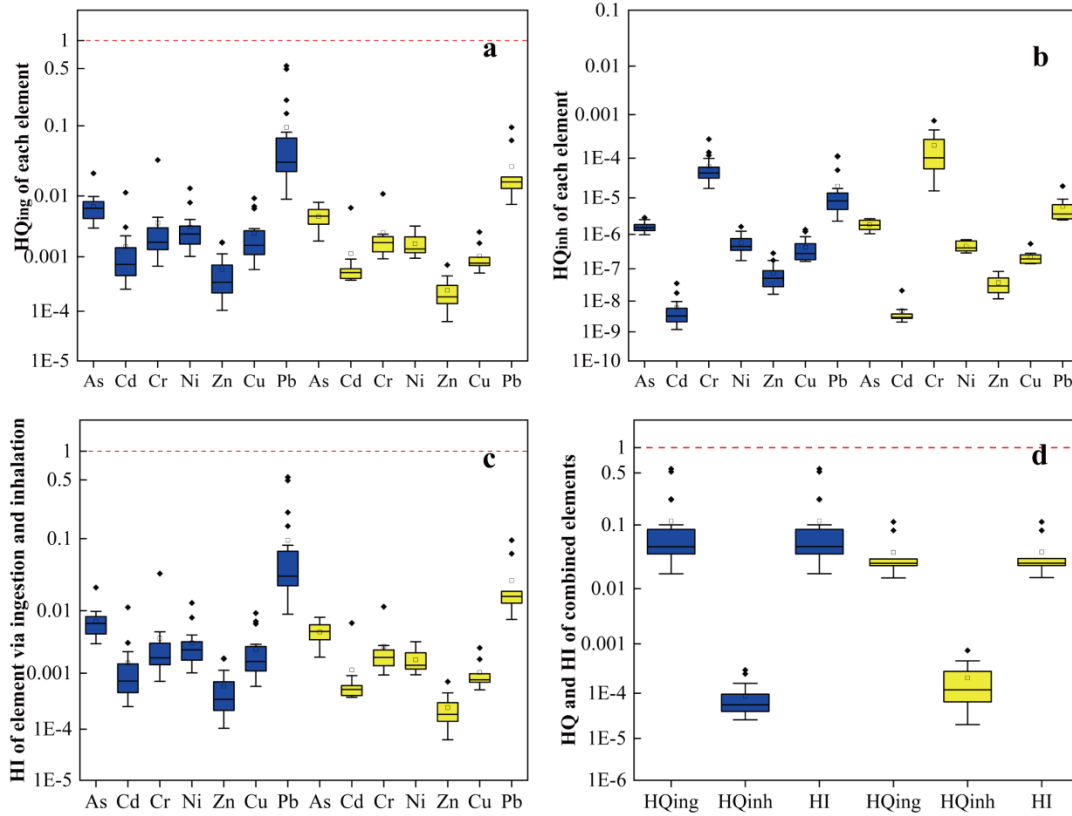
313 The health risks through the different exposure routes were in the order of ingestion >  
314 inhalation (Fig.5 a,b), indicating that exposure to soils due to ingestion contributed to the  
315 largest to the total calculated health risk (Zhuo et al., 2019; Liu et al., 2020). Comparatively,  
316 non-carcinogenic risks for children were higher than for adults (Fig. 5 1,2), and higher in the  
317 urban area than in peri-urban area (Fig.5 d) and the same trend was observed for carcinogenic  
318 risk, suggesting that children faced more potential health risks from exposure to elements.

319 The non-carcinogenic risk for each element decreased in the order of Pb > As > Cr > Ni > Cu >  
320 Cd > Zn in both areas, which indicated Pb (> 80%) as the main contributor to the estimated  
321 human health risk.

322 In terms of carcinogenic risk, the TCR probabilities for As, Cd, Cr and Pb to children and  
323 adults were under the acceptable level ( $< 1 \times 10^{-4}$ ), indicating no significant risks to adults and  
324 children exposed to soils. Soil ingestion was calculated as the most important pathway of  
325 exposure (Fig.6 a,b), but inhalation has a higher contribution to the carcinogenic risk than to  
326 the non-carcinogenic. Chromium (42%) and As (37%) were the dominant contributor to  
327 cumulative carcinogenic risk. This was consistent with previous studies revealing As and Cr  
328 being the major carcinogen and Pb the major non-carcinogen factors (Eziz et al., 2018; Fan et  
329 al., 2019; Bourliva et al., 2020).



