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RESEARCH ARTICLE

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Accumulation and distribution of selenium in some vegetable crops grown in selenate-Se treated clay loam soil

Abstract A greenhouse experiment was conducted to study the accumulation of selenium by some vegetable crops commonly grown in the Indian Punjab. Eleven vegetable crops were raised in an alkaline clay loam soil treated with different levels of selenate-Se, i.e., 0, 1.25, 2.5 and 5.0 $mg \cdot kg^{-1}$ soil. Dry matter yield of both edible and inedible portions of different vegetable crops decreased with increasing Se level in soil except potato (*Solanum tuberosum*), radish (*Raphanus sativus*) and cauliflower (*Brassica oleracea* var. *botrytis*) which recorded 10%–21% increase in inedible dry matter at 1.25 $mg \cdot kg^{-1}$ Se soil. Application of 5 $mg \cdot kg^{-1}$ selenate-Se soil resulted in complete mortality in the case of radish, turnip (*Brassica rapa*) and brinjal (*Solanum melongena*). Some vegetable crops including tomato (*Lycopersicum esculentum*), cauliflower and pea (*Pisum sativum*), though, survived the toxic effect at the highest concentration of Se yet did not bear any fruit. Potato and spinach (*Spinacea oleracea*) proved to be highly tolerant crops. Selenium concentration in the edible as well as inedible portions of all the vegetables increased with an increase in the level of applied Se. Selenium accumulation in the edible portion of vegetable crops in the no-Se control ranged from 2.2 to 4.9 $mg \cdot kg^{-1}$ Se dry weight. At 1.25 $mg \cdot kg^{-1}$ Se soil, the edible portion of radish accumulated the greatest concentration of Se (38 $mg \cdot kg^{-1}$ Se dry weight) with that of onion (*Allium cepa*) bulb the lowest (9 $mg \cdot kg^{-1}$ Se dry weight). Inedible portions of vegetables accumulated Se 2–5 times more than that absorbed by edible portions. Total Se uptake by edible portions of different vegetables was the greatest at 1.25 $mg \cdot kg^{-1}$ Se soil, ranging from 7 to 485 $\mu g \cdot pot^{-1}$. The results suggest that vegetable crops vary in their sensitivity to the presence of selenate-Se in soil. Vegetative portions were several times richer in Se than other parts of vegetable crops.

Keywords selenate-Se, vegetables, Se accumulation, clay loam soil

1 Introduction

The fate of Se in the soil-plant system has been extensively investigated since its discovery as an essential element for animal health. Most of the cultivated plants possess the ability to absorb, metabolize and store significant amounts of Se in their tissue when grown on soils containing available Se. Although higher plants do not require Se for their growth, higher concentrations of Se as a pro-oxidant, may lead to reduction in dry matter yield (Hartikainen et al., 2000). The threshold Se concentration of about 20 $mg \cdot kg^{-1}$ (dry weight) in shoots of rye grass (*Lolium perenne*) has been reported by Cartes et al. (2005). Both availability and toxicity of Se are determined by forms of Se in the soil, which in turn are affected by several factors such as pH, organic matter, texture, presence of competitive ions, organic compounds and microbiological activity (Hopper and Parker, 1999; Wang and Gao, 2001). Selenate is taken up metabolically by the root system and transported to shoots more readily than selenite (Asher et al., 1977; Arvy, 1993). Consumption of Se-rich vegetables and cereal grains has recently been associated with abnormal conditions and ill health of human beings in China (Yang et al., 1983) and India (Dhillon and Dhillon, 1997).

