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Effect of chromium toxicity on growth, chlorophyll and some macronutrients of *Solanum lycopersicum* and *Solanum melongena*

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ABSTRACT

A study was conducted to evaluate the effect of Cr on growth, photosynthetic pigment and nutrient uptake of tomato (*Solanum lycopersicum* L.) and eggplant (*S. melongena* L.). Tomato and eggplant crops were irrigated with waters having four concentrations of Cr (0.1, 0.5, 2.5 and 7.5 ppm). Normal water was used as control (0 ppm) in both the crops. Application of Cr contaminated irrigation water decreased plant height, leaf area/plant, number of fruits/plant, fresh fruit weight/plant, fruit yield/plant, dry weight/plant, above plant biomass/plant. The decrease summarized for various parameters across treatments ranged from 62% to 84% and 56% to 77% in tomato and eggplant, respectively. The inhibitory effects on photosynthetic pigments gradually increased with increase in concentration. 7.5 Cr ppm concentration resulted in the lowest pigment level (mg/g FW) and maximum inhibition rate compared to control. It was also observed that the N, P and K content in fruits were significantly affected by the Cr treatments in both the crops. Accumulation of Cr was more in tomato compared to eggplant indicating that tomato was more sensitive to chromium when compared to eggplant. The impact of Cr on the various parameters quantified by using linear, exponential, quadratic and polynomial of degree 3. The responses were described by the polynomial of degree 3 with $R^2 > 99\%$ for the both crops.

Key words: Chromium, Eggplant, Growth parameters, Models, Photosynthetic pigment and Tomato

Contamination with heavy metals has acquired global dimensions resulting in losses in agricultural yield and hazardous health effects on humans and livestock through the food chain (Meagher 2000, Raskin and Ensley 2000). They are major environmental pollutants, which are discharged into the environment by burning of fossil fuels, release of industrial wastes and use of agrochemicals (Pandey *et al.* 2011).

Heavy metals decrease plants growth by affecting water and mineral uptake, membrane function, inhibition of enzyme activities, oxidation and cross linking of proteins, inhibition of cell division, induction of DNA damage and cell death by primarily disturbing the cellular redox environment causing oxidation stress both in roots and leaves (Tamas *et al.* 2008, Faizan *et al.* 2011). Some heavy metals at low doses are essential micronutrients for plants, but at higher doses may cause metabolic disorders and growth inhibition (Fernandes and Henriques 1991).

India is the second largest producer of the vegetables in the world, next only to China. Tomato (*Solanum lycopersicum* L.) and eggplant (*Solanum melongena* L.) occupy third and fourth positions in India amongst the vegetable crops in terms of both area and production. Vegetables are easily available and a cheap source of nutrients, vitamins, minerals and other elements essential for human well being. Vegetables add variety, colour and texture to our diets (Rai *et al.* 2004). Although vegetable production has appreciably increased over the last two decades, its supply is not sufficient to meet the demands of the ever increasing population for achieving nutritional security.

In some countries, the wastewater (mix of domestic wastewater and industry effluent) is discharged into rivers and then the contaminated river water is used for irrigation (van der Hoek *et al.* 2002, van der Hoek 2004). In India, wastewater is being increasingly used for irrigating crops such as vegetables, fruits, cereals, flowers and fodder. Wastewater irrigated vegetables take up heavy metals and accumulate them in their edible parts (Singh *et al.* 2010, Yahia *et al.* 2013) and inedible parts in quantities high enough to cause clinical problems both to animals and human beings consuming these metal-rich plants (Alam *et al.* 2003). While farmers can suffer from harmful health effects from the contact with wastewater, consumers are more at risk by eating vegetables cultivated with wastewater. The metals may enter the food chain either through water supplies and aquatic organisms or through arable produce and grazing animals (Thornton 1991).

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A pot culture experiment was designed to investigate the role of Cr and its sensitivity on growth and yield of tomato and eggplant as it was very obvious that very limited work has been done on these aspects. The results obtained have been described and discussed in this paper. Models are often used to quantify the response of plant to various parameters. Linear, exponential, quadratic and polynomial of degree 3 models were used for quantifying the response of various parameters to increasing Cr concentrations.

MATERIALS AND METHODS

The pot experiment was conducted in the nethouse of Water Technology Centre, Indian Agricultural Research Institute, New Delhi. Two vegetables crops, viz. tomato (cv Pusa Rohini) and eggplant (cv Pusa Upkar), were grown in the winter seasons of 2008-09 and 2009-10. Fifteen day old seedlings were transplanted in pots on 23 October 2008 and 26 October 2009. The soil used in the experiment was sandy loam in texture (sand 76%, silt 10%, clay 14%). Initial pH (7.8), EC (0.72 dS/m), organic carbon (0.48%), available nitrogen (228 kg/ha), phosphorus (22.2 kg/ha) and potassium (358 kg/ha), contents respectively.

