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Greenhouse cultivation mitigates metal-ingestion-associated health risks from vegetables in wastewater-irrigated agroecosystems

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HIGHLIGHTS

- Vegetable farmlands in Baiyin, Gansu, China were severely polluted by As and Cd.
- Greenhouses had lower plant metal levels and bioconcentration factors than fields.
- Greenhouse cultivation mitigated the health risks via vegetable ingestion.
- Higher soil organic matter and faster growth in greenhouses may be the reasons.

GRAPHICAL ABSTRACT

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ABSTRACT

Wastewater irrigation can elevate metal concentrations in soils and crops and increase the metal-associated health risks via vegetable ingestion in arid and semiarid northwestern China. Here, we investigated the As, Cd, Cr, Cu, Ni, Pb, and Zn concentrations in four vegetable species from Dongdagou and Xidagou farmlands in Baiyin, Gansu, China. We evaluated the effects of irrigation type (Dongdagou: industrial wastewater; Xidagou: domestic wastewater) and cultivation mode (open field and greenhouse) on the vegetable metal concentration, metal partitioning, soil-to-plant bioconcentration factor (BCF), and the health risk index. All stream waters, soils, and vegetables were found most severely polluted by As and Cd, with higher severity in the industrial-wastewater-irrigated Dongdagou than the domestic-wastewater-irrigated Xidagou. All vegetables had higher or, at least, comparable metal mass allocated in the shoot than in the root. Greenhouse cultivation could reduce metal-ingestion-associated health risks from edible vegetable biomass by decreasing the soil to plant bioaccumulation (BCF) and the metal concentration. This effect was always significant for all vegetables within Xidagou, and for carrot within Dongdagou. This mitigation effect of greenhouse cultivation could be attributed to the metal sorption by a higher level of soil organic matter and faster growth rate over metal uptake rate in greenhouses compared to open fields. Such mitigation effect was, however, insignificant for leafy vegetables within Dongdagou, when much more severely polluted water for irrigation was applied in greenhouses compared to open fields

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within Dongdagou. The present study highlights greenhouse cultivation as a potential mitigating approach to providing less-polluted vegetables for residents in the severely polluted area in addition to the source pollution control.

1. Introduction

Metal contamination can cause deterioration in water, soil, and crop quality in agroecosystems and pose threats to public health risks (Kabata-Pendias, 2010; Khan et al., 2015; Li et al., 2014). Irrigation with metal-containing wastewater introduces potentially toxic metals in soils and crops that tend to increase the metal-associated health risks to the human beings (Culbard et al., 1988; Hu et al., 2013a; Liu et al., 2013; Liu, 2003). In recent decades, the fast urbanization and industrialization and improper farming practices in China have brought about increased atmospheric metal deposition, and agrochemical and irrigational metal input to a large number of agroecosystems (Cao et al., 2010; Cheng, 2003; Khan et al., 2008; Li et al., 2006; Liu et al., 2007, 2013; Wang et al., 2011). Despite the critical role of suburban vegetable bases in supporting the sustainable city development (Nabulo et al., 2012; Zhou et al., 2000), many plantations of Chinese cities such as Beijing, Tianjin, Hangzhou, and Xi'an have various degrees of soil and vegetable metal contamination (Chen et al., 2008; Hao et al., 2009; Khan et al., 2008; Liu et al., 2005; Wang et al., 2005, 2006; Xue et al., 2012; Ye et al., 2015). Zeng et al. (2007) summarized the metal pollution in vegetable-growing lands of China and found that lands in eastern China are mainly contaminated by Cd, Hg, and Zn, those in middle China by As, Cd, Hg, Zn, and Cu, and those in western China by As, Cd, Cu, Cr, and Hg. Also, the most severely contaminated vegetable-growing lands are from the mining or wastewater irrigated areas.

In particular, in semiarid and arid areas of northwestern China, irrigation with industrial and domestic wastewater has long been a common practice because of the lack of water resources (Nan et al., 1999). This management has caused high accumulation of metals in soils (Nan and Zhao, 2000), which will be further bioaccumulated by the crops (Nan and Cheng, 2001) and enter the human body directly through food consumption (Dai et al., 2012). Since 2011, the State Council of China has commenced the "Comprehensive prevention and control of heavy metal pollution" as part of its five-year development plan for the country. In 2015, 30 priority contaminated areas were established to be funded for soil remediation by the Chinese Ministry of Finance and Chinese Ministry of Environmental Protection, and the first listed area is Baiyin City, Gansu Province (http://jjs.mof.gov.cn/zhengwuxinxi/tongzhigonggao/201506/t20150602_1248397.html).

