J. Agr. Sci. Tech. (2013) Vol. 15: 357-368

Response of Corn to Cadmium and Drought Stress and Its Potential Use for Phytoremediation

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ABSTRACT

In the present study, the effects of different cadmium (Cd) levels of irrigation water (0, 5, 10 and 20 mg L^{-1}) on corn plants (foliage) under different irrigation intervals (1, 3, and 7 days) were investigated. Clear Cd toxicity symptoms appeared on the plants at the end of the experiment. The results showed that stem dry weight (DW) followed by transpiration (T) and plant height were the measured plant parameters most sensitive to increasing Cd levels of irrigation water. In addition, Cd reduced water uptake by corn and led to more soil moisture. The results also demonstrated that corn might produce more shoot biomass with Cd application, which should be taken into consideration if no visible symptoms of Cd toxicity and considerable amounts of the metal uptake are present. Cadmium application through irrigation did not show a marked impairment in the nutrient status of the plants. Moreover, accumulation of Cd in the leaves was more than the stems by 24, 56, and 27% at 1, 3, and 7-day irrigation frequencies, respectively. Also, corn stem was found to be more sensitive to Cd than leaf. The results showed that corn might be used for phytoremediation of Cd under optimum moisture conditions and light contamination of the soil. Furthermore, shoot Cd concentration followed an asymptote pattern as a function of soil Cd, which was expressed by a plateau-type model under each irrigation interval.

Keyword: Cadmium, Corn, Drought, Phytoremediation, Stress.

INTRODUCTION

Water availability for irrigation has become a major issue for agriculture in arid regions. Consequently, wastewater reuse has attracted public attention as an alternative water source. There are numerous reports on the application of wastewater to agronomic crops, rangelands, forests, and recreation areas in the literature. Land application of wastewater also has the advantage of recycling nutrients and organic matter and protecting fresh water resources owing to a reduction in the discharge of wastewater (Saucedo *et al*., 2005). However, the uncontrolled use of wastewater in agriculture has potential health implications for consumers. Studies have documented adverse animal and human health effects resulting from the use of untreated or inadequately treated wastewater in agriculture. Also, the effluent of wastewater treatment plants generally contains high levels of microorganisms and various heavy metals (Grifferty and Barrington, 2000; Toze, 2006). A principle drawback of irrigation with treated wastewater is the potential heavy metal accumulation in soil and feedstuff which may cause health risks both to animals and humans (Dikinya and Areola, 2010).

Cadmium is a heavy metal whose presence in the environment is of great concern, because of its toxicity to living

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[DOR: 20.1001.1.16807073.2013.15.2.11.0]

organs. Cadmium inhibits the plant root and shoot growth and yield production, affects plant nutrients uptake and homeostasis and reduces its water uptake (Rascio *et al*., 1993). This unwarranted plant element is taken up by roots and translocated to aerial organs of feed/food crops, entering the food chain with a significant potential to impair animal and human health (di Toppi and Gbrielli, 1999; Tyler and McBride, 1982). Corn is an important food and feed crop, capable of accumulating Cd in its shoot (Walker *et al*., 1977 and Sameni *et al*., 1987). Corn has potential in phytoremediation, whereby metal accumulating plants are used to remove toxic metals from soil and water (Chaney *et al*., 1998). In the present study, the response (agronomic behavior and chemical composition) of the plant to different Cd levels of irrigation water under water stress conditions and its potential for Cd phytoremediation were investigated. Shoot tissue Cd concentration model was also studied.

MATERIALS AND METHODS

A bulk sample of the top layer (0-20 cm) of a calcareous silty clay soil (fine, mixed, mesic, Typic calcixerepts) was collected from an uncultivated field at Bajgah Agricultural Experiment Station, 16 km north of Shiraz, Fars Province, I. R. of Iran. The soil was then air-dried and passed through a 2 mm sieve (some of its physico-chemical properties are shown in Table 1). The soil was mixed uniformly with 150 mg N kg^{-1} as urea, 50 mg P kg^{-1} as KH_2PO_4, 5 mg Fe kg^{-1} as Fe-EDDHA and 5, 10 and 5 mg kg^{-1} Zn, Mn and Cu, respectively as their sulfate salt. The pots were filled with 6 kg of treated soil. The Van Genuchten Model (Van Genuchten, 1980) for soil moisture retention curve was determined using hanging water column and pressure plates apparatus in order to convert the soil moisture to the corresponding matric potential.

Table 1. Physico-chemical characteristics of soil used in this study.