The experiment was laid out in Completely Randomized Block Design (CRD) with three replications. The four Cr concentrations in irrigation water were 0.1, 0.5, 2.5 and 7.5 ppm in addition to control (0 ppm concentration). Chromium sulphate ($Cr_2(SO_4)_3 . 6H_2O$) was used as source of Cr. The first irrigation was given with normal water at the time of transplanting but subsequent irrigations were given with Cr enriched water at 5 day intervals in both tomato and eggplant crops.

Recommended doses of fertilizers were applied to both the crops in all the treatments as basal dose. In tomato, the dose was 150 kg N/ha (3.28 g N/pot), 60 kg P_2O_5/ha (3.77 g P_2O_5/pot) and 60 kg K_2O/ha (1g K_2O/pot) while in eggplant, it was 50 kg N/ha (1.09 g N/pot), 370 kg P_2O_5/ha (23.23 g P_2O_5/pot) and 100 kg K_2O/ha (1.67 g K_2O/pot) through urea for nitrogen, single super phosphate for phosphorus and muriate of potash for potassium.

The leaf samples were collected for the estimation of chlorophyll at the time of flowering. Fruit samples were collected as and when they ripened and analyzed for Cr accumulation. The observations were recorded for number of days to first fruit harvest, the plant height (cm), leaf area (cm^2) and number of fruits harvested/plant. The average fresh fruit weight (g)/ treatment was calculated by dividing the total fruits yield (g) by number of fruits harvested. The number of fruits harvested in different pickings was calculated by adding fruit yield/plant. After the harvest of crops, the above ground biomass was averaged for all treatments.

Chlorophyll a (Chl a), chlorophyll b (Chl b) and Chlorophyll (a+b){chl (a+b)} were extracted and estimated according to Arnon (1949). About 0.1 g of fresh leaves from all the treatments were cut into tiny segments and kept in 7 ml Dimethyl Sulphoxide (DMSO) and incubated at 65ºC for one hour. To this aliquot, 3 ml DMSO was added to make up the total volume to 10 ml. Optical densities were taken at 645 nm and 663 nm using UV-VIS Double Beam Spectrophotometer 2201(Hiscox and Israelstam 1979). Pigment contents were calculated in mg/g FW.

Whole plants were collected from each pot and the samples washed by distilled water. The air dried plant tissues were then ground into 0.25 mm size, then subjected to wet digestion and analyzed for N, P and K. Total nitrogen in plant samples was determined by Kjeldahl digestion-distillation method (Buresh *et al.* 1982), whereas the total phosphorus content in plant was determined calorimetrically by Vanado molybdate method in HNO_3 medium (Koeing and Johnson 1942) and total potassium was estimated directly by Systronics Flame Photometer 128 (Piper 1950).

Ripened fruits were selected from each pot for the determination of Cr content. They were first rinsed 3-4 times with deionized water, and than oven-dried at 70°C for 48 h followed by di-acid digestion with $HNO_3/HClO_4$ (3:1, v/v) solution. The digested samples were dissolved in deionised water (25 ml) and stored at 4°C until analysis. An aliquot (2.0 ml) of the digest was analyzed for Cr using Atomic Absorption Spectrophotometer (AAS, Analytic Jena, and model Zeenit 007).

An attempt was made to quantify the impact of Cr concentrations on yield attributing characters and yield parameters by using the following models:

Linear: $y = a + bx$ .... (1)

Exponential: $y = a.e^{bx}$ .... (2)

Quadratic: $y = a + bx + cx^2$ .... (3)

Polynomial (Degree 3): $y = a + bx + cx^2 + dx^3$ .... (4)

In all the above equations, 'y' is the plant morphological parameter, viz. number of days to first fruit harvest/plant, plant height (cm), leaf area (cm^2), number of fruits/plant, fresh fruit weight/plant (g), fruit yield/plant (g), dry weight (g) and above ground plant biomass/plant (g), 'x' is Cr concentration, 'a' is the constant and 'b', 'c', 'd' are regression coefficients having different values in different equations.

All the data were analyzed statistically using SAS version 9.2.