Baiyin City, Gansu Province in northwestern China, also called "*Tong Cheng*" (which means "Copper City" in Chinese), has been famous for its mineral resources and metal mining, smelting and processing industries since the 1950s. It is one of the most important non-ferrous metal mining and smelting bases in China for the production of metals, including Cu, Zn, Pb, Ni, Fe, Au, and Ag (Li et al., 2006; Nan and Zhao, 2000). The city is divided into two basins based on the watersheds, namely Dongdagou (or "East Big Ditch") and Xidagou (or "West Big Ditch"), with large amounts of nonferrous metal mining and smelting plants along the middle-upper reaches of Dongdagou Stream, and one copper processing plant along the middle-upper reaches of Xidagou (Nan and Zhao, 2000). Both Dongdagou and Xidagou Streams receive industrial and domestic wastewater; the former receives primarily industrial wastewater and the latter primarily domestic wastewater. The streams have been the primary source of water for irrigation of agroecosystems in the two basins for decades. The total concentration of Cd in arable soils in Dongdagou basin ranged from 3.4 to 77.9 mg/kg (Liu, 2003), higher than in other well-known polluted areas of China, such as the Zhangshi wastewater irrigation area near Shenyang (0.8 to 7.3 mg-Cd/kg-soil) (Wu et al., 1991), and the polluted paddy soils around Dabaoshan mine in Guangdong (3.0 to 5.5 mg-Cd/kg-soil) (Zhuang et al., 2009).

Importantly, there are large farmlands (13.3 km^2) in the Dongdagou and Xidagou basins that produce most of the crop products for millions of residents in nearby cities (Hu et al., 2014). Nan et al. (2002) investigated the soil, wheat, and corn metal concentration in farmlands of the Dongdagou and Xidagou basins and found that soils and crop grains in wastewater-irrigated Dongdagou farmland were severely contaminated by Cd and Pb (5–10 times as FAO/WHO guidelines; (World Health Organization, 2011)), whereas those in Xidagou farmlands were not severely contaminated. Detailedly, the mean Cd and Pb concentrations of wheat grain were 0.61 mg/kg and 1.29 mg/kg, and the mean Cd and Pb concentrations of corn grain were 0.52 mg/kg and 2.07 mg/kg. Li et al. (2006) investigated the soil and vegetables collected in 2003 in the same region and found that the leafy vegetables were more severely contaminated than non-leafy vegetables, and Chinese cabbage was the most severely contaminated with 1.85 ± 0.76 mg As and 1.31 ± 0.58 mg Cd per kg sample. Dai et al. (2012) studied the soil and wheat metal levels in this area and found that the mean levels of Cd (0.76 mg/kg) and Pb (9.96 mg/kg) in wheat grains exceeded the limited values of hygienic standard for grain by factors of 50 and 8, respectively (World Health Organization, 2011). Despite the fact that all these studies suggested that the consumption of the crops from this area may cause a health effect, the local farmlands are still one major source of crops to millions of residents in Baiyin and nearby cities such as Lanzhou, Jingtai, and Jingyuan.

Both open field and greenhouse cultivations of vegetables are common in Baiyin. These two different cultivation modes may cause different types of metal contamination possibly due to distinct cultivation environments and contamination sources (Bose and Bhattacharyya, 2008; Liu et al., 2011; Song et al., 2009; Yang et al., 2013). Song et al. (2009) studied metal concentrations in vegetables from 416 samples from Beijing and found that As, Cr, Cu, Cd, Pb, and Ni in vegetables from open fields were all significantly higher than those grown in greenhouses, which implies that greenhouse cultivation might be developed as a mitigation approach to reducing the health risk of metals from vegetable ingestion. However, most of the current studies on the comparison of open field and greenhouse cultivations focus on vegetable products without a systematical control or monitoring of fertilization, irrigation, and cultivation cycles and full consideration of irrigation water and soil metal levels. Also, few studies compared the soil and plant metal uptake in open fields and greenhouses in wastewater-irrigated semiarid regions (Brunetti et al., 2011; Li et al., 2012).

It has been more than 10 years since the investigation on the soils and vegetables in 2003 in this critical region (Li et al., 2006). To assess the most recent contamination levels and comprehensively understand the effects of different types of wastewater irrigation (industrial versus domestic, or Dongdagou versus Xidagou) and cultivation modes (greenhouse versus open field) on the metal bioaccumulation in vegetables and the metal-associated health risks for vegetable ingestion, we analyzed metal concentration in soils and above- and below-ground biomass (shoot and root) of four types of common vegetables planted in controlled environments. This study eventually aimed to understand whether the greenhouse cultivation would mitigate the metal-ingestion-associated health risks from vegetables with comprehensive information of irrigation water, soil, and vegetable metal pollution.