Soil properties	Amount/type
Sand (%)	14.1±0.50[a]
Clay (%)	40.4±0.21
Texture	Silty clay
Field capacity (dry weight basis, %)	21.64±0.55
Bulk density (Mg m^{-3})	1.42±0.11
OM (%)	1.1±0.05
Soil pH (paste)	7.84±0.21
CEC (cmole kg^{-1})	14.1±0.50
EC_e (dS m^{-1})	0.50±0.11
Background Cd (mg kg^{-1})[b]	0.31±0.09

[a] Mean±SD (n= 3), [b] DTPA extractable.

The seeds of corn (*Zea mays* L., *cv* single cross 704) were planted in pots in a glasshouse under natural light with average day and night temperatures of 36° and 11°C, respectively. Each pot was irrigated with distilled water to near field capacity by weight, for 15 days after planting. Then, corn was thinned to 3 plants per pot and irrigated with different Cd concentration at 1, 3, and 7 day intervals (common intervals for investigation of the moisture treatments (wet to dry) on corn plant under glasshouse conditions in the study area). Irrigation was done by raising the soil moisture to near field capacity by weight. The amounts of applied water were regarded as representative of evapotranspiration (ET), since no water was lost by drainage. The Cd levels of irrigation water were 0, 5, 10 and 20 mg L^{-1}, obtained by adding $CdCl_2.H_2O$ to the distilled water. These levels were selected to represent reasonable amounts of Cd in raw wastewater (according to Shayegan and Afshari (2004), the maximum Cd in raw wastewater reported in Iran is 0.75 mg l^{-1}) and to insure that considerable amounts of applied Cd remained available for plant uptake. The experimental design was completely randomized design with three replications. In order to measure evaporation, pots without plants were used in each treatment. Irrigation and Cd treatments were continued for 75 days after planting.

At harvest (plants were harvested as fodder), the above-ground sections of the plants were cut at the soil surface and separated to stem and leaf. The harvested plant materials were washed with tap and then with distilled water, dried to a constant weight at 65°C, weighed and ground with an electric mill to pass a 40-mesh screen. Representative samples were dry-ashed at 550°C for 4 hours, extracted with 2M HCl, filtered through Whatman No. 42 filter paper and analyzed for Cd, iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) by an atomic absorption spectrophotometer (model Perkin Elmer 4110), potassium (K) by flame photometer (model Ciba-Corning 400) and phosphorous (P) by using the blue ammonium-molybdate method with spectrophotometer (model Jenway 6405 UV/Visible) at 880 nm.

The total transpiration (T) was obtained by cumulative applied water minus cumulative evaporation. Water use efficiency (WUE) was calculated as the ratio of shoot dry weight (DW) to total volume of *ET*:

$$WUE = \frac{DW(g)}{ET(l)} \qquad (1)$$

The efficiency of the plant parts for phytoremediation was evaluated by means of bioconcentration factor or *BCF*; the ratio of Cd concentration (*C*) in plant to Cd concentration in the soil as:

$$BCF = \frac{C_{Plant}}{C_{Soil}} \qquad (2)$$

In addition, the translocation of Cd within the plants shoots was investigated by calculating the translocation factor (TF) as:

$$TF = \frac{BCF_{Shoot}}{BCF_{Root}} \qquad (3)$$

Moreover, cadmium uptake was calculated by multiplying stem and leaf DW and their Cd concentrations. Hence, the apparent Cd recovery, i.e.:

$$apparent\ Cd\ recovery(\%) = \frac{(Cd\ uptake)_T - (Cd\ uptake)_C}{(Soil\ accumulated\ Cd)_T} \times 100 \qquad (4)$$

was used to the relative efficiency of the crop for Cd removal from soil. In equation 4, *T* and *C* refer to different treatments and the control, respectively.

The collected data were subjected to analysis of variance (ANOVA) for the main and combined effects of irrigation intervals (I) and Cd levels of irrigation water (Cd) by using MSTATC software. Duncan's Multiple Range Test was used to compare the means where *F*-value indicated significant difference. A significance level of 0.05 was considered in the statistical analysis of data (ANOVA and means comparison).

