



# Effects of Soil Properties and Land Use Types on the Bioaccessibility of Cd, Pb, Cr, and Cu in Dongguan City, China

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## Abstract

In order to determine the potential heavy metal contamination in soil across Dongguan City, 124 soil samples from seven land use types were collected, four heavy metals (Cd, Pb, Cr, and Cu) were analyzed. Total Cd, Cr, and Cu contents were significantly higher than the background values for Guangdong Province. Lead bioaccessibility in urban green land was lower than that in industrial and abandoned districts. The bioaccessibility of heavy metals was affected by total metal concentrations, soil properties, and land use types. The results showed that there was a negative correlation between the bioaccessibility of heavy metals (except for Cu) and their total concentrations. Soil pH and organic matter were the main factors affecting the bioaccessibility of Cd, Cr, Pb, and Cu in most land use types. Furthermore, sand, P, and clay also affected Pb, Cr, and Cu bioaccessibility. With the exception of the industrial zone periphery and urban green land, the bioaccessibility of heavy metals was mainly affected by clay.

**Keywords** Heavy metals · Dongguan City · Bioaccessibility · Soil properties · Land use types

The anthropogenic activities in Dongguan City, including industrial activities (e.g., plating, machine building, and electronics manufacturing) and agricultural activities, have resulted in high pollution levels, especially heavy metal pollution (Zhang et al. 2018). A proportion of the heavy metals may be transferred to soil, where heavy metals accumulate (Huang et al. 2017). Soil is regarded as a sink for contaminants generated from various sources, and can pose a risk to human health (Xia et al. 2016). Therefore, it is important to quantify the heavy metals exposure risk from soil in Dongguan City.

Generally, human health risk assessment is based on total concentration, which indicates the entire ingested contaminant that is available through the gastrointestinal tract (Xia et al. 2016). However, risk assessments give limited information about the chemical behavior of heavy metals and their potential fate (Andrea et al. 2018), and can substantially

overestimate the actual health risks because humans probably do not absorb 100% of the contaminant (Walraven et al. 2015). Therefore, only a fraction of the total soil heavy metal can be assimilated by humans (Gu et al. 2016). However, *in vitro* methods overcome the shortcomings of *in vivo* experiments, which are costly and time consuming (Bradham et al. 2018). *In vitro* experiments directly reflect the effects of heavy metals in soils on the digestive system, and the amount of heavy metals that can be dissolved by the human gastrointestinal tract (Huang et al. 2017).

*In vitro* assays, such as a two-step physiologically based extraction test (PBET), have been widely used to simulate stomach and intestine liquids to evaluate the oral bioaccessibility of pollutants in the human gastrointestinal system. The health risk of heavy metals in soils need to be characterized by multiple pathways (ingestion, inhalation, and dermal), and should incorporate bioaccessibility adjustments. Some researchers have reported that the bioaccessibility of heavy metals in soils depends on the soil matrix and type, particle size, and chemical composition (Cai et al. 2016; Pelfrêne and Douay 2018). Furthermore, Luo et al. (2012) and Mendoza et al. (2017) reported that the bioaccessibility of Cd, Co, Cr, Cu, Ni, Pb and Zn in soils was significantly correlated with soil properties (total metal contents, sand, silt, and clay). Furthermore, different land use types showed

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significant differences in heavy metal pollution and physicochemical properties (Zhao et al. 2019). Walraven et al. (2015) reported that the oral Pb-bioaccessibility of soils due to different anthropogenic land uses was highly variable. Another study showed that land use significantly affected the bioaccessible concentrations of Cd and Pb because a change in land use significantly affects soil conditions and the oral bioaccessibility of metals (Pelfrène et al. 2013). Therefore, it is necessary to establish the relationships between soil properties, total metal concentration, and metal bioaccessibility in the gastrointestinal phase.

The objectives of this study were (1) to investigate the soil properties and the ranks for heavy metal contamination in soil from Dongguan City; (2) to determine the bioaccessibility of heavy metals in the different land use types, and (3) to analyze the relationships between soil properties and total and bioaccessible heavy metals in soil.