Depending on the kind of Se species present in soil, plants may exhibit quantitative differences in the amount of Se absorbed. Among 18 garden vegetables grown in the soil at different levels of organic/selenate forms of Se, cabbage plants can accumulate the highest Se concentration in their tissues. As compared with the edible portion, Se content is high in inedible portions of all the vegetables (Hamilton and Beath, 1964). Significant differences in Se

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uptake can be observed among different vegetable crops grown in the fly-ash-amended soil (Furr et al., 1978). Among the selected Se-accumulating vegetables, the highest Se concentration is reported in the broccoli floret and composite leaves when grown in the soil treated with selenate rather than selenite (Banuelos and Meek, 1989). Selenium content of Swiss chard grown in loamy sand soil amended with compost can increase to $0.29\,mg \cdot kg^{-1}$ compared to that in the no-Se amended soil (Warman et al., 1995). Selenium uptake is also significantly reduced in the leaves of *Lactuca sativa* in the presence of carboxymethylcellulose (Pezzarossa et al., 2007). Interaction between carboxymethylcellulose and Se makes it less mobile as indicated by the increase in insoluble Se fractions in soil (Ferri et al., 2003).

Plants that are able to accumulate Se in their tissues can be used to supplement the mammalian diet in Se deficient areas (Wu et al., 1988). Selenium-rich plants can be given directly to human beings as supplementation or to animals as food (Hambuckers et al., 2008) which can improve animal health and also the Se status of humans through meat consumption. Dietary Se intake by urban and rural populations in and around Lahore in Pakistan Punjab ranges between 41.2 and $52.1\,\mu g \cdot d^{-1}$ and may be described as a marginal low level (Mian, 1998). Beneficial effects of Se are mainly dependent upon the chemical forms in the diet and the most readily assimilated form of Se has been reported as selenomethionine (SeMeth) (Patrick, 2004). The US Food and Nutrition Board (2000) has suggested a $5\,mg \cdot kg^{-1}$ Se diet as the critical level between toxic and nontoxic feeds and daily dietary intake of 50–200 μg Se as the safe and adequate range for adults. An average dietary intake of adults in the US has been found to range from 80 to $100\,\mu g \cdot d^{-1}$. While studying the cancer risks in a well-nourished population, we observed that Se supplementation by $200\,\mu g \cdot d^{-1}$ decreased the risk of prostate cancer in men by 51% (Duffield-Lillico et al., 2003).

Compared to Se of animal origin, Se derived from plant tissues is well bioavailable (Cantor et al., 1975). Due to its well-known antioxidant properties, selenium occupies considerable importance in vegetables. On the other hand, Se accumulation in edible parts of vegetable plants because of the increased availability of different Se species in the soil can lead to Se toxicity to consumers. The present investigation was undertaken to determine the ability of some commonly grown vegetables to absorb selenium from the soil when added in the form of selenate-Se. Relationships between dry matter yield and Se level in the soil and the Se distribution in edible and inedible portions of some vegetable crops have been studied.

2 Materials and methods

2.1 Greenhouse study

In a greenhouse experiment eleven vegetable crops were grown in polythene lined pots containing 4 kg air-dry soil. The experimental soil was clay loam in texture, alkaline in reaction (pH 8.25), having electrical conductivity $0.20\,dS \cdot m^{-1}$, organic matter 0.30%, total Se content $0.135\,mg \cdot kg^{-1}$ and hot water soluble Se $0.015\,mg \cdot kg^{-1}$. The soil was treated with four Se levels of 0, 1.25, 2.5 and $5.0\,mg \cdot kg^{-1}$ added as $Na_2SeO_4 \cdot 5H_2O$ in solution form. All the treatments were replicated four times. Optimum levels of N, P and K were applied to each crop through urea, potassium dihydrogen orthophosphate and potassium chloride, respectively (Table 1). Among the eleven vegetable crops, spinach (*Spinacea oleracea*), cauliflower (*Brassica oleracea* var. *botrytis*), tomato (*Lycopersicum esculentum*) and brinjal (*Solanum melongena*) were grown from seedlings raised in a nursery; pea (*Pisum sativum*), carrot (*Daucus carota*), radish (*Raphanus sativus*) and turnip (*Brassica rapa*) from seeds; garlic (*Allium sativum*) and onion (*Allium cepa*) from bulbs and potato (*Solanum tuberosum*) from tubers. Five seedlings, tubers, bulbs or