RESULTS AND DISCUSSION

Growth

The plants treated with 10 and 20 mg Cd L^{-1} showed symptoms of shoot length reduction and old leaf bleaching, especially at the end of the experiment. The same inhibitory effects of Cd on maize plants grown on culture media were reported by Rascio *et al*. (1993). According to the ANOVA, the *I* and Cd treatments significantly affected all measured growth parameters. Moreover, $I \times Cd$ treatment significantly affected plant height, leaf *DW* and *ET*. All corn growth responses significantly decreased with increasing irrigation interval (Figure 1a-b). Corn had significantly fewer leaf numbers, lower height, leaf area, leaf *DW, ET* and T at higher Cd levels (10 and 20 mg L^{-1}) and stem *DW* at the highest Cd treatment (20 mg L^{-1}) relative to the control (Figure 1-c-d). Stem *DW* followed by *T* and plant height were the growth parameters most sensitive to increasing Cd levels of irrigation water up to 20 mg L^{-1} (their reduction were 18%, 16.8%, and 14.5%, respectively). Table 2 shows the interaction effect between *I* and

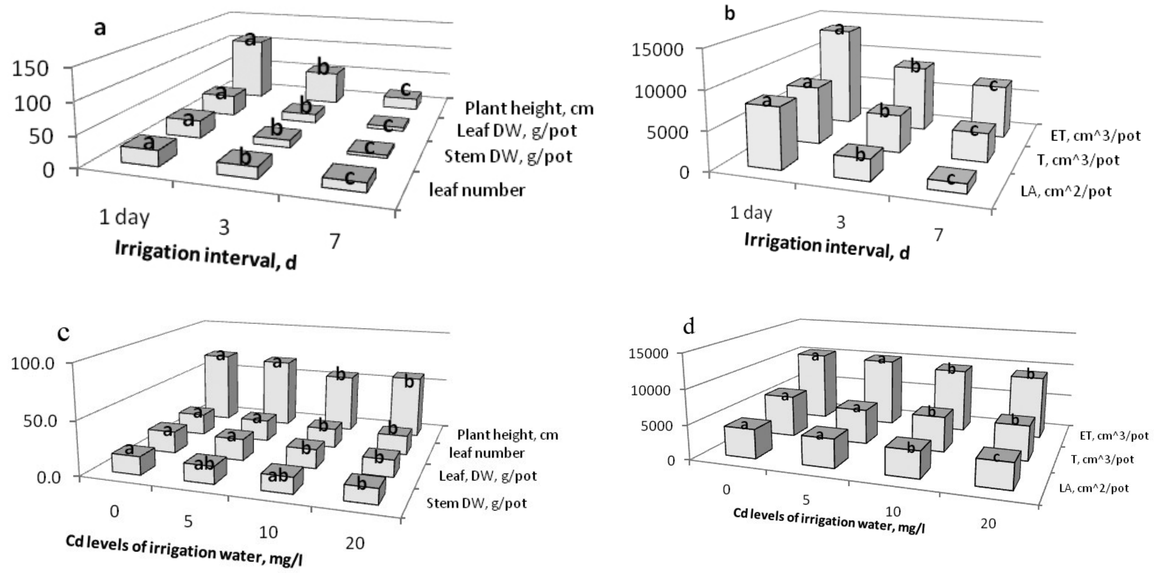

Figure 1. Effect of irrigation interval and irrigation water Cd levels, on corn growth parameters: (a and c) Plant height, leaf number and stem and leaf dry weight (DW), (b and d) Leaf area (LA), transpiration (T) and evapotranspiration (ET). Means within each plant parameter followed by the same letter are not statistically different at $P \leq 0.05$.

Cd treatments on plant height, leaf *DW*, and *ET* of the corn plant. Increasing Cd levels, even up to 20 mg L^{-1}, had no significant effect on these growth parameters under water stress conditions, while at other irrigation regimes a significant reduction occurred with 10 or 20 mg Cd L^{-1}.

The mean matric potentials which the plants experienced in their growing period are summarized in Table 5. As expected, the maximum soil matric potential (i.e. minimum soil water depletion) occurred at the 1-day irrigation interval. Moreover, greater Cd levels resulted in higher soil matric potentials which are compatible with *ET* and *T* rates at each irrigation frequency.

Table 2. Interaction effects of irrigation intervals and Cd levels of irrigation water on corn height, leaf dry weight and ET.

Irrigation interval	Cd level of irrigation water (mg l^{-1})			
(d)	0	5	10	20
		Plant height (cm)		
1	120.0a [a]	116.0a	98.3b	100.0b
3	66.0c	63.0c	48.7d	47.7d
7	20.8e	20.3e	18.5e	17.0e
		Leaf dry weight (g pot^{-1})		
1	36.5a	37.0a	33.1ab	32.1b
3	18.1c	16.7cd	13.4de	9.9ef
7	6.5fg	6.5fg	6.1fg	5.0g
		ET (10^{-3} m^3)		
1	14.56a	13.95a	12.41b	12.59b
3	9.16c	9.11c	8.71c	8.39c
7	7.27d	7.26d	7.01d	6.53d

[a] Means within each plant parameter followed by the same letter are not statistically different at $P \leq 0.05$.