## Materials and Methods

Dongguan City is located in Guangdong Province, Southern China, which is in the eastern part of the Pearl River Delta (Fig. 1). It covers 2465 km<sup>2</sup>, and the terrain has a northeast to southwest slope. It is a prefecture-level city with 32 towns and is a typical industrial city, where the minerals are mainly distributed in the mountains and hilly areas across central, southern, and eastern Dongguan City. It has good transport networks that connect it to other areas (Sun et al. 2018).

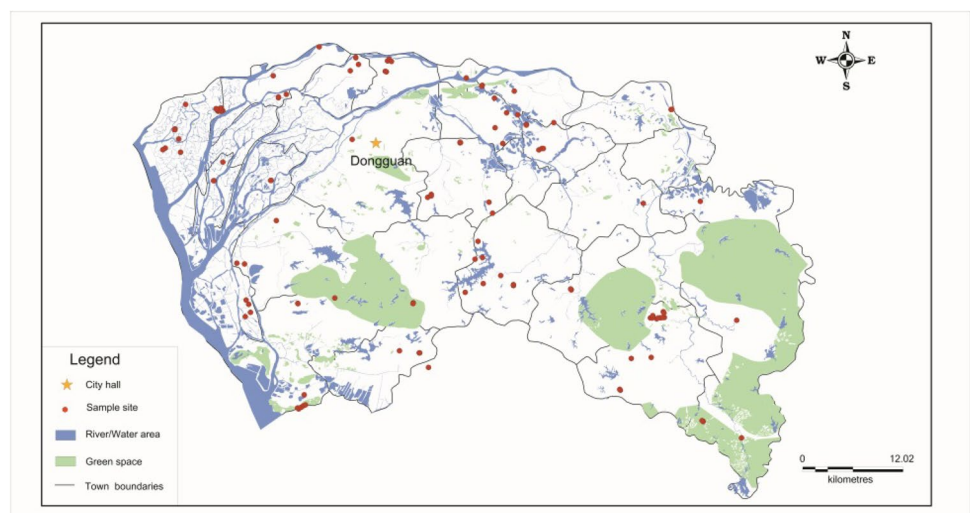
A total of 124 topsoil (0–20 cm depth) samples were collected in Dongguan City (Fig. 1). Sample site selection was based on the urban layout and hydrogeological conditions. The 1 kg samples were a mixture of five subsamples taken randomly from the upper 20 cm soil layer of a 5 m<sup>2</sup> area using a quadrat. Each subsample was collected using a bamboo spade and stored in sealed kraft packages. The

bamboo spade was cleaned each time there was a change in sampling site. After collection, the soil samples were air-dried on a shady platform. Then, the pH of a proportion of each soil sample was determined and the soil was sieved using a 2 mm nylon sieve. Then, another part of the sample was sieved through a < 150 µm nylon sieve and the soil was used to determine the organic matter (OM), P, K, and total concentration of heavy metals. The remaining part was sieved through a < 250 µm nylon sieve and used to analyze heavy metal bioaccessibility, cation exchange capacity (CEC), and N.

The soil samples were divided into the following seven categories based on land use type: (1) industrial district (ST1): the main pollutant sources were battery factories, chemical production plants, textile factories, and paper mills; (2) abandoned industrial district (ST2): the main pollutant sources were closed plastic factories, cement factories, and electroplating factories; (3) industrial zone periphery (ST3): the main pollutant sources were sewage discharge ports, electroplating printing, dyeing, and residential areas; (4) urban green land (ST4): the main pollutant sources were anthropogenic activities in residential areas, leisure areas, and squares; (5) roadside area (ST5): the main pollutant sources were highways, national highways, railways, and residential areas; (6) solid waste landfill (ST6): the main pollutant sources were domestic waste landfill sites and storage areas for used batteries and lamps; and (7) vegetable plots (ST7): the main pollutant sources were residential areas, furniture factories, and agricultural activities.

The particle size distribution, pH, organic matter content, total N, P, and K contents, and CEC were analyzed in each soil sample. The soil particle size distribution was determined by hydrometer method; the soil pH was measured by a pH meter (Acidity Meter, PHS-10, China) in a mixture of soil and deionized water (1/5, m/V); soil organic matter was characterized by a wet oxidation

**Fig. 1** Soil sample sites in Dongguan City



method (Nelson and Sommers 1996); and the N, P, and K contents were measured using the Kjeldahl method (NY/T 53-1987), a colorimetric method (NY/T 88-1988), and flame photometry (NY/T 87-1988), respectively. Then, the total Cd, Pb, Cr, and Cu concentrations in the soils were measured after being digested with a mixture of HNO<sub>3</sub>, HF, and HClO<sub>4</sub> in polyvinyl-fluoride crucibles.