Table 1 Basal nutrient requirement of different vegetable crops

common name	botanical name	cultivar	basal dose of nutrients applied/($mg \cdot kg^{-1}$)		
			N	P_2O_5	K_2O
carrot	*Daucus carota*	Pusa Kesar	25	12	30
potato	*Solanum tuberosum*	Pusa Chandermukhi	50	25	50
pea	*Pisum sativum*	Arkel	20	25	—
garlic	*Allium sativum*	Punjab Garlic 1	50	25	—
onion	*Allium cepa*	N 53	40	20	20
cauliflower	*Brassica oleracea* var. *botrytis*	Pusa Deepali	50	25	25
tomato	*Lycopersicum esculentum*	—	55	25	25
radish	*Raphanus sativus*	Pusa Himani	25	12	—
turnip	*Brassica rapa*	PTWG	25	12	—
brinjal	*Solanum melongena*	Shyamala	25	25	12
spinach	*Spinacea oleracea*	Punjab Hara	35	12	—

seeds (3–4 seeds per hill) of different vegetable crops were planted in each pot. Ten days after planting, only three plants were retained in each pot. After harvesting, the plants were separated into edible and inedible parts, washed free of any surface contamination and dried in an oven at (55±5)°C to a constant weight. The dry weight of each plant part was recorded. Plant materials were grinded in a Wiley mill and the samples were stored in air-tight plastic containers for Se analysis.

2.2 Selenium analysis

Soil (0.25 g of 100 mesh size) and plant (0.5 g) samples were digested in 10 mL mixture of perchloric and nitric acids in the ratio of 2:5. The acid digests were subjected to Se analysis fluorometrically (Bio-Rad's VersaFluor™ Fluorometer) as described by Levesque and Vendette (1971). For estimating hot water soluble Se, 10 g of the experimental soil was taken in a conical flask (250 mL capacity), suspended in 50 mL glass-distilled water and refluxed over a boiling water bath for 30 min (Jump and Sabey, 1989). Soil suspension was then filtered through a Whatman filter paper No. 42 and the filtrate was analyzed for Se as described above.

2.3 Statistical analysis

Statistical analysis of data pertaining to dry matter yield and Se content of different vegetable crops consisted of variance analysis for a completely randomized design using IRRISTAT version 5.0 (IRRI, the Philippines). The data from the highest Se level ($5\,\mathrm{mg\cdot kg^{-1}}$) was not included in the statistical analysis because some vegetable crops did not survive at high Se levels.

3 Results

3.1 Selenium toxicity symptoms

Progressive restrictions in plant growth, size of leaves and burning of leaf margins were observed as visual symptoms in vegetable crops grown in the selenate-Se treated alkaline clay loam soil (Table 2). In the presence of $5\,\mathrm{mg\cdot kg^{-1}}$ Se soil, complete mortality was observed in the cases of radish, turnip and brinjal. Adverse Se effects on seed germination were not observed and the seedlings died 10–12 days after germination. Among the crops raised from the nursery, brinjal seedlings proved highly sensitive and did not survive beyond 25–30 days at $5\,\mathrm{mg\cdot kg^{-1}}$ Se soil. Tomato, cauliflower and peas did not produce fruit. In the case of potato, garlic and onion, the tuber/bulb formation did not take place properly. Among all the crops, potato and spinach could withstand the toxic Se effect to a large extent. At $2.5\,\mathrm{mg\cdot kg^{-1}}$ Se soil, leaves of radish, turnip and carrot increased in number but were small in size and root growth was severely restricted.

3.2 Dry matter yield

In the no-Se control plants, dry matter produced by edible parts of different vegetables varied from 0.9 to $15.0\,\mathrm{g\cdot pot^{-1}}$ and it was the highest in spinach and the smallest in garlic (Table 3). In the presence of $1.25\,\mathrm{mg\cdot kg^{-1}}$ Se soil, a significant decrease in dry matter yield was observed in cauliflower, pea, carrot, turnip, radish and onion. The decrease varied from 25% to 79%. Edible portions of pea and onion and turnip were the most adversely influenced. The decrease in yield was greater than 50%. The increase in selenate-Se application level of $2.5\,\mathrm{mg\cdot kg^{-1}}$ in soil