[DOR: 20.1001.1.16807073.2013.15.2.11.0]

In other words, Cd reduced water uptake by corn and led to more remaining moisture of the soil. Barcelo *et al.* (1988) also reported reduced water uptake by Cd-treated bush bean plants. In the present study, Cd levels had no significant effect on the *WUE* (data not shown). In general, corn had greater *WUE* in the 1-day irrigation interval. The plants had slightly higher *WUE* when treated with Cd at 1 and 7-day irrigation frequencies as compared with the control. This means that with a given volume of effluent supply, corn produces more shoot biomass with Cd application. This is important in feed production if no visible symptoms of Cd toxicity appear and plants take up a considerable amount of the metal. There are some evidence in the literature indicating that the growth of plants exposed to low Cd levels might be stimulated (Kirkham, 1978).

Pearson correlation coefficient (r) was used to investigate the linear correlation between all pairs of measured parameters in soil and plant (data not shown). All measured growth parameters showed a significant negative correlation ($P< 0.01$ or 0.05) with leaf K, stem K and P and leaf and stem Zn, Cu and Mn content (with *r* ranging from -0.41 to -0.91).

Chemical Composition

An ANOVA for the main and combined effects of *I* and Cd treatments on chemical composition of corn leaf and stem showed that only Fe and Cd concentrations were not affected by I treatments. In addition, cadmium treatments influenced the leaf Cu, Zn and Cd of corn, while $I\times Cd$ treatments only affected leaf Mn and stem Zn of the corn plant. Figure 2 shows that corn had significantly more leaf and stem P, stem K, and leaf and stem Zn under water stress conditions, while both plant parts had significantly less amounts of Cu and Mn in the 1-day irrigation interval. Moreover, leaf K significantly increased with increasing irrigation frequencies. According to Figure 3, significant increases in leaf Cu, Zn, and Cd were observed at the highest Cd level. Conflicting findings are reported in the literature regarding the effect of Cd on Zn absorption by plants. For example, Sameni *et al.* (1987) reported either increase or decrease in Zn concentration of tomato shoot and no significant change in Zn of corn shoot as a result of increasing soil Cd levels. In contrast to our results for Cu, Wallace *et al.* (1977) indicated that Cd treatment decreased the Cu concentration in corn shoot. Cd-treated plants significantly accumulated more Cd in their leaves than that of the control. The interaction effect of I and Cd treatments on leaf Mn and stem Zn of corn are shown in Table 3. According to Table 3, corn had significantly lower leaf Mn content under optimum soil moisture regime. Furthermore, there was no substantial difference between leaf Mn concentration in the control and Cd-treated plants, a finding which is in agreement with

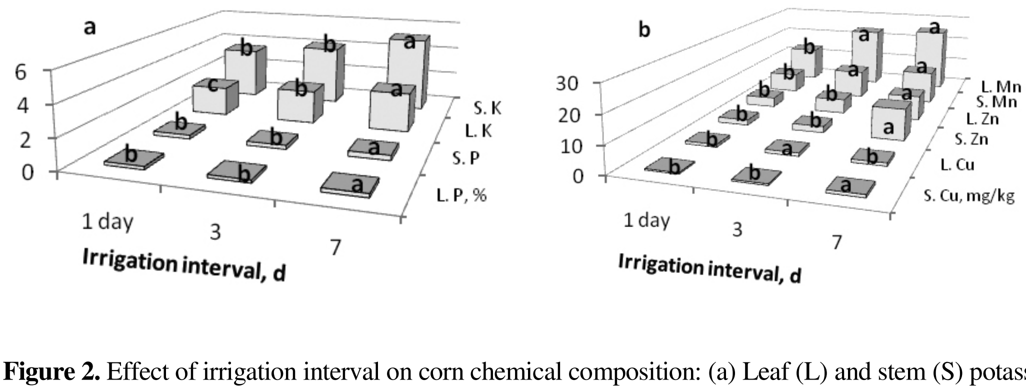

Figure 2. Effect of irrigation interval on corn chemical composition: (a) Leaf (L) and stem (S) potassium (K) and phosphorous (P), (b) L and S copper (Cu), zinc (Zn) and manganese (Mn).
Means within each plant parameter followed by the same letter are not statistically different at $P\leq 0.05$.