The *in vitro* bioaccessibility test was determined by PBET experiments with some modifications proposed by Ruby et al. (1996). PBET experiments included two sequential processes: a gastric phase and an intestinal phase. The gastric solution (1 L) for the first phase was prepared by adding 1.25 g pepsin, 0.5 g citrate, 0.5 g malate, 8.766 g sodium chloride, 0.42 mL lactic acid, and 0.5 mL acetic acid, and adjusting the pH to 2.0 with HCl. The soil samples were combined with the gastric phase solution to achieve a soil:solution ratio of 1:100 (g mL<sup>-1</sup>). Then, the mixture was shaken at 100 rpm for 1 h in a thermostatic bath maintained at 37 °C. In the second phase, the pH of the gastric solution after the first phase reaction was adjusted to 7.0 with NaHCO<sub>3</sub>. Then, 40 mg of porcine bile salts and 14 mg of porcine pancreatin were added to simulate the intestinal solution. The mixtures were shaken in a thermostatic bath maintained at 37 °C for a further 3 h. During the process, the pH of the filtrate was maintained to within 0.5 pH units of the initial pH. After 2 h, 10 mL of the supernatant was removed using a disposable syringe and filtered through a cellulose acetate disk filter (0.45 μm), and stored in a refrigerator at 4 °C until further analysis.

The heavy metal bioaccessibility was determined by ICP-MS (ISO 17294-1:2005 and ISO 17294-2:2003). After ten soil samples had been analyzed from the study set, a blank sample, a triplicate soil sample, and a Chinese soil standard material (GBW07415) was included in the sample batch. Heavy metals bioaccessibility was calculated using the following equation:

$$\text{Bioaccessibility}(\%) = \left[ \frac{C_{\text{bioaccessible}}}{C_{\text{total}}} \right] \times 100 \quad (1)$$

where  $C_{\text{bioaccessible}}$  represents the PBET-extractable metal concentration and  $C_{\text{total}}$  is the total metal concentration in the samples.

The statistical analysis was performed by SPSS 18.0. A one sample *t* test was used to determine the difference between total metal contents and their background values. The significant differences among the metal bioaccessibilities, soil properties, and total metal concentrations were tested by one-way analysis of variance (ANOVA) ( $p < 0.05$ ). The correlation analysis between element concentrations was conducted after transforming the raw data using the natural logarithm due to the lognormal distribution of the element concentrations.

## Results and Discussion

The soil physicochemical properties of the samples are summarized in Table 1. The soil pH ranged from 5.2 to 6.5, which meant that it was slightly acidic. The organic matter concentration ranged from 1.0 to 1.9 g kg<sup>-1</sup> was low. This may be because of sampling to a depth of 20 cm, causing the dilution of organic matter in the upper portion of the profile (Lamb et al. 2009). Land use types ST1 and ST4 had the maximum and minimum values for organic matter, respectively. In ST1, one of soil samples was collected from a sludge dumping site, and its organic matter concentration was 22.1 g kg<sup>-1</sup>, which was caused by the high organic matter content in the sludge (Li et al. 2019). With the exception of this sample, the average organic matter concentration of ST1 was 1.1 g kg<sup>-1</sup>, which was close to the average value of the soil organic matter concentration in other land use types. However, ST4 had low organic matter, which may be due to the fact that it is essentially a manmade new soil (Lan et al. 2019) and the leaves are often cleaned up so that organic matter cannot accumulate, also because the industrial activities were small, heavy metal pollution was not serious. ST2 had the highest sand proportion (62.8% ± 6.0%) in the seven land use types, but it had lowest silt proportion (22.7% ± 3.4%) and clay proportion (14.52% ± 2.6%). In contrast, the sand proportion (37.4% ± 4.0%) in ST5 was the lowest in the seven land use types, but it had the highest silt proportion (42.1 ± 5.3%). The soil from ST5 contained the highest silt proportion, but the lowest sand proportion. This was due to the high dust emissions (Swet et al., 2016). The means of total N, P, and K were 1.0, 16.3, and 8.9 g kg<sup>-1</sup>, respectively. In ST6, the P content was significantly higher than that in the samples from other land use types (except for ST7). The CEC varied from 7.9 to 10.1 cmol kg<sup>-1</sup>. Generally, the results showed that the soil properties were different in the seven land use types in Dongguan City.

