Heavy metal accumulation in untreated wastewater-irrigated soil and lettuce (Lactuca sativa)

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ORIGINAL ARTICLE

Heavy metal accumulation in untreated wastewater-irrigated soil and lettuce (*Lactuca sativa*)

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Abstract Contamination of agricultural soils due to human activities is a major concern globally. The use of urban untreated wastewater for irrigation has been on-going for a long time and the major driving forces of this practice include water scarcity, easy availability, low/no cost and wastewater as a source of plant nutrients. Contamination of agricultural soils with heavy metals as a result of using untreated wastewater for irrigation as well as translocation of the heavy metal into the lettuce was investigated. Soil samples were analysed for pH, electrical conductivity, organic carbon, cation exchange capacity and extractable heavy metals while lettuce samples were analysed for total heavy metal content. The soil samples were found to be sandy clay loam and sandy loamy in texture and alkaline. The organic carbon contents were found to be relatively low with low salt accumulations at both farms. The heavy metal levels in the soil samples from Airport residential farm were in the order Zn > Pb > Cu > Ni > Cd > Cr whilst that of Dzorwulu farm was in the order Zn > Pb > Cu > Ni > Cr > Cd. The soils from the Airport farm were found to be contaminated with Pb, Cu and Zn while the Dzorwulu farm showed contamination for all the metals except Ni. All the heavy metals were observed to have a high degree of transfer from the soil into the lettuce except for Cr at the Airport farm. Heavy metal concentrations in the lettuce samples were all above the FAO/WHO recommended levels. From the observations in this work, irrigation of farm lands with untreated wastewater tends to introduce contaminants into the soils which can be easily transferred into the farm produce. The high levels of these heavy metals pose a health risk to the consumers of such crops.

Keywords Contamination · Irrigation · Translocation · Vegetables · Wastewater

Introduction

The use of untreated urban wastewater for irrigation has been going on for a long time and the major driving forces of this practice include water scarcity, easy availability, low/no cost and the idea that the wastewater serves as a source of plant nutrients (Carr 2003). In many semi-arid and arid regions of the world, fresh surface water is usually only available in sufficient quantities during the rainy season. Water for irrigation is required for the long dry season. Groundwater may be expensive to access because of low water tables that translate into the high costs associated with drilling wells and pumping the water (Cofie and Drechsel 2007).

Irrigation of farmlands with untreated wastewater is a very common practice in many developing countries around the world (Bradford et al. 2003; Lente et al. 2014). In Ghana, this practice is usually observed in the peri-urban areas such as Accra, Kumasi and Tamale. From a general survey among vegetable farmers carried out in 2002, it was found that about 84 % of nearly 800 farmers farming in

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Accra and its environs, and almost all 700 farmers in Tamale used untreated wastewater for irrigation during the dry seasons (Agodzo et al. 2003).

The importance of vegetables in our diet cannot be overemphasised. However, the ability of farmers to supply the ever-growing population with the needed quantity of vegetables is limited by the irregular rainfall pattern and lack of proper irrigation systems. Therefore, farmers resort to the use of untreated wastewater which is readily available for cultivation of the produce. Untreated wastewaters are known to contain appreciable amount of pollutants including heavy metals (Singh et al. 2010; Oliveira et al. 2007; Pescod 1992). The use of these untreated wastewaters tends to introduce pollutants into the soils which become bioavailable for plant uptake (Jassir et al. 2005). Although some metals are of essential value to the human system in trace quantities, the amount usually introduced through the irrigation with untreated wastewater are normally above the accepted levels and therefore causes contamination of the crops (Toze 2004). Thus, wastewater irrigation of vegetables and fodder may serve as the transmission route for heavy metals in the human food chain (Delgado et al. 1999). The consumption of such crops can lead to various health risks.

Intake of heavy metal-contaminated vegetables may pose a risk to the human health due to the ability of heavy metals to accumulate in living organisms and their toxicity at elevated levels. Prolonged consumption of heavy metals contaminated vegetables or foodstuffs may lead to chronic accumulation of the metals in the kidney and liver. This can cause disruption of numerous biochemical processes, leading to various fatal illness such as kidney failure and diseases of bone and the nervous system (Jarup 2003; Trichopoulos 2001).