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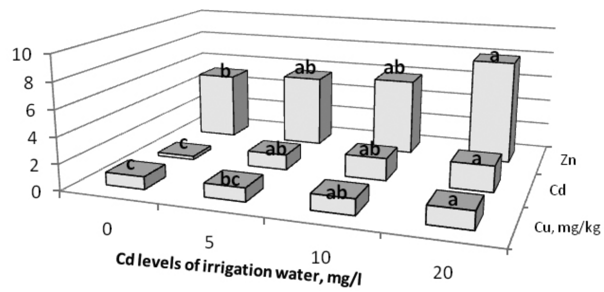

Figure 3. Effect of irrigation water Cd levels on corn Leaf Zn, Cu and Cd concentration. Means within each plant parameter followed by the same letter are not statistically different at $P\leq 0.05$.

those of Castillo-Michel *et al*. (2009) for Mn concentration of corn shoot. Moreover, Zn concentration of corn stems was significantly greater under drought stress conditions.

The Cd concentrations in corn leaf and stem were in the range of 0.9-4.1 and 0.3-4.2 mg kg^{-1} *DW*, respectively. However, leaves potentially accumulated more Cd than stems by 24, 56, and 27% in 1, 3, and 7-day irrigation intervals, respectively, since they had greater BCFs. Moreover, *TF* index (Table 5) was generally >1 showing that large amounts of Cd were transported to, and accumulated in, the leaves. In the present study, the *TF* of Cd was to some extent soil moisture dependent and was higher under the 3-day irrigation interval as compared to the other irrigation regimes. Youn-Joo (2004) reported a *TF*< 1 between corn shoot and root indicating that Cd was accumulated mainly in the roots.

Added soil Cd presented a significant positive correlation with leaf Cd and Cu (P< 0.01) and stem Cd (P< 0.05). Peralta-Videa *et al.* (2002) also reported similar correlation in alfalfa plants. In addition, leaf Cd was positively correlated with the Cu (P< 0.05) and Fe (P< 0.01) in leaves and the Cd in stems (P< 0.01; r= 0.54). A positive correlation was also found between Cd and Fe in the stems. John *et al*. (1972) also found that concentrations of Cd in plants grown on Cd-treated soils had a significant positive correlation with Fe, Zn, and Cu levels in the same plant part.

Cd Toxicity

As noted before, it seems that mature leaf tissues were more sensitive to the toxic

Table 3. Interaction effects of irrigation intervals and Cd levels of irrigation water on leaf Mn and stem Zn of corn.

Irrigation interval (d)	Cd level of irrigation water (mg l^{-1})			
	0	5	10	20
		Leaf Mn (mg kg^{-1})		
1	10.63b [a]	15.57b	13.03b	14.47b
3	24.37a	21.43a	23.03a	25.77a
7	27.20a	23.27a	25.13a	24.83a
		Stem Zn (mg kg^{-1})		
1	0.14d	0.77d	0.76d	6.35bc
3	1.69cd	2.26cd	3.28cd	2.11cd
7	13.22a	11.43a	10.18ab	11.97a

[a] Means within each plant parameter followed by the same letter are not statistically different at $P\leq$ 0.05.

[DOR: 20.1001.1.16807073.2013.15.2.11.0]

effects of Cd than stem tissues. Based on the lines of best fit between yield reduction versus Cd concentration, the water and final soil and shoot Cd concentrations required to reduce leaf and stem dry weight by 10 and 50% were calculated (Table 4). According to the results, corn stem was more sensitive to Cd, as certain growth reduction occurred at a lower Cd concentration. In the present study, the corn stem had more complex behavior than the corn leaf as there was no clear significant relationship between its growth reduction and Cd concentration of water, soil and plant. Corn leaf was more tolerant to Cd at the 1and then the 7-day irrigation interval. Based on the available data, corn stem was also more tolerant to soil and water Cd under water stress conditions. Youn-Joo (2004) observed a median effective concentration value of Cd of corn (the concentration which implies 50% growth reduction, EC_{50}) in Cd-amended soils ranging between 208 and 265 mg kg^{-1}. In our study, in which corn was gradually exposed to Cd, the results are much lower than those reported by Youn-Joo (2004). Sameni *et al*. (1987) reported a 50% reduction in the shoot growth of corn occurring at 171 mg Cd kg^{-1} of soil. They also observed that shoot Cd concentration associated with 50% growth suppression was 29 mg kg^{-1} for corn, which was higher than our findings for leaf and stem.

