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Cadmium (Cd) and Lead (Pb) Concentrations Effects on Yields of Some Vegetables Due to Uptake from Irrigation Water in Ghana

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Abstract: Heavy metal contamination of agricultural soils from wastewater irrigation is of serious concern since it has implications on human health. Systemic health problems can develop as a result of excessive accumulation of dietary heavy metals such as cadmium (Cd), lead (Pb) and chromium (Cr) in the human body. A study was carried out at the Kwame Nkrumah University of Science and Technology (KNUST) campus in Ghana using water to which Cd and Pb had been added to irrigate cabbage, carrots and lettuce. Cadmium and Pb solutions of concentrations 0, 0.05 and 0.1 mg L^{-1} and 0, 30 and 50 mg L^{-1}, respectively were formulated and used to irrigate the crops. Plant and soil samples from the experimental fields were collected for laboratory analysis. Results showed reduction in yields of lettuce from the treatments. Cadmium treatment of lettuce with 0.05 mg L^{-1} concentration of irrigation water reduced yield by 11% whilst 0.1 mg L^{-1} Cd concentration of irrigation water treated lettuce yield reduced by 16%. However, there were increases of 61 and 53%, respectively in yields of carrots irrigated with water containing 0.05 and 0.1 mg L^{-1} Cd in comparison with carrots irrigated with water containing 0 mg L^{-1}. Yields of crops irrigated with irrigation water containing Pb concentrations of 30 and 50 mg L^{-1} were reduced compared with yields from the control plots. Plant Cd and Pb concentrations increased with irrigation water concentrations significantly with p-value of Cd <0.0001 and for Pb <0.05. Cadmium concentrations for cabbage were between 0.09 and 1.11 mg kg^{-1} whilst carrots and lettuce had values between 0.04, 1, 0.12 and 1.02 mg kg^{-1}, respectively. Lead concentrations in cabbage ranged between 0.18 and 15.2 mg kg^{-1}, for carrots and lettuce they were 0.43 to 6.24 mg kg^{-1} and 1.41 to 187 mg kg^{-1}, respectively.

Key words: Cadmium, lead, uptake, irrigation water, carrots, cabbage, lettuce

INTRODUCTION

According to Nouri (1980) deposition of metals to soil may be deleterious to crop growth and soil productivity and may also produce crops containing unacceptably high metal levels for animal and

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human health. The uptake of heavy metals and their distribution in crops differ among species and among cultivars within particular species. Variation of Cd uptake by cultivars has been reported of, for example, potato (McLaughlin *et al*., 1994), wheat (Chaudri *et al*., 2001; Oliver *et al*., 1995), maize (Florijn and van Beusichem, 1993) and spinach and carrots (He and Singh, 1994). Heavy metal contamination of agricultural soils from wastewater irrigation is also of serious concern as a result of human health implications (Hough *et al*., 2003; Mensah *et al*., 2007; Sipitey, 2007). Serious systemic health problems can develop as a result of excessive accumulation of dietary heavy metals such as cadmium (Cd), lead (Pb) and chromium (Cr) in the human body (Oliver, 1997). Heavy metals are not degradable; hence, they can accumulate to toxic levels in soils due to long term application and in the body of consumers of produce from such soils (Bohn *et al*., 1985). Produce from contaminated soils or irrigation water application has a higher probability of increasing the metal concentration to high levels, beyond the permissible level for human consumption. Metals, in ionic form in soil solution, get to the roots of plants by mass flow (transpiration flux) and diffusion (Marschner, 1995). Root solute uptake is coupled with the root water uptake (Ingwersen, 2001). Accordingly, the root metal uptake may depend on the water uptake rate even when active uptake is dominant. The use of industrial and municipal wastewater for vegetable production is a common practice in many parts of the world (Feigin *et al*., 1991; Urie, 1986), particularly in developing countries including Ghana (Cornish *et al*., 1999). Access to adequate high quality water for irrigation in the urban/peri-urban communities of Ghana has been a major concern (Cornish *et al*., 1999). About 80-90% of vegetables consumed by the people in the urban communities are produced in the urban/ peri-urban areas where high quality water may not be accessible. Where accessible, the high cost of irrigation water makes its use prohibitive. Growers of vegetables therefore use wastewater from drains that receive effluents from all sources and other urban polluted water bodies. A few of them use hand-dug wells if the water table is high. Irrigation of crops is by the use of watering cans and the method is either broadcasting or planting bed specific with an application rate that could be about 25-30 L m^{-2} for a single application.

