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Phytoavailability and phytovariety codetermine the bioaccumulation risk of heavy metal from soils, focusing on Cd-contaminated vegetable farms around the Pearl River Delta, China

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ABSTRACT

Five random vegetable farms were selected to investigate the bioaccumulation risk of heavy metals (HMs) by different type of vegetables around the Pearl River Delta (PRD), China. The concentration order of four major HMs in the surface soil samples was Cd < Cu < Pb < Zn, with only Cd concentrations (1.4–1.8 mg kg^{-1}) significantly higher than the permissible limit ($\leq$0.3 mg kg^{-1}) for agricultural soils. Soil DTPA-extractable (phytoavailable) Cd concentrations differed markedly amongst the five farms, and varied within 0.017–0.17 mg kg^{-1}. Meanwhile, 28.0% of vegetable samples collected from these five farms were contaminated with Cd according to the permissible limit ($\leq$0.05 mg kg^{-1}), and 71.4% of these polluted samples belonged to stem/leaf vegetables. The average bioaccumulation factors of Cd from cultivated soil to stem/leaf vegetables and melon/fruit/bean vegetables varied within 0.021–0.050 and 0.005–0.020 (soil total Cd basis), and 0.50–2.01 and 0.13–0.53 (soil DTPA-extractable Cd basis), respectively. Redundancy analysis (RDA) showed that DTPA-extractable Cd, which negatively but significantly correlated ($P < 0.05$) to soil pH, was the key factor in influencing vegetable Cd accumulation, notably stem/leaf vegetables. The results show that Cd was the primary metal of risk in vegetable farms around the PRD region, and stem/leaf vegetables posed about 2.2 times higher health risks associated with exposure to Cd than melon/fruit/bean vegetables.

1. Introduction

Soil serves many vital functions within our society, particularly for food production. Unfortunately, the contamination of heavy metals (HMs) in farm soils and the subsequent uptake by plants constitute a major environmental problem in many developing countries such as China (Lin et al., 2007), mainly attributed to cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) (Wong and Bradshaw, 2002). It has been commonly observed that crops and vegetables grown in HM-contaminated soils tend to have a greater accumulation of HMs in their edible or non-edible parts than those grown in uncontaminated soils (Sharma et al., 2007). As a result, the potential human health risks associated with HM contamination of agricultural soils have been of considerable public concern (Muchuweti et al., 2006). For example, ingestion of vegetables containing high concentrations of HMs have been documented as a major route for these elements entering the human body (Singh et al., 2010), causing detrimental health hazards to the consumer. Therefore, consumer interest for the safety and quality of vegetable products has increased worldwide in recent years (Gruda, 2005). Nevertheless, the accumulation of metal by plant does not appear to be solely dependent on the total concentration of metal in the soil (Medina et al., 2005), but may be greatly influenced by metal phytoavailability (Hart et al., 2002). On the other hand, phytovariety has also been proposed to be a major influencing factor, as various vegetable species may differ markedly in metal accumulation from the same contaminated sites (Yang et al., 2009). This will require elucidation of the extent of toxic metal contamination in different ecological compartments to establish whether they are bioaccumulated and biomagnified through food chains (Leung et al., 2006).

The Pearl River Delta (PRD) is located at China's south coast, and has a humid subtropical climate and favors agricultural growth, allowing for an annual production of 10–15 crops of vegetables and

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3 crops of grains. It is one of the first regions in China to experience immense industrialization and urbanization in the recent several decades. However, HM accumulation in agricultural soils has also become increasingly serious in this area, owing to rapid economic development and increasing reliance on fertilizers and agrochemicals (Wong et al., 2002). Therefore, a study of the PRD may provide valuable and insightful information not only for other regions in China, but also for other rapidly developing countries in the future. However, to date, the information regarding HM contamination in vegetables cultivated in farms around the PRD is limited. Since HM-contaminated vegetables are likely to pose higher health risks associated with dietary metal intake, a better understanding of soil and plant factors that control metal bioaccumulation by crops may also be useful in the selection of agronomic countermeasures for the future. Therefore, the objectives of this work were to: (1) obtain information on HM (Cd, Cu, Pb, and Zn) accumulation status in selected vegetable farms and edible products around the PRD region; (2) investigate the association between HM contaminations in edible vegetables with soil parameters at different farm sites; and (3) raise countermeasures for decreasing potential health risks of human consumption on vegetables with emphasis on exposure to toxic metals.

2. Materials and methods

2.1. Soil and vegetable sampling

Both surface soil samples and edible vegetable samples were collected from five farms around the PRD region, Southern China (Fig. 1). The locations of the selected farms were: (1) DDH, Dengta Town, Dongyuan County, Heyuan City (23°59′N, 114°47′E); (2) SHH, Shuikou Town, Huicheng District, Huizhou City (23°09′N, 114°32′E); (3) DHH, Duozhu Town, Huidong District, Huizhou City (23°02′N, 114°57′E); (4) HG, Haizhu District, Guangzhou City (23°03′N, 113°22′E); and (5) SD, Shatian Town, Dongguan City (22°54′N, 113°36′E). All these soils are classified as Orthic Anthrosol (IUSS, 2006). From each farm, triplicate samples each of five random vegetable species, including both stem/leaf vegetables and melon/fruit/bean vegetables, were collected, and five random replicates of soil samples per farm were also taken from a depth of 0–15 cm.