RESULTS AND DISCUSSION

Days to first fruit harvest

Irrigation with chromium polluted waters resulted in a significant delay in the number of days to first fruit harvest in both the crops. In tomato, the delay was to the extent of six days, i.e. 61 days in control to 67 days in the 7.5 ppm treatment (Table 1), whereas in eggplant, it increased from 95 days in control to 101 days in 7.5 ppm treatment and showing the same magnitude (Table 2). However, it must be noted that in eggplant, the first fruit was harvested in control (0 ppm) 95 days after sowing compared to 61 days in tomato. It was also observed that the initial concentration of Cr (0.1 and 0.5 ppm) had a greater impact than subsequent concentrations. For example, the first fruit harvest was delayed by 2 days when Cr concentration increased from 0

Table 1 Effect of irrigation water containing varying levels of chromium on yield attributing characters and yield of tomato

Parameter	Year	Treatment*					Mean	CD	SE
		T_1	T_2	T_3	T_4	T_5			
Number of days to first fruit harvest	2008	60.80	62.40	64.60	65.20	66.50	63.90	0.07	0.03
	2009	60.60	63.10	65.50	66.30	67.13	64.53		
	Mean	60.70	62.75	65.05	65.75	66.82			
Plant height (cm)	2008	54.89	53.69	45.75	35.95	20.59	42.17	0.33	0.15
	2009	55.67	54.26	45.89	36.89	21.26	42.79		
	Mean	55.28	53.98	45.82	36.42	20.93			
Leaf area/plant (cm^2)	2008	8.92	6.60	6.00	4.00	2.74	5.65	0.21	0.09
	2009	8.97	6.78	6.50	5.40	2.15	5.96		
	Mean	8.95	6.69	6.25	4.70	2.45			
Fresh fruit weight/plant (g)	2008	340.90	333.16	268.16	145.60	80.98	233.76	5.65	2.48
	2009	339.67	298.97	269.01	149.08	79.57	227.26		
	Mean	340.29	316.07	268.59	147.34	80.28			
Fruit dry weight/plant (g)	2008	65.75	59.57	47.93	38.69	15.84	45.56	3.97	1.74
	2009	65.20	60.10	46.80	36.40	15.20	44.74		
	Mean	65.48	59.84	47.37	37.55	15.52			
Number of fruits/plant	2008	30.50	28.34	20.31	10.63	5.30	19.02	0.71	0.31
	2009	30.00	26.28	19.20	12.20	4.30	18.40		
	Mean	30.25	27.31	19.76	11.42	4.80			
Fruit yield/plant (kg)	2008	10.40	9.44	5.45	1.55	0.43	5.45	0.17	0.08
	2009	10.19	7.86	5.16	1.82	0.34	5.07		
	Mean	10.29	8.65	5.31	1.68	0.39			
Above ground biomass/plant (g)	2008	96.68	92.83	85.04	75.00	32.98	76.51	0.35	0.15
	2009	95.73	92.84	85.01	75.01	32.97	76.31		
	Mean	96.21	92.84	85.03	75.01	32.98			

Note: Values in parentheses are significant at $P \leq 0.01$, *T_0, 0 ppm; T_1, 0.1 ppm; T_2, 0.5 ppm; T_3, 2.5 ppm; T_4, 7.5ppm.

Table 2 Effect of irrigation water containing varying levels of chromium on yield attributing characters and yield of eggplant

Parameter	Year	Treatment*					Mean	CD	SE
		T_1	T_2	T_3	T_4	T_5			
Number of days to first fruit harvest	2008	94.80	96.20	97.80	99.20	101.23	97.85	0.22	0.10
	2009	94.60	96.80	98.20	100.10	109.00	99.74		
	Mean	94.70	96.50	98.00	99.60	101.25			
Plant height (cm)	2008	41.75	38.95	37.09	29.07	17.97	32.97	0.33	0.15
	2009	41.65	39.95	37.85	28.16	18.69	33.26		
	Mean	41.70	39.45	37.47	28.62	18.33			
Leaf area/plant (cm^2)	2008	16.57	14.46	10.69	8.96	4.25	10.99	0.13	0.06
	2009	16.75	14.39	10.89	8.89	4.19	11.02		
	Mean	16.66	14.43	10.79	8.93	4.22			
Fresh fruit weight/plant (g)	2008	145.21	139.00	112.50	83.06	66.53	109.26	5.30	2.32
	2009	143.89	135.63	111.68	81.98	64.69	107.57		
	Mean	144.55	137.32	112.09	82.52	65.61			
Fruit dry weight/plant (g)	2008	18.55	16.73	15.64	12.06	6.90	13.98	0.71	0.31
	2009	18.23	16.29	15.40	11.30	6.40	13.52		
	Mean	18.39	16.51	15.52	11.68	6.65			
Number of fruits/plant	2008	8.00	7.00	5.00	3.33	1.67	5.00	1.44	0.63
	2009	7.67	6.67	4.67	2.67	2.00	4.74		
	Mean	7.80	6.79	4.85	3.18	1.83			
Fruit yield/plant (kg)	2008	1.16	0.97	0.56	0.28	0.11	0.62	0.16	0.07
	2009	1.10	0.90	0.52	0.22	0.13	0.58		
	Mean	1.13	0.94	0.54	0.25	0.12			
Above ground biomass/plant (g)	2008	38.83	36.28	29.71	19.89	14.71	27.88	0.56	0.25
	2009	38.78	36.25	28.64	18.94	14.73	27.47		
	Mean	38.81	36.27	29.18	19.42	14.72			