The mean concentrations of Cd, Pb, Cr, and Cu were 0.23, 57.5, 38.9, and 40.6 mg kg<sup>-1</sup>, respectively. The background values for soils in Guangdong Province (CEMS, 1990) are Cd: 0.06 mg kg<sup>-1</sup>, Pb: 36.0 mg kg<sup>-1</sup>, Cr: 50.5 mg kg<sup>-1</sup>, and Cu: 17.0 mg kg<sup>-1</sup>. The one-sample *t* test showed that the Cd, Pb, and Cu contents had significantly increased in Dongguan City soils (Cd:  $p = 0.002$ , Pb:  $p = 0.003$ , Cu:  $p = 0.001$ ). However, the Cr range was considerable (7.6–141.2 mg kg<sup>-1</sup>), and the mean was significantly lower than the background value for Guangdong Province ( $p = 0.004$ ). The standard deviation for Cu was larger than its mean, which showed that the dispersion degree for Cu was very large, influence factors of Cu content variety are various, such as Cu contents associated with anthropogenic sources (e.g., agricultural chemicals,

**Table 1** Means and standard deviations of the soil properties in the seven land use type areas across Dongguan City

Land use type	N	Sand (%)	Silt (%)	Clay (%)	pH	Organic matter (g kg <sup>-1</sup> )	Total N (g kg <sup>-1</sup> )	Total P (g kg <sup>-1</sup> )	Total K (g kg <sup>-1</sup> )	CEC (cmol kg <sup>-1</sup> )
ST1	28	50.0±2.8a	27.2±1.0a	22.8±1.3a	5.5±1.6a	1.9±4.0a	1.2±2.9a	16.6±6.6b	9.4±5.2a	9.4±5.2a
ST2	25	62.8±6.0a	22.7±3.4a	14.5±2.6a	6.1±1.3a	1.4±0.6a	0.8±0.6a	14.1±6.0b	7.9±2.0a	7.9±2.0a
ST3	26	48.7±2.0a	29.2±1.5a	22.1±0.5a	5.2±1.6a	1.3±0.7a	1.0±0.8a	15.2±4.8b	10.1±3.7a	10.1±3.7a
ST4	5	48.0±0.4a	29.4±1.2a	22.6±1.7a	6.5±0.9a	1.0±0.4a	0.4±0.2a	14.4±3.5b	8.0±1.9a	8.0±1.9a
ST5	25	37.4±4.0a	42.1±5.3a	20.5±0.1a	5.4±1.8a	1.1±0.3a	1.3±0.6a	15.0±7.7b	7.9±3.7a	7.9±3.7a
ST6	9	52.5±2.0a	28.5±1.3a	19.0±5.5a	6.4±1.0a	1.1±0.5a	0.5±0.3a	26.2±9.3a	9.0±5.5a	9.0±5.5a
ST7	6	52.8±2.5a	28.5±2.7a	18.7±5.2a	5.7±0.9a	1.5±1.1a	1.5±1.1a	20.9±2.1ab	10.0±6.4a	10.0±6.4a
All	124	50.2±2.1	29.8±0.7	20.0±1.5	5.6±1.5	1.4±2.0	1.0±1.5	16.3±7.0	8.9±4.1	8.9±4.1

Data are means ± SD. Values followed by different letters in different land use types are significantly different (*p* < 0.05).

such as fertilizers and pesticides) (Ebong et al. 2018). According to the national standards for soil quality in China (GB 15618-2018 and GB 36600-2018), ST4 belongs to the first type of development land, and ST1, ST2, ST3, ST5, and ST6 belong to the second type of development land. The heavy metal concentrations in all the development land samples did not exceed the risk screening values for soil contamination of development land. Only one soil sample in ST7 had a Cd concentration that exceeded the risk screening values for soil contamination of agricultural land, but it did not exceed the intervention values for soil contamination.