Continuous irrigation with untreated wastewater increases heavy metal content of the soil which leads to increase in plant uptake, and also contamination of groundwater through leaching of the heavy metals (Delgado et al. 1999). Metals are persistent pollutants that can biomagnify in the food chain, becoming increasingly dangerous to human at the tail end of the food chain.

Although heavy metal contamination of soil resulting from wastewater irrigation is a cause for serious concern due to the potential health risk it poses, little work has been done to explore the impact this practice has on the concentration of heavy metals in soil and crops. This work seeks to assess the effect of irrigation with untreated wastewater on levels of heavy metals in farmlands. The heavy metal, after accumulation in the soil, becomes bioavailable to crops, and this translocation of the heavy metal from the soil into crops is also investigated for lettuce (*Lactuca sativa*).

Materials and methods

Study area

The study was carried out in Accra, the capital city of Ghana which lies within the coastal savannah zone with an estimated population of 2.573 million (Ghana Statistical Service 2012). Accra records mean annual rainfall of 810 mm. The rainfall pattern is bimodal with the major season falling between March and June, and a minor rainy season between September and October. The vegetation of Accra consists of dense shrubs with isolated patches of grass and trees such as baobab and neem trees are also quite common (Obuobie et al. 2006).

Two main vegetable growing sites within the Accra metropolis where untreated wastewater has been used continuously for a period of 10 years were selected for the study. These are the Dzorwulu vegetable farm site, adjacent to the Electricity Company of Ghana (ECG) substation, and airport residential vegetable farm near the Centre for Scientific and Industrial Research (CSIR). The main source of irrigation water in the study site is urban drains. In Dzorwulu farm area, water from the Onyasia stream which is connected with drains carrying wastewater from residential homes and small scale mechanic workshops is used for irrigation. At the Airport farm site, waste from the main drain that gathers water from the airport, some commercial centres and residential areas is used for irrigation.

Sample collection and preparation

At each site, ten (10) composite topsoil samples (0–15 cm) were randomly taken from farms with a hand trowel. Soil samples were also taken from areas where wastewater has never been used but closed to the farms were as control. The samples were kept in polythene bags and transported to the laboratory where they were air dried at room temperature, pulverised, and sieved to obtain <2 mm fraction. The pulverised samples were oven dried at 105 °C for 24 h to remove remaining water. Ten (10) lettuce samples were also collected from each farm at the same location where soils were taken. The samples were washed, dried in an air-circulating oven at 25 °C to a constant weight, pulverised and stored for further analysis.

Soil analysis

The pH was measured using (2:5 w/w) soil water ratio, electrical conductivity (EC) (1:5 w/w soil water ratio). Particle size analysis was carried out using hydrometer method as described by Bouycous (1962). Organic carbon was determined by a modified Walkley and Black procedure as described by Nelson and Sommers (1982), cation exchange capacity (CEC) at pH 7 with ammonium acetate (Chapman 1965).

Determination of heavy metals in soil and lettuce samples

The heavy metal content of the soil samples were extracted using Diethylene-triamine-pentaacetic acid (DTPA) solution buffered at pH 7.3. 5 g of dried soil was mixed with 25 mL of DTPA extracting solution at pH 7.3 and kept on a rotary shaker at 120 rpm for 2 h. The mixture was then filtered through a Whatman No. 1 filter paper and the volume topped to the 50 mL mark with deionized water. The metal concentrations of the filtrate were determined using flame atomic absorption spectrophotometer (VARIAN model AA 220 FS, Australia). Calibration curves were obtained for the metals using their standard solutions. The heavy metal content of the lettuce was determined by digesting 1 g of dried lettuce sample with 40 mL of 3:1 HCl and HNO_3 at 150 °C for 2 h. The digested samples were cooled and filtered through Whatman No. 1 filter paper and the volumes were topped to 50 mL using deionized water before running on the AAS.