In Ghana, there has been limited study of metal uptake by crops and there has not been any study on metal uptake by vegetables from irrigation water due to transpiration. This study was carried out at the Kwame Nkrumah University of Science and Technology (KNUST) campus using water to which Cd and Pb had been added to irrigate cabbage, carrots and lettuce. The objectives of the study were to determine (1) whether or not plant Cd and Pb concentrations increased with increase of their concentrations in irrigation water, (2) changes of plant Cd and Pb concentrations as the plants grew and (3) Cd and Pb concentration effects on cabbage, carrots and lettuce yields.

MATERIALS AND METHODS

Experimental Field

Experimental mini plots of 1.8×1.8 m were set up on an experimental field at KNUST agricultural experimental land with grass vegetation from May to September 2005. Cabbage, carrots and lettuce were grown in three replicates on the plots. Cadmium and Pb solutions of 0, 0.05 and 0.1 mg L^{-1} and 0, 30 and 50 mg L^{-1}, respectively, were formulated and used to irrigate the crops. Cadmium and lead nitrate salts were added to 200 L capacity containers filled to the 200 L mark with treated water from the main supply and stirred to obtain the predetermined Cd and Pb solution concentrations and a sample tested to confirm the predetermined concentrations.

The crops were irrigated each other day using 11 L of the solution per plot per irrigation. A plastic watering can was used to avoid introduction of additional metal which would have been the case if a galvanized container had been used. Treatment with Cd and Pb solutions started on the day of transplantation of the seedlings of cabbage and lettuce.

Sample Collection

Plant samples were collected at three different growth stages during the plants' growth which was divided almost into three equal segments. Lettuce samples were collected after 20, 40 and 55 days whilst cabbage and carrot samples were collected 40, 70 and 100 days after transplantation and sowing. The plant samples were washed with distilled water, chopped into pieces on a washed and rinsed kitchen chopping board with distilled water rinsed kitchen knife to an average size of 2 cm^2, sun-dried for about 6 h before oven-drying at 80°C for about 20 h. The dried samples were milled to <1 mm particle size.

Analysis of Samples

The plant samples were digested using EPA Method 3052 (USEPA, 1996). Nine millilter of HNO_3 and 2 mL of HCl were added to 0.25 g of plant sample in a Teflon tube. The content of the Teflon tube was digested using MRS 200 microwave digester. The samples were left in the microwave after digestion until the temperature reduced to about 30°C. The digested sample in a solution form was poured into a 15 mL centrifuge tube. One millilter of the digested sample was diluted in a ratio of 1:4 using deionized water in a 15 mL centrifuge tube before analyzing it for Cd and Pb with an Agilent 7500 ICP-MS. A standard reference material 1573a of tomato leaves certified by National Institute of Standards and Technology (NIST) was also digested and analyzed for Cd as a quality assurance control.

Data generated were analyzed statistically using the SAS software package to establish the significance of relationships between the various parameters being considered.

RESULTS

Crop yields were influenced by Cd and Pb concentrations. The yields of lettuce from the Cd treatment plots were on the average 3.26, 2.92 and 2.7 t ha^{-1} for 0, 0.05 and 0.1 mg L^{-1} irrigation water concentrations, respectively. The yields for the plots treated with 0.05 and 0.1 mg L^{-1} of Cd were reduced by 11 and 16%, respectively, of the yield of the control treatments (0 mg L^{-1}). In the case of Pb treatments of lettuce the yields were 4.44, 3.83 and 2.52 t ha^{-1} for 0, 30 and 50 mg L^{-1} irrigation water treatments, respectively. Comparing the yields from 30 and 50 mg L^{-1} irrigation water treatments to that of 0 mg L^{-1} irrigation water, there were reductions of 14 and 43%, respectively.

Carrots responded differently to Cd and Pb in the irrigation water. Plots with carrots irrigated with Cd solutions yielded 3.98, 10.18 and 8.54 t ha^{-1} for 0, 0.05 and 0.1 mg L^{-1} concentration treatment plots, respectively. A comparison of the yields from 0.05 and 0.1 mg L^{-1} treatment plots with those from 0 mg L^{-1} plots showed increases of 61 and 53%, respectively. Yields from Pb irrigated carrot plots were 6.86, 4.86 and 6.05 t ha^{-1} for 0, 30 and 50 mg L^{-1} irrigation water treatments, respectively. There were reductions of 29 and 12%, respectively, comparing yields from 30 and 50 mg L^{-1} irrigation water treatments with yields from 0 mg L^{-1} irrigation water treatments.