Note: Values in parentheses are significant at $P \leq 0.01$; *T_0, 0 ppm; T_1, 0.1 ppm; T_2, 0.5 ppm; T_3, 2.5 ppm; T_4, 7.5ppm.

and 0.1 ppm and again by almost the same number of days when it increased from 0.1 and 0.5 ppm. The delay was halved when the concentration increased from 0.5 to 2.5 ppm or from 2.5 to 7.5 ppm (Table 1). In case of eggplant, the delay was evenly spaced between all the concentrations (Table 2).

Plant height and leaf area

Plant height is one parameter which indicates a visible impact of any stress or toxic element. In case of tomato, there was a slight decrease in the plant height at low concentrations of Cr but the impact was very significant at Cr concentration of 7.5 ppm with the height being reduced to half of control. In case of eggplant, there was a decrease of greater magnitude even at low concentrations but the highest concentration of Cr (7.5 ppm) reduced the plant height by around 56% compared to more than 62% in tomato (Tables 1 and 2).

In case of leaf area of tomato, the reduction was to the extent of 30% at Cr concentration of 0.5 ppm, and almost 73% at concentration of 7.5 ppm, compared to the control. In eggplant crop, there was a significant reduction in leaf area to the extent of 35% up to Cr concentration of 0.5 ppm, while it was almost 75% at concentration of 7.5 ppm, compared to the control.

There was obviously a clear cut difference in the response of tomato *vis-a-vis* eggplant. It is also important to note that there was a significant difference in plant height and leaf area of the two crops in absolute terms (Tables 1 and 2).

Fresh fruit weight and dry weight

Cr at higher concentrations caused adverse effects on fresh fruit weight and dry weight. There was a significant reduction in fresh weight and dry weight of fruits when the concentration increased from 0 ppm to the level of 7.5 ppm in comparison to control. In eggplant, the highest concentration of Cr (7.5 ppm) reduced the fresh fruit weight by around 55% compared to more than 76% in tomato. In case of fruit dry weight in tomato, it decreased by 76% while in eggplant it decreased by 64% compared to the control. Tomato proved to be more sensitive than eggplant with the difference ranging from 22% as far as fresh weight of fruits was concerned but only 12% in case of dry weight of fruits between the two crops (Tables 1 and 2).

Number of fruits and yield

The impact of Cr was significant when the concentration increased from 0 ppm to the level of 7.5 ppm. This signified a drastic reduction in number of fruits of tomato by 84% at 7.5 ppm concentration. In eggplant, the reduction was 77% compared to the control at the same concentration level. In case of fruit yield in tomato, it decreased by 96% while in eggplant it decreased by 89% compared to the control. In this case also, tomato was relatively more sensitive than eggplant.

Above ground biomass

The impact of Cr on the above ground biomass has also been shown in Tables 1 and 2. The impact of Cr resulted in a significant reduction in above ground biomass compared to the control. This signified a drastic reduction in above ground biomass of tomato by 66% at 7.5 ppm concentration. In eggplant, the reduction was 62% compared to the control at the same concentration level. For this parameter also, tomato was slightly more sensitive than eggplant with the difference ranging from 4% to as far as above ground biomass was concerned.

Photosynthetic pigments

Analysis of the leaf tissue of tomato and eggplant at the time of flowering stage as influenced by increasing Cr concentrations exhibited inhibitory effect with respect to chlorophyll a, chlorophyll b and total chlorophyll contents at all concentrations compared to control (Fig 1). The inhibitory effects gradually increased with increase in concentrations. Cr treatment at 7.5 ppm concentration resulted in the lowest pigment level (mg/g FW) and maximum inhibition rate compared to control for all parameters, viz. chlorophyll a (0.89; 55.49%), chlorophyll b (0.69; 57.85%) and total chlorophyll (1.58; 56.55%) in tomato, while the highest pigment content (mg/g FW) for chlorophyll a (2.00 mg/g FW), chlorophyll b (1.63 mg/g FW) and total chlorophyll (3.62 mg/g FW) were recorded in the control in tomato. On the other hand, eggplant also showed a significant declining trend with increasing Cr