Results and discussion

Physico-chemical properties of the soil

The mean pH values for the wastewater-irrigated soil samples from both farm sites were 7.62 ± 0.05 and 7.25 ± 0.26 for the Airport and the Dzorwulu sites, respectively, which is in optimum range for plant growth (Kordlaghari et al. 2013) (Table 1). The results showed a little but significant increase in soil pH, in soils irrigated with the wastewater when compared with the samples from the control sites (Table 1). According to Kordlaghari et al. (2013) irrigation with wastewater can cause a little raise in soil pH. The increase in pH might have been caused by the prolonged use of untreated wastewater with high nitrogen content for irrigation. Soil pH has great influence on the mobility and bioavailability of heavy metals (Nigam et al. 2001). The recorded pH of the soil samples from the farm sites were near neutral. At this pH, soils' ability to hold metal ions is high and prevents metal ions from leaching out. The implication is that metal ion mobility within the soil is low, and therefore plant uptake becomes difficult.

Soil conductivity is an indirect measurement that correlates very well with several physical and chemical properties of the soil such as particle size and soil texture (Wiatrak et al. 2009). The conductivity for the soil samples were 0.25 ± 0.03 and 0.40 ± 0.03 µS cm^{-1} for the Airport and the Dzorwulu farm samples, respectively (Table 1), and can be classified as non-saline according to the classification by Boulding (1994).

Analysis of the data on EC showed that the increase in EC at the farm sites was not significant from the control sites. In spite of raise in EC of soil irrigated with the wastewater, still the soil is normal and pose no salinity risk. The study area has a high annual precipitation, this coupled with the low levels of organic carbon will results in low ion holding capacity so the risk of metal accumulation is low. As a result, significant portion of ions added to the soil from the irrigation process might have leached from the top soil. Again, soil-metal ion retention capacity is also reduced at neutral pH.

Soil organic carbon improves the physical properties of soil. It increases the CEC, water-holding capacity, structural stability and overall health of soil (Gao et al. 1997; Okalebo et al. 1993). The organic carbon contents of the soil samples from both sites were very low. The Airport site recorded a mean value of 1.18 ± 0.02 % while the Dzorwulu site had a mean value of 0.90 ± 0.06 % as presented in Table 1. Compared to the control samples, the Airport farm site recorded no significant difference in organic carbon content while significant difference was observed for the Dzorwulu farms. This observation can be attributed to the source of the irrigation water used.

The mean CEC values obtained were 1.58 ± 0.03 and 1.75 Cmol kg for the Airport farm and Dzorwulu farm,

Table 1 Physico-chemical parameters of the soil samples

Sample site	pH	% Carbon	CEC (Cmol kg^{-1})	Conductivity (µS cm^{-1})	Textural class (USDA)
Airport	7.62 ± 0.05	1.18 ± 0.02	1.58 ± 0.03	0.25 ± 0.03	Sandy clay loam
Control	7.01 ± 0.01	1.09 ± 0.03	1.27 ± 0.04	0.21 ± 0.03	Sandy loam
LSD	0.520	NS	NS	NS	
Dzorwulu	7.64 ± 0.01	0.90 ± 0.06	1.75 ± 0.04	0.40 ± 0.05	Sandy loam
Control	7.25 ± 0.26	0.77 ± 0.05	1.62 ± 0.03	0.37 ± 0.03	Sandy loam
LSD	0.262	0.107	NS	NS	

LSD least significant difference, *NS* values represent not significant respectively, as presented in Table 1. Both values were not significantly different from the control. CEC is a measure of the quantity of cations that is held by a soil. It gives information about soil fertility, nutrient retention capacity, buffering capacity and the capacity to protect groundwater from cation contamination. CEC is dependent on the organic carbon and texture class of the soil. In general, the higher the organic carbon and clay content, the higher the CEC (Yoo and James 2002). The results obtained at both sites indicated low CEC values and thus low metal retention capabilities of the soils. This may be due to the low levels of organic carbon and the textural class of the soils in the study areas.

Heavy metals in soil samples

The concentrations of heavy metals measured in the soil samples from both farm sites except Cr in the Airport farm site were higher than the control samples as presented in Table 2. This showed that even though the metal holding capacity of the soils in the study area was very low they were able to bind to some of the metals in the wastewater that are used for irrigation. Zn recorded the highest concentration (21.73 ± 0.01 mg kg^{-1}) in the Airport soil samples. Concentrations of metal in soils from both farms were in the order of Zn > Pb > Cu > Ni > Cd > Cr. Even though the metals concentration in the airport soil samples were higher than their control samples, no significant difference was found for Cd, Cr, Cu, Ni and Pb ($p > 0.05$). Zn recorded the highest concentration of 43.12 ± 0.63 mg kg^{-1} in the Dzorwulu samples while Cd recorded the least concentration (Table 2). Concentrations of Cu, Pb and Zn were significantly different ($p < 0.05$) from the control whilst Cr, Ni and Cd were not.