Table 2 shows the bioaccessibility of heavy metals in the different soils across Dongguan City. These are based on the gastrointestinal step in the PBET experiment. They were 52.5 ± 25.4% (Cd), 17.2 ± 10.6% (Pb), 2.60 ± 2.67% (Cr), and 26.0 ± 17.3% (Cu). The ANOVA showed that there were significant differences among the Cd, Pb, Cr, and Cu bioaccessibilities in the seven land use types.

Cadmium bioaccessibility ranged from 3.3 to 95.0% and followed the order: ST7 (81.5%) > ST5 (60.8%) > ST4 (57.7%) > ST6 (54.6%) > ST1 (52.4%) > ST3 (44.8%) > ST2 (43.7%). The ST1, ST2, and ST3 had significantly different Cd bioaccessibilities compared to ST7. In ST4, that of Pb was only 9.17 ± 2.31%, which was the lowest value of all the seven land use types. However, ST1 (19.1 ± 12.8%) and ST2 (22.6 ± 13.2%) had higher Pb bioaccessibilities. Luo et al. (2012) suggested that Pb bioaccessibility was positively correlated with total Pb content (*R*<sup>2</sup> = 0.861). That of chromium in ST6 was significantly different from other land use types. The mean of Cu bioaccessibility was 26.0 ± 17.3%, which was lower than most of 15 soil samples in China (the means of gastric phase and small intestine phase were 45.3% and 52.1%, respectively) that was reported by Naiyi et al. (2014). The Cu concentration in ST2 was significantly higher than that in other land use types.

The correlations among bioaccessibility of heavy metals, total metal concentrations and selected soil physiochemical properties were further examined by multiple regression analysis (Table 3). The dataset was first transformed into a normal distribution. The factors were metals bioaccessibility, total metal concentration, silt, organic matter, total N, total P, total K, and CEC. The bioaccessibility of most heavy metals had negative correlations with their total concentrations, except for Cu. That of Cu had positive correlation with its total concentration in ST1. This may be because ST1 had the highest clay proportion (22.8 ± 1.3%) and highest organic content (1.9 ± 4.0 g kg<sup>-1</sup>), they have a strong adsorption of copper, which led to a decrease in Cu<sup>2+</sup> content in the small intestine simulating solution. Those of Cr, Pb, and Cu were mainly affected by soil pH and organic matter. In addition, sand, P, and clay also had important effects on Pb, Cr, and Cu bioaccessibility. Different land use types had different

**Table 2** Heavy metal bioaccessibility (%) and total concentrations ( $\text{mg kg}^{-1}$ ) for the heavy metals across the seven land use types

Land use type	N	Cd		Pb		Cr		Cu	
		Total	Bioaccessibility	Total	Bioaccessibility	Total	Bioaccessibility	Total	Bioaccessibility
ST1	28	0.16±0.17b	52.4±31.8b	92.0±65.4a	19.1±12.8ab	33.4±14.2a	1.91±1.88b	33.1±16.8b	17.4±13.4a
ST2	25	0.30±0.22a	43.7±22.4b	36.7±20.1b	22.6±13.2a	45.3±31.6a	2.97±1.86b	100.7±103.3a	37.5±26.0a
ST3	26	0.28±0.21ab	44.8±15.8b	45.8±19.5b	13.6±9.1b	37.4±12.3a	2.29±1.59b	22.5±8.8b	21.2±9.0a
ST4	5	0.11±0.05b	57.7±39.0ab	67.4±21.1ab	9.17±2.3b	58.5±16.6a	0.50±0.17b	24.7±7.2b	22.0±9.1a
ST5	25	0.20±0.16b	60.8±24.5ab	53.5±14.2b	14.5±3.7b	35.5±11.4a	2.54±1.66b	20.6±6.9b	28.3±10.3a
ST6	9	0.26±0.15ab	54.6±12.7ab	51.3±17.4b	17.1±7.7ab	34.3±25.3a	6.28±6.60a	26.3±10.9b	19.5±8.1a
ST7	6	0.19±0.06b	81.5±9.60a	51.6±14.9b	18.7±7.5ab	49.4±25.6a	2.04±0.97b	20.4±10.9b	42.4±17.0a
All	124	0.23±0.19	52.5±25.4	57.5±39.8	17.2±10.6	38.9±20.6	2.60±2.67	40.6±55.9	26.0±17.3

Data are means ± SD. Values followed by different letters in different land use types are significantly different. ( $p < 0.05$ ).