(1)



(2)

331

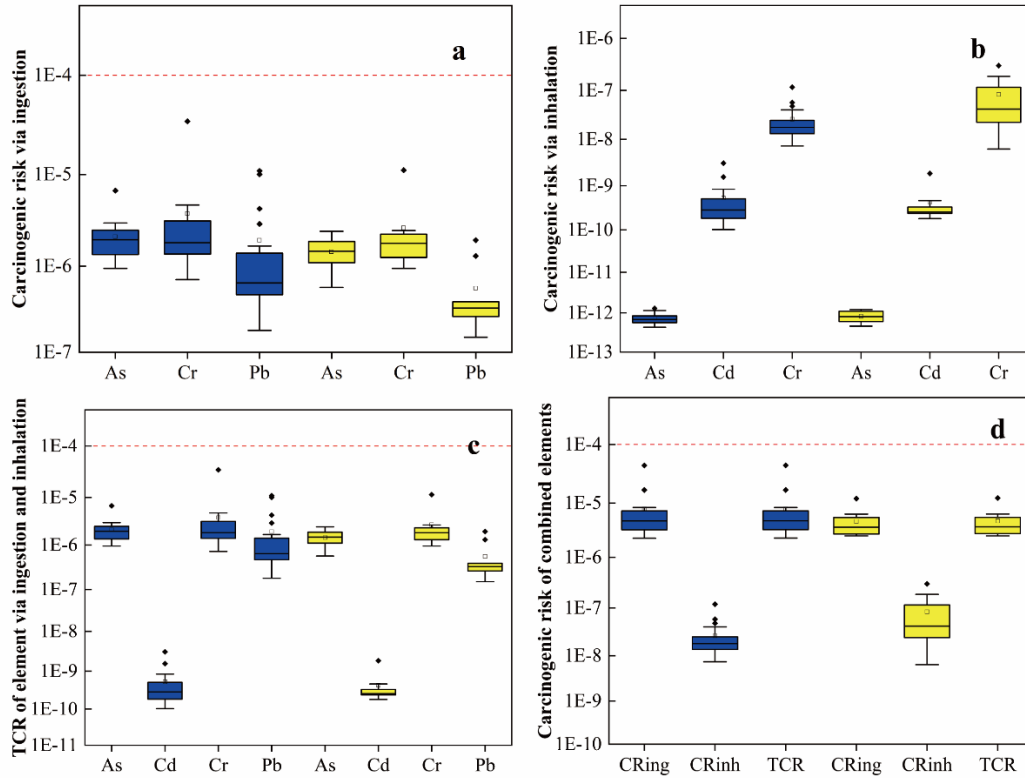
332 Figure 5. Non-cancer Hazard Quotients (HQ) and Hazard Indexes (HI) of PTE in urban (blue)

333 and peri-urban (yellow) areas via ingestion and inhalation exposure pathways calculated for

334 children (1) and for adults (2). In detail: (a) HQ of each element through ingestion; (b) HQ of