The enrichment factors (EF) were measured as the amount or ratio of the sample metal enrichment above the concentration present in the reference station or material. It was calculated as follows:

$$\mathrm{EF} = \frac{C_n}{C_{\mathrm{ref}}} \times \frac{B_{\mathrm{ref}}}{B_n},$$

where C_n is the content of the examined element in the examined environment, C_{ref} is the content of the examined element in the reference environment, B_n is the content of the reference element in the examined environment and B_{ref} is the content of the reference element in the reference environment (Loska et al. 1997).

The calculations indicated that the soils from both farm sites were significantly enriched with Pb, Cu and Zn (Table 3). This showed that the main human activity which is irrigation of the soils with untreated waste water, has significantly enriched the soil with Pb, Zn and Cu. Although the Dzorwulu soil samples recorded high metal concentrations than the Airport samples, the Airport soil samples were highly enriched with the heavy metals. This is due to the fact that the Airport soil samples have high metal holding capacity such as organic carbon content and clay than the Dzorwulu samples.

The geo-accumulation index (Igeo) was calculated as by Muller (1962) as follows:

$$I_{\mathrm{geo}} = \log_2\left(\frac{C_n}{1.5} \times B_n\right),$$

where C_n is the measured concentration of element n in the sediment sample and B_n is the geochemical background for the element n which is was taken from the control samples. The factor 1.5 is introduced to include possible variation of the background values that are due to lithogenic variations.

According to contamination classification by Huu et al. (2010), the Airport soil samples showed significant contamination with Pb while Ni showed the least contamination (Table 3). The Igeo values recorded at the Airport

Table 3 Enrichment factor (EF), Geo-accumulation index (Igeo) and Transfer coefficient (TC) of heavy metals in soils from study areas

Heavy metals	Sampling sites					
	Airport			Dzorwulu		
	EF	Igeo	TC	EF	Igeo	TC
Cu	1.921	0.357	1.380	1.095	0.408	1.087
Pb	3.214	1.100	1.432	0.862	0.063	1.430
Zn	1.764	0.235	2.740	1.137	0.462	1.470
Ni	1.195	−0.327	1.968	0.603	−0.452	1.854
Cd	1.043	−0.524	1.042	0.286	0.522	1.000
Cr	1.000	−0.585	0.045	1.000	0.276	7.608

Table 2 Heavy metal concentration (mg kg^{-1}) in soil samples

Sample site	Cu	Pb	Zn	Cr	Ni	Cd
Airport	4.78 ± 0.02	17.90 ± 0.01	21.73 ± 0.01	0.03 ± 0.00	0.80 ± 0.00	0.07 ± 0.01
Control	2.48 ± 0.01	5.56 ± 0.01	12.31 ± 0.01	0.03 ± 0.00	0.66 ± 0.00	0.06 ± 0.01
LSD	NS	NS	7.553	NS	NS	NS
Dzorwulu	7.40 ± 0.01	24.02 ± 0.45	43.12 ± 0.63	0.06 ± 0.01	0.78 ± 0.08	0.05 ± 0.01
Control	3.71 ± 0.03	15.33 ± 0.83	20.86 ± 0.62	0.03 ± 0.01	0.71 ± 0.06	0.02 ± 0.01
LSD	0.686	8.878	12.41	NS	NS	NS

Table 4 Heavy metal concentrations (mg kg^{-1}) in lettuce from vegetable farms in Accra

Sample site	Cu	Pb	Zn	Cr	Ni	Cd
Airport	6.60 ± 0.27	25.65 ± 0.27	59.55 ± 0.10	0.70 ± 0.01	1.57 ± 0.21	0.07 ± 0.02
Dzorwulu	8.05 ± 0.03	34.37 ± 0.12	63.39 ± 0.10	0.52 ± 0.01	1.45 ± 0.06	0.05 ± 0.03
LSD	NS	0.432	1.668	NS	0.107	NS
FAO/WHO STD	0.10	0.10	0.10	0.20	0.10	0.02

farm site were in the order of Pb > Cu > Zn > Cr > Cd > Ni. However, the Dzorwulu soil samples recorded no significant pollution for all the metals that were considered for this work.