**Table 3** Multiple regression analyses between environmental variables and total and bioavailable heavy metals.  $\text{Cd}_B$ ,  $\text{Pb}_B$ ,  $\text{Cr}_B$ , and  $\text{Cu}_B$ : bioaccessibility of Cd, Pb, Cr, and Cu;  $\text{Cd}_T$ ,  $\text{Pb}_T$ ,  $\text{Cr}_T$ ,  $\text{Cu}_T$ : total Cd, Pb, Cr, and Cu concentrations

Sample site	N	Equation	$R^2_{\text{adj}}$
ST1	28	$\log\text{Pb}_B = -0.075 + 0.632\log\text{Pb}_T$	0.425
		$\log\text{Cr}_B = 1.589 - 0.792\log\text{Cr}_T + 0.819\log\text{OM} - 0.002\text{clay}$	0.490
		$\log\text{Cu}_B = 0.586 - 0.063\log\text{Cu}_T + 0.123\text{pH} + 0.493\log\text{OM}$	0.336
ST2	25	$\log\text{Cr}_B = 1.085 - 0.060\log\text{Cr}_T - 0.003\text{clay}$	0.146
ST3	26	$\log\text{Cd}_B = 2.062 + 0.011\log\text{Cd}_T - 0.080\text{pH} + 0.265\log\text{OM}$	0.406
		$\log\text{Pb}_B = 2.359 - 0.201\log\text{Pb}_T - 0.905\text{pH}$	0.099
		$\log\text{Cr}_B = 1.211 + 0.239\log\text{Cr}_T + 1.304\log\text{OM} - 1.332\log\text{K}$	0.301
ST4	5	$\log\text{Cu}_B = 2.151 + 0.033\log\text{Cu}_T + 0.854\log\text{OM} - 0.894\log\text{K}$	0.444
		$\log\text{Pb}_B = 2.232 - 0.098\log\text{Pb}_T - 0.962\log\text{P}$	0.901
ST5	25	$\log\text{Cu}_B = 4.336 + 0.263\log\text{Cu}_T - 1.383\log\text{silt}$	0.772
		$\log\text{Cd}_B = 1.396 - 0.363\log\text{Cd}_T$	0.276
		$\log\text{Cr}_B = 2.283 - 1.121\log\text{Cr}_T + 0.651\log\text{N} - 0.264\log\text{P}$	0.808
ST6	9	$\log\text{Cu}_B = 1.462 + 0.253\log\text{Cu}_T - 0.002\text{clay}$	0.661
		$\log\text{Cr}_B = -0.006 - 0.069\log\text{Cr}_T - 0.005\text{clay} + 0.253\text{pH}$	0.889
ST7	6	$\log\text{Cu}_B = -0.730 + 0.175\log\text{Cu}_T + 0.290\text{pH}$	0.559
		$\log\text{Cd}_B = -1.345 - 0.209\log\text{Cd}_T + 2.321\log\text{P}$	0.882
		$\log\text{Cr}_B = -0.236 - 2.337\log\text{Cr}_T + 2.033\log\text{OM} + 3.065\log\text{P}$	0.997
		$\log\text{Cu}_B = 0.723 + 0.481\log\text{Cu}_T - 0.005\text{clay} + 1.301\log\text{K}$	0.985

levels of heavy metal contamination and can cause diverse influences on heavy metals bioaccessibility. In most land use types, soil pH and organic matter had important impacts on heavy metals bioaccessibility. With the exception of ST3 and ST4, clay also had important effects on heavy metals bioaccessibility.

The bioaccessibilities of Cd, Cr, and Cu were positively correlated with organic matter ( $p = 0.037$ ,  $0.001$ , and  $0.001$ , respectively), but they were negatively correlated with pH and clay. The regression equation  $R^2$  values for Cr and Cu were 0.374 and 0.240, respectively. This was consistent with Poggio et al. (2009) who reported that soil clay strongly adsorbs Cu. However, Pb bioaccessibility was only related to sand. A previous study showed that the higher the contents of organic matter and sand in the

soil, the lower the contents of silt and clay, which means that Pb becomes more bioaccessible (Zhang 2013). In this study, the higher the sand proportion, the higher the Pb bioaccessibility. There was no correlation between Pb bioaccessibility and organic matter. This was consistent with Zhang (2013) and could be due to the fact that the intestinal solution is weakly alkaline.