Potential Use for Phytoremediation

Research is presently focused on low-cost, easy, and safe technologies for solving environmental problems. Phytoremediation is one of these techniques whereby green plants are used to remove or degrade the environmental pollutants such as heavy metals. In the present study, the Cd-phytoremediation potential of corn was evaluated by *BCF* (Equation (2)) and the percentage of recovered Cd (Equation (4)). The *BCF* is an important plant feature in phytoremediation, which implies uptake of pollutants, their mobilization and storage in

Table 4. Water, soil and plant tissue Cd concentrations for 10 and 50 % growth reduction of corn leaf and stem at various irrigation intervals.

Growth reduction	Irrigation interval (d)		
(%)	1	3	7
Leaf			
	Irrigation water Cd concentration (mg l^{-1})		
10	16.00	4.70	10.83
50	73.14	22.09	44.16
	Soil Cd concentration (mg kg^{-1})		
10	37.67	7.24	13.60
50	171.00	30.76	53.60
	Plant Cd concentration (mg kg^{-1})		
10	2.46	- [a]	1.55
50	9.87	-	6.15
Stem			
10	Irrigation water Cd concentration (mg l^{-1})		
50	-	4.42	10.27
	-	21.08	36.93
10	Soil Cd concentration (mg kg^{-1})		
50	-	6.78	11.57
	-	29.00	40.17
10	Plant Cd concentration (mg kg^{-1})		
50	-	-	9.15
	-	-	13.56

[a] In these cases there were no clear relationship between growth reduction and Cd concentration.

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the aerial plant parts (Marchiol *et al*., 2004). The *BCF* values of >1 indicate that plants have a good ability to take up the contaminants from polluted substrate and accumulate them in their above ground tissue. In this study, The *BCF* of both plant parts was < 0.5 (Table 5) indicating that corn did not have a satisfactory ability to take up Cd from the soil. Moreover, the leaf *BCF*s were generally greater, meaning that the potential Cd-accumulation of the leaf was greater than that of the stem. The greatest *BCF* was obtained at the 7-day irrigation interval (Table 5). The lower *BCF* under normal soil moisture conditions was mainly due to greater Cd accumulation in the soil as the result of greater amounts of applied water at the 1-day irrigation interval. Robinson *et al*. (2000) also demonstrated a general decrease in the *BCF* of forest species with increasing soil Cd levels.

The Cd recovery percentages are shown in Figure 4. At a given Cd level, plants generally recovered more Cd at the 1-day irrigation interval than the other two irrigation regimes. This could be attributed to the higher soil matric potential (Table 5) and, consequently, greater water and metal uptake and higher shoot dry weight. Angle *et al.* (2003) observed a greater metal uptake and biomass production at higher soil moisture values. The amounts of Cd recovered in this study are not effective in phytoremediation *per se*. In other words, the recovered Cd was very low even under an optimum soil moisture regime, because of the substantial Cd accumulation in the soil. It seems that most of the Cd applied through irrigation accumulated in the soil and became partially unavailable for plants or concentrated in plant roots. Dikinya and Areola (2010) reported higher soil Cd levels under maize cultivation irrigated with secondary treated waste water relative to the levels in the control sites. This may be due to higher adsorption capacity of Cd to clays (Sanchez *et al*., 1999). From Figure 4, it is also clear that rises in Cd levels decreased the percentage of Cd recovery. It could thus be realistically hypothesized that corn could perform better in the case of light water and consequently soil pollution. In order to artificially enhance Cd uptake, soil amendments might also be used to improve phytoremediation efficiency (Chen and Cutright, 2001; Motesharezadeh *et al*., 2010).

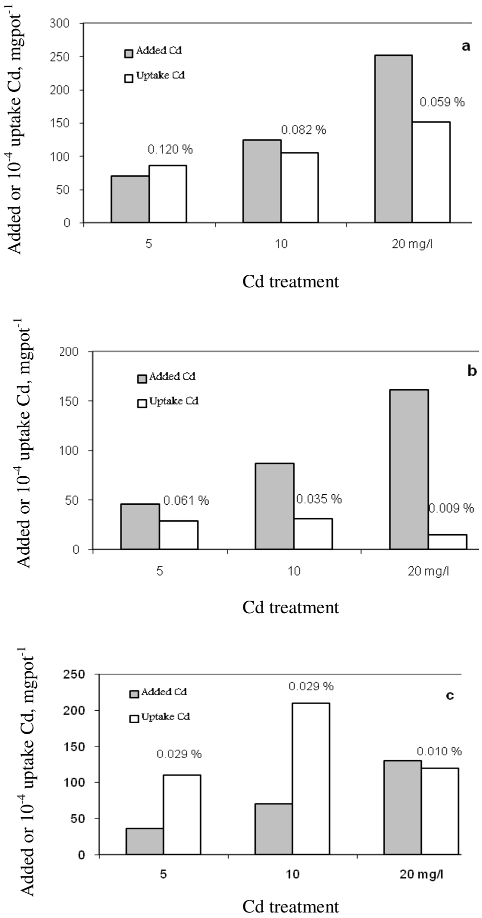

Figure 4. Percentage of recovered, uptake (white bar) and added (gray bar) Cd at various irrigation and Cd treatments, (a) 1-day; (b) 3-day, and (c) 7-day irrigation interval.