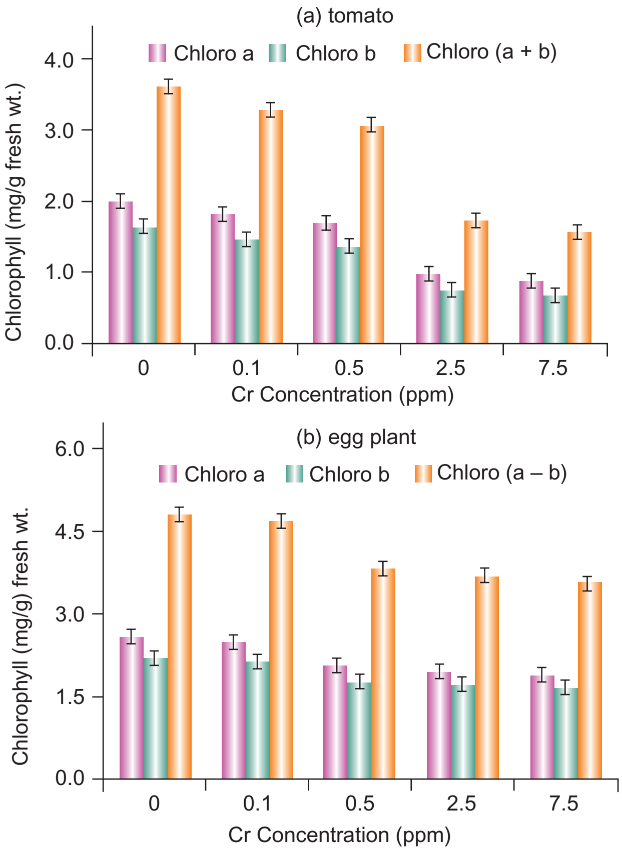

Fig 1 Effect of Cr on photosynthetic pigments of (a) tomato and (b) eggplant

Table 3 Effect of Cr on Macronutrient (N, P and K) contents in tomato fruits

Parameter	Year	Treatment*					Mean	CD	SE
		T_1	T_2	T_3	T_4	T_5			
Nitrogen (%)	2008-09	3.18	2.85	1.48	1.32	0.95	1.96	0.050	0.022
	2009-10	3.12	2.96	1.69	1.59	1.23	2.12		
	Mean	3.15	2.91	1.59	1.46	1.09			
Phosphorus (%)	2008-09	0.33	0.27	0.20	0.15	0.11	0.21	0.009	0.004
	2009-10	0.32	0.25	0.21	0.16	0.12	0.21		
	Mean	0.33	0.26	0.21	0.15	0.12			
Potassium (%)	2008-09	4.59	3.98	3.64	3.26	1.99	3.49	0.042	0.019
	2009-10	4.54	4.16	3.92	3.33	2.05	3.60		
	Mean	4.57	4.07	3.78	3.30	2.02			

Note: All the treatments are significant at P # 0.01

Table 4 Effect of Cr on Macronutrient (N, P and K) contents in eggplant fruits

Parameter	Year	Treatment*					Mean	CD	SE
		T_1	T_2	T_3	T_4	T_5			
Nitrogen (%)	2008-09	3.10	2.07	1.18	1.06	0.89	1.66	0.040	0.018
	2009-10	3.27	2.19	1.07	1.10	0.62	1.65		
	Mean	3.19	2.13	1.13	1.08	0.76			
Phosphorus (%)	2008-09	0.51	0.43	0.41	0.20	0.15	0.34	0.014	0.061
	2009-10	0.48	0.49	0.34	0.30	0.23	0.37		
	Mean	0.50	0.46	0.38	0.25	0.19			
Potassium (%)	2008-09	4.38	4.20	3.17	2.78	1.93	3.29	0.042	0.019
	2009-10	4.46	4.04	3.09	2.90	2.01	3.30		
	Mean	4.42	4.12	3.13	2.84	1.97			

Note: All the treatments are significant at P # 0.01

concentration (0 to 7.5 ppm). The lowest pigment level (mg/g FW) and maximum inhibition rate for chlorophyll a (1.90; 26.91%), chlorophyll b (1.70; 23.82%) and total chlorophyll (3.60; 25.48%) were observed in eggplant leaves at 7.5 ppm Cr concentration. As expected, the highest pigment content in eggplant (mg/g FW) for chlorophyll a (2.60 mg/g F), chlorophyll b (2.23 mg/g F) and total chlorophyll (4.82 mg/g F) were recorded in control.