Plant Cd and Pb concentrations increased with irrigation water concentrations. The increase was significant with p-value for Cd less than 0.001 and for Pb less than 0.05. The increases were however not linear. Plant metal concentration varied with the type of crop (Table 1).

Cadmium concentrations for cabbage were between 0.09 and 1.11 mg kg^{-1} whilst carrots and lettuce had values of 0.04 to 1.0 and 0.12 to 1.02 mg kg^{-1}, respectively. Lead concentrations in cabbage ranged between 0.18 and 15.2 mg kg^{-1} and for carrots and lettuce they were 0.43 to 6.24 and 1.41 to 187.4 mg kg^{-1}, respectively. Cadmium and Pb concentrations in lettuce were the highest among the three crops.

Cadmium and Pb concentrations of the first set of harvested cabbage samples were very high. This might be due to the fact that the samples were leaves and not cubs, the edible part because at the time of the first sampling the head had not formed.

Table 1: Relationship between cadmium (Cd) and lead (Pb) concentrations in cabbage, carrots and lettuce crops and irrigation water (IW)

Crop	Days	IW conc. ($mg\ L^{-1}$)	Av crop Cd conc. ($mg\ kg^{-1}$ dry wt.)	IW conc. ($mg\ L^{-1}$)	Av crop Pb conc. ($mg\ kg^{-1}$ dry wt.)
Cabbage	40	0.00	0.249 (0.125)*	0	0.601 (0.095)*
		0.05	0.542 (0.284)*	30	11.76 (3.98)*
		0.10	0.961 (0.215)*	50	15.22 (5.82)*
	70	0.00	0.093 (0.024)*	0	0.183 (0.015)*
		0.05	0.389 (0.067)*	30	0.367 (0.093)*
		0.10	0.592 (0.142)*	50	0.499 (0.082)*
	100	0.00	0.344 (0.185)*	0	0.216 (0.125)*
		0.05	0.85 (0.219)*	30	0.874 (0.185)*
		0.10	1.11 (0.328)*	50	0.945 (0.426)*
Carrots	40	0.00	0.062 (0.021)*	0	0.557 (0.298)*
		0.05	1.038 (0.334)*	30	3.22 (0.912)*
		0.10	0.732 (0.295)*	50	6.07 (1.09)*
	70	0.00	0.432 (0.041)*	0	0.73 (0.262)*
		0.05	0.701 (0.168)*	30	2.61 (0.656)*
		0.10	0.898 (0.688)*	50	4.32 (1.17)*
	100	0.00	0.181 (0.029)*	0	0.427 (0.18)*
		0.05	0.997 (0.208)*	30	4.54 (1.23)*
		0.10	0.799 (0.298)*	50	6.24 (2.64)*
Lettuce	20	0.00	0.263 (0.082)*	0	1.41 (0.563)*
		0.05	0.602 (0.238)*	30	21.80 (4.45)*
		0.10	0.549 (0.181)*	50	21.90 (3.62)*
	40	0.00	0.241 (0.092)*	0	1.62 (0.827)*
		0.05	1.00 (0.843)*	30	79.20 (24.9)*
		0.10	0.534 (0.101)*	50	82.40 (22.90)*
	55	0.00	0.121 (0.053)*	0	2.25 (0.812)*
		0.05	0.968 (0.392)*	30	133.60 (44.6)*
		0.10	1.022 (0.311)*	50	187.40 (39.9)*

( )*: Standard deviation values in parenthesis

From the data in Table 1 there were no systematic increases with time of Cd concentrations for any of the crops. However, Pb concentrations in lettuce increased consistently during the period of growth with time and irrigation water concentration.

Plant Cd and Pb uptake rates of the three crops, in mg day^{-1}, increased with irrigation water concentrations by a trend similar to those of plant and irrigation water concentrations relationships (Fig. 1a, b).

For both Cd and Pb, lettuce had the highest concentration values. Also Cd and Pb concentrations in all plants increased with time. Those of lettuce were significant. Langmuir model equation for metal uptake in plants was fitted to data points to show the trend of plant Cd and Pb concentrations as the irrigation water concentration varies.