Cadmium bioaccessibility was strongly affected by soil pH and organic matter in ST3. Cui and Chen (2010) showed that Cd bioaccessibility significantly correlated with soil pH in simulated gastric juice. Xia et al. (2016) found that organic carbon was the predominant soil property controlling the physiologically-related Cd bioaccessibility. Furthermore, Cd bioaccessibility decreased when organic material was added to the soil solution (Cui et al. 2016). It has also

been shown that organic amendment could effectively remediate heavy metals in soils (Park et al. 2011).

Lead bioaccessibility was significantly correlated with total Pb concentration and P content in ST4 ( $R^2=0.901$ ). In the regression equation  $\log Pb_B = 2.232 - 0.098 \log Pb_T - 0.962 \log P$ , Pb bioaccessibility is negatively related to P content ( $p=0.035$ ). Furthermore, Pb bioaccessibility significantly decreased when P was added to Pb contaminated soils. This is consistent with Li et al. (2017) who reported P amendment significantly decreased Pb bioaccessibility. Yin and Shi (2014) suggested that increasing soil pH can also significantly decrease Pb bioaccessibility. This is consistent with the correlation between Pb bioaccessibility and soil pH in ST3. It has also been reported that Pb bioaccessibility in soils with higher organic matter contents was 2.5 times that in soil with lower organic matter levels (Mercier et al. 2002), which was different from the results obtained in this study. Chromium bioaccessibility was negatively correlated with clay content in the soils from ST1, ST2, and ST6 ( $p=0.031$ , 0.027, and 0.010, respectively). The multiple regression equation  $R^2$  values were 0.490, 0.146, and 0.889, respectively. This may be due to heavy metal absorption by the clay minerals in the soils and limited heavy metals mobility (Xu et al. 2017). Therefore, higher clay contents reduce Cr bioaccessibility.

The Cu regression equation was  $\log Cu_B = 0.586 - 0.0631 \log Cu_T + 0.123pH + 0.493 \log OM$  for ST1, and the correlation coefficient  $R^2$  value was 0.336. Therefore, Cu bioaccessibility was correlated with pH and organic matter ( $p=0.016$  and 0.028, respectively). This is consistent with Naiyi et al. (2014) who reported the relationship between soil pH and Cu bioaccessibility in the gastric phase and the total Cu content in the intestinal phase. Schewertfeger and Hendershot (2012) found that  $Cu^{2+}$  and  $Al^{2+}$  competed with each other for absorption sites on soil organic matter, which may have affected the  $Cu^{2+}$  content in the small intestine simulation solution. These correlations were explored in order to identify whether there is a possible interaction between the soil properties, total metal concentrations, and Cd, Pb, Cr, Cu bioaccessibility. However, we found that the total metal concentrations could not be used to assess Cu bioaccessibility in the different polluted land use types. Instead, we need to consider the soil properties and land use types. These parameters can be used to more accurately predict the bioaccessibility of heavy metals.

In conclusion, the total Cd, Pb, and Cu concentrations in soils from Dongguan City were significantly higher than the soil background values for Guangdong Province. The Cd, Pb, Cr, and Cu bioaccessibilities were  $52.5 \pm 25.4\%$ ,  $17.2 \pm 10.6\%$ ,  $2.60 \pm 2.67\%$ , and  $26.0 \pm 17.3\%$ , respectively. Lead bioaccessibility was lowest in ST4, but was relatively high in ST1 and ST2 where there are many battery and electroplating plants. The bioaccessibility of most heavy metals

was negatively correlated with their total concentration. However, Pb bioaccessibility in ST1 and Cu bioaccessibility in ST3–ST7 were positively correlated with their total concentrations. That of heavy metals was mainly affected by soil pH and organic matter. Sand, P, and clay also had important effects on Pb, Cr, and Cu bioaccessibility. In most land use types, soil pH and organic matter affected heavy metals bioaccessibility. Clay was also an important factor that influences heavy metals bioaccessibility in soil (except for ST3 and ST4).

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