Macronutrients content

The impact of Cr on N, P and K content in tomato and eggplant fruit has been shown in Tables 3 and 4. Results of N, P and K analysis displayed a declining trend with increasing concentration of Cr. Increase in Cr concentration resulted in a significant ($p<0.01$) decline in the N content in the fruits of tomato crop compared to control. The N content in fruit of tomato crop declined from 3.15% in control to 1.09% in 7.5 ppm Cr treatment. In the plants treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr waters, N uptake was inhibited by 7.78, 49.68, 53.81 and 65.40%, respectively. In case of P, it declined from 0.33% in control to 0.12% in 7.5 ppm treatment. In the plants treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr waters, P uptake was inhibited by 21.21, 36.36, 54.55 and 63.64%, respectively. Similarly, K content in tomato fruits decreased from 4.57 in control to 2.02 in 7.5 ppm treatment which implied that in the plants, treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr waters, K uptake was inhibited by 10.94, 17.29, 27.79 and 58.80%, respectively. In case of eggplant fruit, N content declined from 3.19 in control to 0.76% in 7.5 ppm treatment. The plant N uptake was inhibited by 33.23, 64.58, 66.14 and 76.18% in the 109 plants treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr, respectively. In case of P, it declined from 0.50% in control to 0.19% in 10 ppm treatment. The plants treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr exhibited inhibition in P uptake by 8.01, 24.05, 50.10 and 62.03 %, respectively. Likewise, the K content in

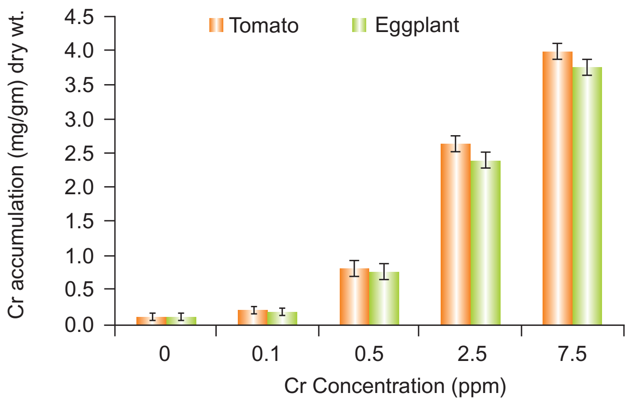

Fig 2 Cr accumulation in fruits of tomato and eggplant

eggplant fruit decreased from 4.42 to 1.97% in 7.5 ppm treatment compared to control. In the plants treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr, K uptake was inhibited by 6.79, 29.19, 35.75 and 55.43%, respectively.

Cr accumulation in fruits of tomato and eggplant fruit

Fruits of tomato and eggplants accumulated Cr in concentration dependent manner which has been shown schematically in Fig 2. In tomato fruits, Cr concentration increased to 3.996 mg/g d.wt. in 10 ppm treatment in tomato and 3.748 mg/g d.wt. in the corresponding treatment in case of eggplant. From this figure, it is clear that tomato fruits accumulate more Cr compared to eggplant.

The performances of the various models for the two crops have been presented in Tables 5 and 6 and evaluated in terms of Coefficient of Determination (R^2) values. In case of Cr, the R^2 values ranged from 0.729 to 0.981 in tomato and 0.786 to 0.999 in eggplant when the linear model was used (Tables 5 and 6). In case of tomato, the use of exponential model resulted in R^2 values ranging from 0.676 to 0.954, while in eggplant the values ranged from 0.839 to 0.999. The use of quadratic model resulted in R^2 values ranging from 0.941 to 0.993 in tomato, and from 0.937 to 0.999 in eggplant. The use of polynomial of degree 3 resulted in R^2 values ranging from 0.988 to 1.00 in tomato and 0.985 to 1.00 in eggplant. The best fit was obtained by the polynomial of degree 3 in both the crops. The quadratic and exponential forms were almost at par in case of both the crops with only a marginal difference between them.