The Langmuir equation is shown in Eq. 1

$$C_{plant} = \frac{K \times Cw}{(1 + n \times K \times Cw)} \quad (1)$$

Where:

C_{plant} = Plant metal concentration ($mg\ kg^{-1}$)
C_W = Irrigation water metal concentration ($mg\ L^{-1}$)
K and n = Constants

Plant Cd and Pb concentrations of the three crops using the Langmuir equation gave a correlation coefficient of 0.999 when related to measured values and a RMSE range of 0.054-0.25 for Cd and 0.11-1.30 for Pb.

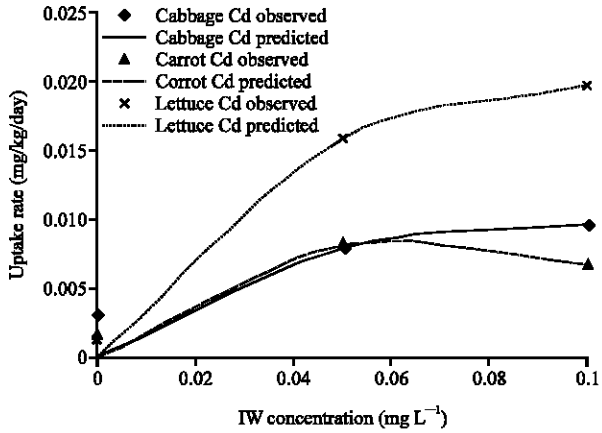

Fig. 1a: Plant Cd uptake rate (mg/kg/day) and irrigation water concentration (mg L^{-1}) relationship for measured and predicted

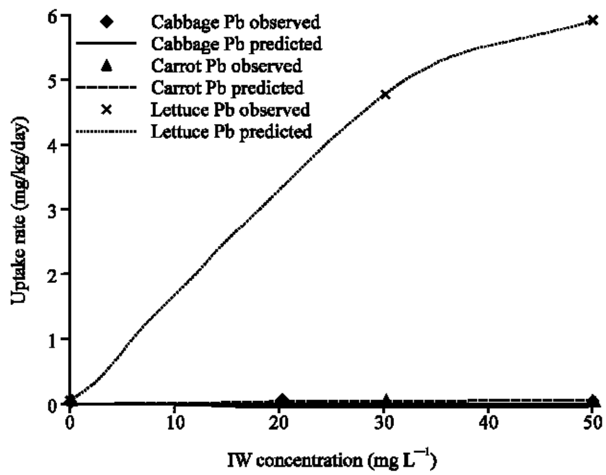

Fig. 1b: Plant Pb uptake rate (mg/kg/day) and irrigation water concentration (mg L^{-1}) relationship for measured and predicted values

DISCUSSION

Crop yield was affected by irrigation water concentration of Cd and Pb. For lettuce there were reductions for both Cd and Pb treatments with increase in concentrations of Cd and Pb in irrigation water. Yields from 0.05 mg L^{-1} Cd treatments concentration reduced by 10.7% of the control (0 mg L^{-1}) whilst treatment with 0.1 mg L^{-1} Cd concentration reduced by 16.4%. For Pb the yield was reduced from that of the control by 13.7 and 43.2% for 30 and 50 mg L^{-1}, respectively. Reduction in yield with Cd and Pb treatments may be as a result of exposure to metals in the irrigation water by passive means of transpiration that creates a potential force to draw water of less nutrient and high Cd and Pb content. The Cd and Pb in the irrigation water compete with plant metal macro and micro nutrients like Ca and Mg required by plants for healthy growth, thus creating nutritional imbalance (Nouri *et al*., 2001). For example, at a dose of 20 mg L^{-1} there was 63% reduction in size of alfalfa shoot size and a lethal effect on the plant at a dose of 40 mg L^{-1}. Öncel *et al*. (2000) found that Cd reduces the level of chlorophyll a and b.

In the results the yield of Cd treated carrots showed a different trend compared with lettuce. Yields from 0.05 and 0.1 mg L^{-1} treated plots increased by 60.9 and 53.3%, respectively, as compared with yields from 0 mg L^{-1} treated plots. This may be ascribed to Cd forming soluble complexes with some soil constituents that were taken up by carrots as nutrients on those plots (Oliver and Naidu, 2003).