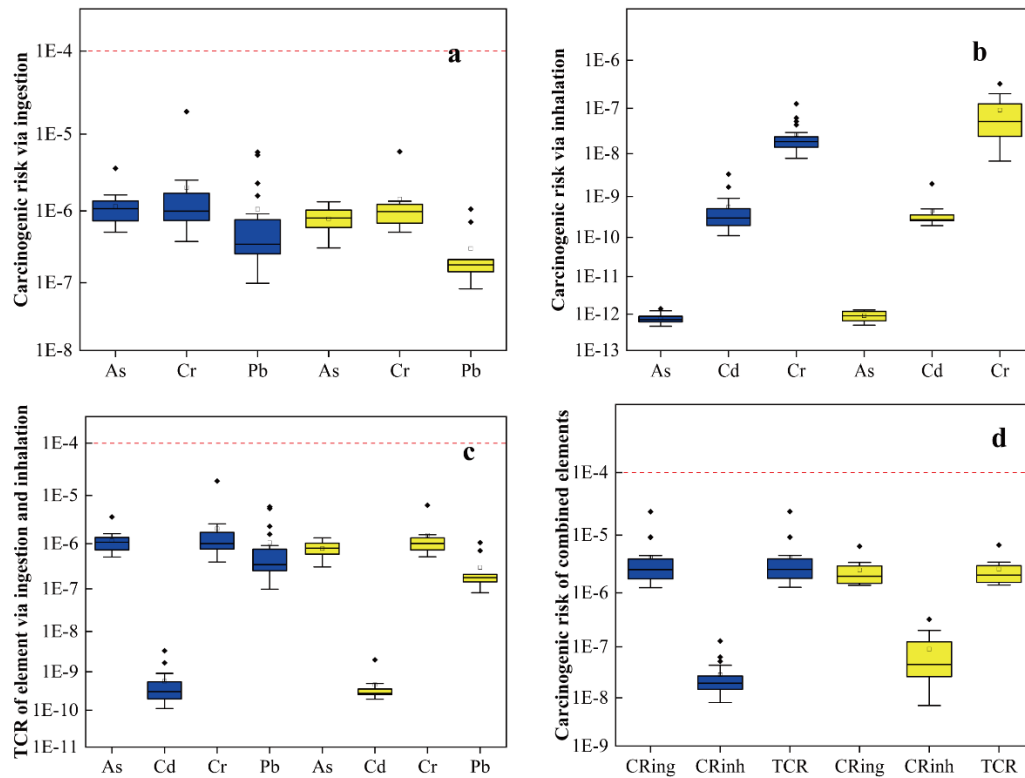
335 each element through inhalation; (c) HI of each element through ingestion and inhalation; (d)

336 HQ and HI of combined elements through ingestion and inhalation.



(1)

337



(2)

338

339 Figure 6. Cancer risk due to PTE in urban (blue) and peri-urban (yellow) areas via ingestion

340 and inhalation exposure pathways for children (1) and adults (2). In detail: (a) CR of each  
341 element through ingestion; (b) CR of each element through inhalation; (c) TCR of each  
342 element through ingestion and inhalation; (d) CR and TCR of combined elements through  
343 ingestion and inhalation.

344

#### 345 **4. Conclusions**

346 In vitro oral and lung bioaccessibility and human health risk assessment of PTE in soil  
347 samples from an urban and peri-urban area in Turin were investigated. The average PTE  
348 contents and chemico-physical parameters of soils were in line with previous works in the  
349 same area. Concerning bioaccessible percentages, they exhibited a decreasing order of Pb >  
350 Cd, Cu > Zn > Co > As, Ni, Sb > Cr in the gastric environment and Pb > Cd, Cu > Zn > Co >  
351 As, Ni, Sb > Cr regarding lung bioaccessibility. Comparing ingestion and inhalation results, a  
352 relative enrichment of bioaccessible concentrations of Pb, Ni, Co and Sb was observed in the  
353 inhalable size fraction (< 10 µm) compared to ingestible one. Conversely, the relative  
354 bioaccessibility of Pb, Cu, Cd, Zn and As was lower, due to the different components of the  
355 extraction solution and extracting pH. The average bioaccessibility values suggested that PTE  
356 would more bioavailable if ingested than inhaled. In addition, a higher solubility of Pb, Cd,  
357 Zn, and Cu was found using both methods, which may reflect a higher level of anthropogenic  
358 pollution.

359 Human health risk was assessed for the ingestion and inhalation pathways, using the  
360 bioaccessible fractions in simulated fluids. Unacceptable non-carcinogenic risk (HQ > 1) was  
361 found through ingestion exposure for children in some urban sites and Pb was the most  
362 hazardous elements for non-carcinogenic risk. Carcinogenic risks were under the threshold  
363 levels for every soil (CR < 10<sup>-4</sup>), with Cr and As being the dominant contributors to risk.  
364 Furthermore, children were more susceptible to PTE toxicity than adults and urban area soils  
365 posed a higher risk than peri-urban ones. Therefore, this elements, and especially Pb pollution  
366 in the urban soils still need more attention, and the necessary soil remediation activities are  
367 needed to reduce the risks of human, especially children, exposure to PTE.

368

369



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373

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