Chromium compounds are highly toxic to plants and are detrimental to their growth and development. Although some crops are not affected at low Cr concentrations (3.8×10^{-4}µM) (Huffman and Allaway 1973a, b), Cr is toxic to higher plants at 100 µM/kg dry weight (Davies *et al.* 2002). Plant growth is chiefly expressed as a function of genotype and environment, which consists of external growth factors and internal growth factors. We have investigated how Cr treatment affected the growth, photosynthetic pigment, chromium accumulation and major nutrients (N, P and K). In case of yield parameters such as number of fruits/plant and fruits yield, the number of fruits/plant decreased by 62% in tomato and 59% in eggplant at 2.5 ppm concentration, and 84% in tomato and 77% eggplant in 7.5 ppm treatment. Fruit yields decreased by 84% in tomato and 78% in eggplant at 2.5 ppm, and 96% in tomato and 89% in eggplant at 7.5 ppm concentration level compared to control. A similar trend was observed in other parameters, namely, plant height, leaf area/plant, fresh fruits weight, fruits dry weight and above ground biomass. Karunyal *et al.* (1994) studied the effect of tannery effluent on leaf area and biomass and reported that all the concentrations tested decreased leaf area and leaf dry weight in *Oryza sativa*, *Acacia holosericea* and *Leucaena leucocephala.* The dry leaf yield of bush bean plants decreased up to 45% when 100 ppm of Cr (VI) was added to soil (Wallace *et al.* 1976). Higher concentrations of heavy metals in surface soil have been reported to inhibit nutrient uptake, physiological and metabolic processes (Ahsan *et al.* 2007) or reduce plant growth (Boussama *et al.* 1999) and also cause chlorosis due to interference with photosynthesis and respiration processes (Sandalio *et al.* 2001, Ekmekci *et al.* 2008), damage to cell membrane (Cunha *et al.* 2008) and root tips (Sheldon and Menzies, 2005), as well as reduced water and nutrient uptake including damage to enzymes (Sanita di Toppi *et al.* 1999; Balestrasse *et al.* 2001). In a study on the effect of Cr (III) and Cr (VI) on spinach, Singh (2001) reported that Cr applied at 60 mg/kg and higher levels reduced the leaf size,

Table 5 Performance of various models (*) used for various yield attributing characters and yield of tomato

Models		Number of days to first fruit harvest	Plant height (cm)	Leaf area/ plant (cm^2)	Fruit fresh weight/ plant (g)	Fruit dry weight/ plant (g)	Number of fruits/ plant	Fruit yield/ plant (kg)	Above ground biomass/ plant (g)
Linear	a	59.642	44.977	9.455	437.14	81.815	38.745	13298	119.700
	b(x)	1.524	–4.267	–1.229	–68.875	–12.221	–6.679	–2678.2	–14.429
	R^2	0.954	0.729**	0.814	0.943	0.952	0.981	0.978	0.793
Exponential	a	59.739	49.618	10.053	606.06	110.32	60.762	36847	145.06
	b(x)	0.024	49.618	–0.201	–0.365	–0.335	–0.455	–0.821	–0.235
	R^2	0.950	0.676**	0.898	0.886	0.839	0.904	0.898	0.704
Quadratic	a	57.862	30.942	12.33	357.41	66.75	34.67	13506	79.936
	b(x)	3.05	7.763	–3.693	–0.539	0.692	–3.186	–2856.1	16.655
	c(x^2)	–0.254	–2.005	0.411	–11.389	–2.152	–0.582	29.642	–5.681
	R^2	0.991	0.954	0.941	0.979	0.993	0.991	0.978	0.965
Polynomial(3)	a	57.694	45.656	16.488	248.98	74.282	25.808	7872	118.53
	b(x)	3.286	–12.907	–9.535	151.78	–9.889	9.263	5057.9	–34.566
	c(x^2)	–0.344	5.878	2.638	–69.477	1.883	–5.33	–2988.4	14.997
	d(x^3)	0.01	–0.876	–0.248	6.454	–0.448	0.528	335.34	–2.397
	R^2	0.991	0.9982	0.988	0.991	0.994	0.999	1.000	0.994

*R^2 values are significant at $P \leq 0.05$ level, ** not significant; 'a' is the constant and 'b', 'c',' d' are regression coefficients

Table 6 Performance of various models (*) used for various yield attributing characters and yield of eggplant

Models		Number of days to first fruit harvest	Plant height (cm)	Leaf area/ plant (cm^2)	Fruit fresh weight/ plant (g)	Fruit dry weight/ plant (g)	Number of fruits/ plant	Fruit yield/ plant (kg)	Above ground biomass/ plant (g)
Linear	a	93.150	8.309	20.524	172.220	22.243	9.555	1410.800	47.189
	b(x)	1.620	–0.777	–3.440	–21.268	–2.831	–1.555	–271.540	–6.503
	R^2	0.999	0.786	0.957	0.971	0.922	0.992	0.976	0.970
Exponential	a	93.241	8.476	–0.383	194.250	–0.238	12.928	2540.700	55.970
	b(x)	0.017	–0.123	27.834	–0.209	26.470	–0.366	–0.582	–0.256
	R^2	0.999	0.839	0.930	0.955	0.846	0.957	0.960	0.948
Quadratic	a	93.050	10.324	20.924	160.370	17.668	9.350	1528.300	43.694
	b(x)	1.705	–2.504	–3.783	–11.111	1.090	–1.379	–372.270	–3.507
	c(x^2)	–0.014	0.288	0.057	–1.693	–0.654	–0.029	16.789	–0.499
	R^2	0.999	0.937	0.958	0.980	0.990	0.993	0.981	0.978
Polynomial(3)	a	92.560	12.998	11.754	99.634	20.580	7.600	1011.100	30.240
	b(x)	2.394	–6.261	9.099	–53.370	–3.002	1.079	354.270	15.392
	c(x^2)	–0.277	1.720	–4.855	18.739	0.906	–0.967	–260.280	–7.707
	d(x^3)	0.029	–0.159	0.546	–1.678	–0.173	0.104	30.786	0.801
	R^2	1.000	0.985	0.992	1.000	0.995	0.999	0.999	0.999