Plant Tissue Cd Concentration Model

Plant uptake of heavy metals is a function of plant species, individual trace elements, and soil characteristics. It may follow many

Table 5. Soil matric potentials, Water Use Efficiency (WUE), leaf and stem Bio concentration Factor (BCF) and Translocation Factor (TF) of corn plant at various irrigation intervals and Cd levels of irrigation water.

Irrigation interval (d)	Cd level (mg l^{-1})	Soil matric potential (bar)	WUE (g kg^{-1} water)	BCF		TF
				Leaf	Stem	
	0	-0.40	4.57	-	-	-
1	5	-0.39	4.65	0.10	0.13	0.77
	10	-0.36	4.98	0.11	0.05	2.53
	20	-0.36	4.89	0.07	0.05	1.41
	0	-0.77	3.65	-	-	-
3	5	-0.76	3.39	0.19	0.04	4.40
	10	-0.72	2.77	0.10	0.07	1.37
	20	-0.65	2.24	0.04	0.02	2.43
	0	-3.91	1.58	-	-	-
7	5	-3.91	1.62	0.15	0.17	0.90
	10	-3.36	1.50	0.17	0.15	1.13
	20	-2.66	1.32	0.09	0.04	2.33

different rate response functions including linear, asymptotic, no response, or even negative (Page *et al*., 1987). A hypothesis has been proposed to explain trace element uptake by various crops in which the uptake does not follow a linear trend with trace element application rates, but rather would approach a maximum (plateau) as metal loading increases (Corey *et al*., 1987). We examined the abovementioned models for Cd concentrations in corn shoot as a function of final soil accumulated Cd concentrations under different irrigation regimes. Grifferty and Barrington (2000) pointed out that plant uptake of trace metal could be different under various transpiration regimes. As Figure 5 shows, the cadmium concentration in corn under each irrigation regime exhibited a plateau-type response that could be modeled with the Mitscherlich plateau equation (Logan and Chaney, 1987) as:

$$y = a + b(1 - e^{-cx}) \qquad (5)$$

Where, *y*= Shoot metal concentration (mg kg^{-1}), x= Soil metal concentration (mg kg^{-1}), *a*= *y* intercept or background plant tissue concentration (mg kg^{-1}), *b*= Asymptote

Table 6. The results of Equation (5) fitting into the Cd concentration of corn shoot versus accumulated Cd in the soil, at 1-, 3- and 7-day irrigation intervals.

Irrigation interval (d)	Coefficients			Coefficient of determination (R^2)
	a	b	c	
1	0.2555 [a]	2.7214	0.0397	0.9961
3	0.1599	0.8389	0.4146	0.9322
7	0.1369	1.5480	0.1799	0.8610

[a] *P*-vlaue of determination of all coefficients and regression models were <0.001.

[DOR: 20.1001.1.16807073.2013.15.2.11.0]