2.2. Soil sample analysis

The air-dried soil samples were sieved through a 2 mm sieve for analyzing soil pH and DTPA-extractable metal (Cd, Cu, Pb, and Zn) concentrations [0.005 M diethylene-triaminepentaacetic acid (DTPA), 0.1 M triethanolamine (TEA) and 0.01 M $CaCl_2$, pH 7.3, solution: soil = 2: 1, extraction for 2 h (Baker and Amacher, 1982)] using a pH meter (Beckman) and an atomic absorption (AA) spectrophotometer (SpetrAA-20, Varian, U.S.), respectively. Metal concentrations were expressed as an oven-dried soil weight for correcting the water content in the soil (105 °C, 24 h). The total concentrations of Cd, Cu, Pb, and Zn in soils were also determined, using the AA spectrophotometer (SpetrAA-20), once a subsample of soil had been sieved through a 0.15 mm sieve and digested (0.5 g) with acid mixture (6 mL hydrochloric acid, 3 mL of conc. nitric acid, and 4 mL perchloric acid), using a microwave accelerated reaction system (MARS-X, CEM Corporation, US). Both the blank and standard reference material [Montana II Soil 2711a, U.S. National Institute of Standards and Technology (NIST)] were included for quality assurance. The recovery rates of total soil Cu, Cd, Zn, and Pb were 85, 92, 94, and 95%, respectively.

2.3. Vegetable sample analysis

The fresh biomass of vegetable samples was determined and the dry weight was also measured after oven–drying at 70 °C for 48 h. Subsamples (1.0 g) of dried and ground vegetable were digested by conc. nitric acid, followed by AA spectrophotometry (SpetrAA-20) to measure tissue Cd, Cu, Pb, and Zn concentrations. Both the blank and standard reference material (Tomato Leaves 1573a, NIST) were included for quality assurance. The recovery rates of plant total Zn, Cu, Pb, and Cd were 93–99, 95–103, 95–105, and 96–105%, respectively. Metal concentrations were expressed as fresh vegetable weight for correcting the water content in the sample.

2.4. Statistical analysis and redundancy analysis

The means and standard deviations were computed for soil pH and soil/vegetable metal concentrations for each sampling site. A boxplot for quantitative random variables of the metal of risk in specific vegetable species was generated, using Explore procedure with SPSS software, whilst disregarding the sampling sources. The bioaccumulation factors (BFs) of toxic metals from contaminated soil

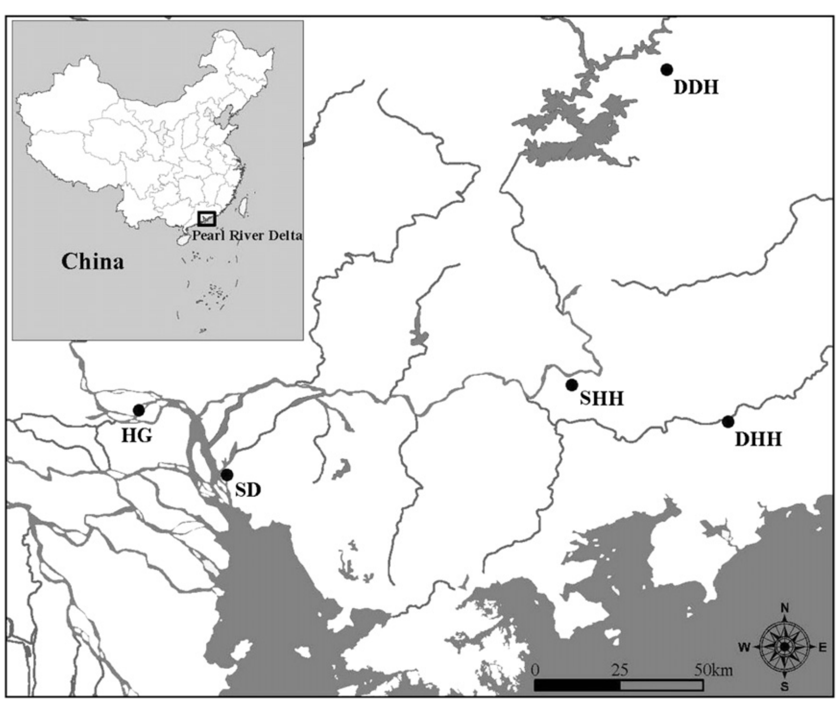

Fig. 1. Locations of the five selected farms around the Pearl River Delta. Map data were extracted from the National Dynamic Atlas (NGCC, 2012). DDH, Dengta Town, Dongyuan County, Heyuan City; SHH, Shuikou Town, Huicheng District, Huizhou City; DHH, Duozhu Town, Huidong District, Huizhou City; HG, Haizhu District, Guangzhou City; SD, Shatian Town, Dongguan City.