Cadmium and Pb concentrations of cabbage, carrots and lettuce increased with Cd and Pb concentrations in irrigation water. Root solute uptake is coupled with the root water uptake (Ingwersen and Streck, 2005) in support of present results. The root solute uptake may depend on the water uptake rate even when active uptake is dominant. During periods of high temperatures there is the likelihood of high decomposition rate of organic matter taking place leading to the release of heavy metals in soil solution to make them mobile or available for uptake by plants (McGrath *et al*., 1994). There is also an increase of saturation deficit at high temperatures. Average maximum daytime temperature during the period of the experiment at the experimental location was about 32°C and relative humidity in the day was around 40-60% although the period was supposed to be the major rainy season. The crops' Cd and Pb concentrations were found to be high and the values are comparable with results obtained from a study on wastewater irrigation of crops in India by Singh *et al*. (2004). Higher Cd and Pb concentrations in the crops found in the present study may therefore be ascribed to high transpiration rates. Marschner (1995) reported from a study of Cd uptake by crops that crop Cd uptake was by mass flow with the transpiration flux. The crops' Cd and Pb concentrations determined in this study are comparable to those in similar studies carried out in Ethiopia (Rahlenbeck *et al*., 1999) and India (Singh *et al*., 2004).

Root solute uptake is assumed to be linearly proportional to the product of soil solution concentration and water uptake (Christensen and Tjell, 1984; Behrendt *et al*., 1995; Trapp, 2000; Schoups and Hopmans, 2002; Grant *et al*., 1998). This may be a reason for the crops (cabbage, carrots and lettuce) Cd and Pb concentrations increasing with the concentrations of the irrigation water as shown in Fig. 1.

Cadmium and Pb concentrations of the cabbage, carrots and lettuce increased as the plants grew as shown in Table 1. Plant metal content varies with time of harvesting and stage of maturity (Sauerbeck, 1991). This was confirmed by the results of a study on barley plants by Nouri *et al*. (2001) and on maize by Chrysafopoulou *et al*. (2005). However the magnitude of time dependence of plant Cd and Pb concentration variations differed among crops and metals according to the study.

The uptake and distribution of metals in crops differs among species and cultivars within a species (Ingwersen and Streck, 2005). Lettuce had the highest Cd and Pb concentrations amongst the three crops tested in this study, confirming Cd concentration in lettuce as reported by other researchers (Petterson, 1997) and from studies on crops like carrots and spinach (He and Singh, 1994). Sauerbeck (1991) indicated that when plants are young mineral absorption is relatively rapid and dry matter production is rather slow. But later when large and active photosynthetic areas are being formed, dry matter production may outstrip absorption of mineral elements, leading to a reduction in their level. During this time there is also a redistribution of elements within the plant and variation between and within different organs may be quite large (Moreno, 1996). Lead is usually accumulated in the roots and only a very small amount is accumulated in the shoots. However some plants translocate Pb effectively to shoots without chelators that aid Pb translocation from roots (Chrysafopoulou *et al*., 2005). High Pb concentrations in lettuce showed the probability of lettuce being one of such plants that effectively translocate Pb from roots to shoots. High Pb concentrations in plants may be an indication of metal uptake from irrigation water by transpiration since Pb concentrations in plants do not exceed 10 mg kg^{-1} with the exception of leafy plants such as lettuce (Kabata-Pendias and Pendias, 1986).

CONCLUSION

Irrigation water quality is essential to ensure the quality of the produce for which the water is used. The use of irrigation water of high metal concentration leads to increase of plant metal concentration and as the water concentration of the metal increased there was also an increase in plant concentration. Plant Cd and Pb concentrations showed increases with time. Cadmium concentrations in lettuce increased by 66% for a period of 20 days that of carrots increased by 42% and for cabbage the increase was 118% for 40 days. Lead concentrations in lettuce increased by 130% for the same number of days as Cd. For carrots Pb concentration increased by 44% and Pb concentration in cabbage increased by 89% for 40 days. However the amount of metal increment depended on the stage of plant maturity.

Irrigation water containing elevated metal concentration generally reduced the yield of crops. Crop yield reduction by the effect of Cd ranged between 10.2 and 16.4% whilst reduction of crop yield by Pb was between 13.7 and 43.2%, depending on the irrigation water concentration. Thus, the Cd and Pb concentrations of irrigation water negatively affect food security.

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