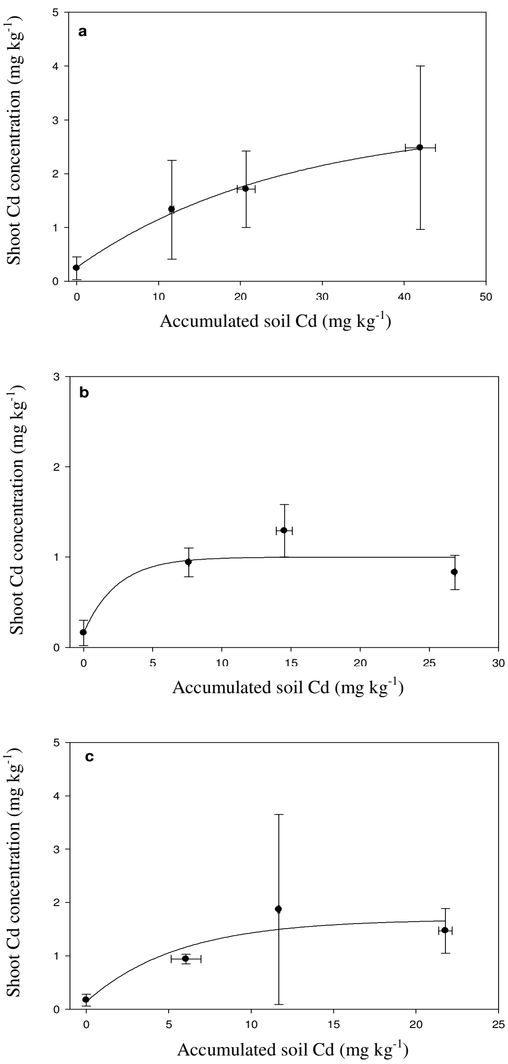

Figure 5. Cadmium concentration in corn shoot in relation to accumulated Cd in the soil: (a) 1-day; (b) 3-day, and (c) 7-day irrigation interval. (Points show Mean±SD of shoot (vertical error bars) and soil (horizontal error bars) Cd).

(plateau) plant tissue concentration (mg kg^{-1}) above background and *c*= Slope of the curve in the region between the asymptote and intercept. The results of the curve fitting are tabulated in Table 6. According to Figure 5 and Table 6, the maximum Cd concentration in corn would be 2.97, 1.00 and 1.68 mg kg^{-1} at the 1-, 3- and 7-day irrigation intervals, respectively. These values might be raised by soil amendments as well as genetic engineering in order to increase the uptake of Cd. Furthermore, Cd accumulation rate (slope of the curve) in corn was greater under the 3-day irrigation frequency than that obtained at other irrigation regimes. Logan *et al*. (1997) also observed a plateau-type response for Cd concentration in corn as a result of increased soil Cd due to sludge application.

CONCLUSIONS

The results of the present study showed that Cd stress induced senescence in corn which was visible on the old leaves. Reduction of growth and water uptake were also observed. However, no substantial nutrient imbalances occurred as a function of Cd application. Cadmium accumulation in leaves was higher than in stems up to a maximum of 56%. Corn leaves were also more tolerant to Cd than stems. Furthermore, shoot Cd concentration followed a plateau-type model with greater potential of Cd accumulation under the 1-day irrigation interval. Although corn plants could recover more added Cd under the 1-day irrigation interval, these amounts do not affirm the potential phytoremediation of maize. Therefore, enhancing the Cd uptake by soil amendments could improve the phytoremediation efficiency. Finally, economical use of cultivated plants for phytoremediation of soils polluted with Cd should be approached with more research and field evaluation.

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واکنش ذرت به تنش کادمیم وخشکی و پتانسیل استفاده از آن برای گیاه پالایی

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چکیده

در این پژوهش اثر سطوح مختلف کادمیم آب آبیاری (صفر، ۵، ۱۰ و ۲۰ میلی گرم در لیتر) بر گیاه ذرت (شاخسار) تحت سه دور مختلف ابیاری (۱، ۳ و۷ روز) بررسی شد. آثار مشخص سمیت کادمیم در پایان آزمایش روی گیاه ظاهر شد. نتایج نشان داد که وزن خشک ساقه و بدنبال آن تعرق و ارتفاع گیاه حساس‌ترین پارامترهای اندازه گیری به افزایش سطوح کادمیم آب آبیاری بودند. بعلاوه کادمیم سبب کاهش جذب آب و رطوبت بیشتر در خاک گردید. نتایج همچنین مؤید این مطلب بود که ذرت در شرایط وجود کادمیم ممکن است زیست توده بیشتری تولید کند که با وجود نبود آثار ظاهری سمیت کادمیم همراه با مقادیر قابل توجه جذب این عنصر، بایستی مورد توجه قرار گیرد. کاربرد کادمیم در آب آبیاری اختلال عمده‌ای در عناصر غذایی گیاه ایجاد نکرد. تمایل به تجمع کادمیم در برگ بیش از ساقه و به ترتیب ۲۴، ۵۶ و ۲۷ درصد در دورهای ۱، ۳ و ۷ روز بود. همچنین ساقه ذرت نسبت به کادمیم حساس‌تر از برگ بود. نتایج نشان داد که ذرت ممکن است در شرایط رطوبت بهینه خاک و آلودگی خفیف با کادمیم برای گیاه پالایی استفاده شود. همچنین غلظت کادمیم شاخسار ذرت در مقابل غلظت کادمیم خاک در هر دور آبیاری با مدلی از نوع plateau بیان گردید.