*All R^2 values are significant at P = 0.05 level; 'a' is the constant and 'b', 'c', 'd' are regression coefficients

caused burning of leaf tips or margin and slowed leaf growth rate. In a study with several heavy metals, Pedreno *et al.* (1997) found that Cr had a pronounced effect on leaf growth and preferentially affected young leaves in tomato plants. Reduction in leaf biomass was correlated with the oxalate acid extractable Cr in *P. vulgaris* (Poschenrieder *et al.* 1993). The Chlorophyll a, b and total chlorophyll reduced from 2.00 to 0.89, 1.63 to 0.69 and 3.62 to 1.58(mg/g FW) in tomato and 2.60 to 1.90, 2.23 to 1.70 and 4.82 to 3.60 (mg/g FW) in eggplant, respectively, with increasing Cr concentration (0 to 7.5 ppm). Bera *et al.* (1999) studied the effect of Cr present in tannery effluent on chloroplast pigment content in mung bean and reported that irrespective of concentration, chlorophyll a, chlorophyll b and total chlorophyll decreased in 6-day-old mung bean seedlings as compared to control. The N uptake was inhibited in tomato crop by 7.78, 49.68, 53.81 and 65.40%, respectively. P uptake was inhibited by 21.21, 36.36, 54.55 and 63.64%, respectively. Similarly, K uptake was inhibited by 10.94, 17.29, 27.79 and 58.80%, respectively. In case of eggplant fruit, N uptake was inhibited by 33.23, 64.58, 66.14 and 76.18% respectively. In case of P, uptake decreased by 8.01, 24.05, 50.10 and 62.03 %, respectively. Likewise, K uptake was inhibited by 6.79, 29.19, 35.75 and 55.43 %, respectively in the plants treated with 0.1, 0.5, 2.5 and 7.5 ppm Cr. There have been reports earlier also on Cr toxicity reduction in photosynthesis, and decrease in chlorophyll a, b, total chlorophyll and carotenoids (Sharma and Sharma 1996, Chatterjee and Chatterjee 2000). The reduction in N, K, P and other elements could be due to the reduced root growth and impaired penetration of the roots into the soil due to Cr toxicity. Khan *et al.* 2001 observed that threshold values of the concentrations of N, P and K in dry weight of rice plants showed significant decrease at 0.5 ppm Cr. Moral *et al.* (1995) reported that the nutrient elements N, P, K, Na, Ca and Mg concentrations in stems and branches were significantly affected by the Cr treatments (50 and 100 mg/L) in tomato. The results obtained in this study are similar to the ones reported earlier by researchers on many other crops as for as the impact of Cr on various plant morphological parameters. However, quantitative studies on its effect on tomato and eggplant are not available. Regression and process based models have been used by many workers for soil and crop responses (Singh 1989, Rajarathinam *et al.* 2007, Verma *et al.* 2007) but not for such studies to quantify the impact of heavy metals on plant growth parameters.

CONCLUSION

This study clearly revealed that presence of Cr in irrigation water significantly decreased growth and development, culminating in the reduction of yield and total dry matter as a consequence of poor production, translocation and partitioning of assimilates from source to the economic parts of the plant. The results have conclusively established that increasing concentration of Cr in the irrigation water caused an increase in the accumulation of these heavy metals in the fruits and impairment of uptake of mineral nutrients and water leading to deficiency in the shoot. It was observed that between the two crops, tomato was relatively more sensitive than eggplant. The polynomial of degree three with $R^2 > 99\%$ was very effective in quantifying the response of both the crops to Cr. Results of such studies will help in identification of suitable crops to the grown in Cr terminated agricultural soils particularly in the peri-urban areas which supply most of the vegetables needed for consumption of the urban population.

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