Heavy metals in lettuce

The lettuce from both farms showed an uptake of all the heavy metals investigated, with Zn recording the highest concentrations of 59.55 ± 0.10 and 63.39 ± 0.10 mg kg^{-1} for Airport and Dzorwulu samples, respectively (Table 4). Levels of heavy metals were in the order of Zn > Pb > Cu > Ni > Cr > Cd at both study sites. Comparing the metal content of lettuce from the two sites, it was observed that the differences between Pb, Zn and Ni were significant ($p < 0.05$). Mean concentrations of metals in the lettuce were higher than the FAO/WHO guideline values of 0.2 mg kg^{-1} for Cr, 0.1 mg kg^{-1} for Pb, 0.10 mg kg^{-1} for Cu, 0.1 mg kg^{-1} for Zn, 0.1 mg kg^{-1} for Ni and 0.02 mg kg^{-1} for Cd (Codex 1995). Prolong consumption of these lettuces which have accumulated high levels of toxic metal such as Pb and Cd could be hazardous.

The soil–plant transfer coefficient (SPT) of all the metals was calculated by dividing the concentration of the metal in a vegetable crop by the metal concentration in the soil using the expression;

$$SPT = \frac{C_p}{C_s},$$

where C_p is the concentration of metals in plants and C_s is the concentration of the metals in corresponding soil.

The transfer of heavy metals from the soil to the lettuce at Dzorwulu site was in the order of Cr > Ni > Pb > Zn > Cu > Cd whereas that for the Airport farm was in the order Zn > Ni > Pb > Cu > Cd > Cr (Table 3). Lettuce samples from Airport farm site had higher transfer coefficient values than lettuce samples from Dzorwulu. This indicates that the metals in the soil from Airport farm area are more bioavailable than those in the soil samples from the Dzorwulu farm site.

The transfer coefficients calculated for all the metals considered at the Dzorwulu farm site were greater than 1, indicating high levels of accumulation of metals in the plant (Alloway and Ayres 1997). The transfer coefficient of heavy metals from soil to plant is an essential indicator that allows the assessment of mobility of heavy metals in soil and the danger of metal translocation to their edible parts. Higher transfer coefficients reflect relatively poor retention in soils or greater efficiency of plants to absorb metals (Alloway and Ayres 1997). High bioaccumulation potential of the plant was observed from the fact that the concentrations of all the metals in the plant were higher than the corresponding soil samples.

Table 5 Correlation coefficients between heavy metal contents in soil and lettuce at both sites

Simple correlations heavy metals	Correlation coefficient values
Cd	0.158
Cr	−0.310
Cu	0.929
Ni	−0.130
Pb	0.918
Zn	0.996

There was positive correlation between the soil and lettuce contents for Zn, Cu, Pb and Cd at both sites which is an indication that there was metal uptake by the lettuce sample from the soil (Table 5). Negative correlation was observed for Cr and Cd at both sites. The soil samples in the study area were poorly enriched with these metals, and therefore their bioavailability was low. Metal uptake by plants can be affected by several factors including metal concentration in soils, soil pH, CEC, organic matter content, type and variety of plant. The physico-chemical properties recorded for these soil samples did not favour metal uptake by plants, and therefore the high concentration of the metals in the plant may be due to the plant's high potential to absorb and retain the metal in their tissues.

Conclusion

Using a variety of pollution indices (enrichment factor, geo-accumulation index and Transfer coefficient), the extent of anthropogenic impact of heavy metals in wastewater use for irrigation and in lettuce produced has been evaluated. The study revealed appreciable levels of heavy metal concentration in the soil and the lettuce samples from the study sites. Generally, there was evidence of significant pollution in the soil with heavy metals such as Cu, Zn and Pb. All the metals analysed on the lettuce showed levels which were above the FAO/WHO recommended levels. Therefore, prolong consumption of this lettuce with high levels of Cd and Pb which are of public health concern can be worrisome. Thus, the use of untreated wastewater for irrigation even though pose little challenges on the properties of the soil, it rather leads to high accumulation of heavy metals in lettuce grown on such soils and pose serious chronic health risk on consumers. All the metals analysed in the plant recorded soil–plant transfer coefficient >1.

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