Table 2 Selenium toxicity symptoms in some vegetable crops

vegetables	amount of selenate-Se applied to soil	
	$2.5\,\mathrm{mg\cdot kg^{-1}}$ soil	$5.0\,\mathrm{mg\cdot kg^{-1}}$ soil
radish, turnip and carrot	Leaves appeared more in number but smaller in size (Rosette appearance). Root growth severely restricted	Seeds germinated, but the seedlings died after 10–12 days of germination. In case of carrot 3–4 seedlings could survive till the end of the experiment
spinach	stunted growth	Burning of leaf tips and margins, stunted growth
cauliflower	stunted growth	Stunted growth, wilted look, drying of 3rd and 4th leaf, no fruit formation
brinjal	restricted growth	Plants turned yellow after 15 days of transplanting followed by drying up leading to death of the plants
onion	severely stunted growth	Burning of leaf tips, severely stunted growth
garlic	restricted growth	Burning of leaf tips, severely stunted growth
pea	severely stunted growth	Severely stunted growth, wilted look and no fruit formation
tomato	restricted growth, leaves smaller in size	Severely stunted growth, wilted look and no fruit formation
potato	—	No conspicuous symptoms were observed except restricted growth of shoots, tubers smaller in size

Table 3 Dry matter accumulation ($g \cdot pot^{-1}$) by different vegetable crops in relation to different amounts of selenate-Se applied to soil

vegetables		selenium levels/($mg \cdot kg^{-1}$)				
		0	1.25	2.5	5.0	mean
edible portion	carrot	5.21	3.88	1.55	0.33	3.55
	potato	13.38	13.31	7.74	4.68	11.48
	pea	4.32	1.26	0.18	—	1.92
	garlic	0.89	0.75	0.63	0.21	0.76
	onion	3.65	0.77	0.27	0.14	1.56
	cauliflower	10.54	7.80	2.16	—	6.83
	tomato	3.27	2.70	1.33	—	2.43
	radish	7.58	4.34	1.03	—	4.31
	turnip	5.98	2.88	0.14	—	3.00
	brinjal	9.35	9.31	5.14	—	7.93
	spinach	14.97	13.93	2.67	3.85	10.52
	mean	7.19	5.54	2.08	—	—
inedible portion	carrot	11.30	6.70	2.65	1.99	6.88
	potato	2.39	2.89	2.06	1.35	2.45
	pea	9.58	7.48	1.63	0.29	6.23
	garlic	1.05	0.49	0.51	0.03	0.68
	onion	7.38	1.19	0.32	0.10	2.96
	cauliflower	14.55	15.79	12.39	1.68	14.24
	tomato	17.88	12.61	8.78	2.29	13.09
	radish	10.84	12.00	4.68	—	9.23
	turnip	13.06	8.24	1.29	—	7.53
	brinjal	22.45	19.76	9.06	—	17.09
	mean	11.05	8.72	4.35	—	—

		Se levels	vegetable crops	Se level×crop
LSD ($P \leqslant 0.05$)	edible	0.33	0.63	1.09
	inedible	0.45	0.83	1.43

resulted in a substantial decrease (29%–98%) in dry matter yield of all the crops. At 5 $mg \cdot kg^{-1}$ selenate-Se soil, pea, cauliflower and tomato did not bear any fruit and brinjal, turnip and radish crops could not grow at all. Among all the crops, potato and spinach proved to be the most tolerant crops.

Dry matter yield of inedible portions of different vegetable crops varied from 1.1 to 22.5 $g \cdot pot^{-1}$ in the no-Se control treatment. The greatest was brinjal followed by tomato, cauliflower, turnip, carrot, radish, peas, onion, potato and garlic (Table 3). With application of 1.25 $mg \cdot kg^{-1}$ Se to soil, the dry matter of inedible portions decreased by 12%–84% in the case of brinjal, tomato, turnip, carrot, peas and onion; whereas it increased significantly in case of potato (21%), radish (20%) and cauliflower (10%). At 2.5 $mg \cdot kg^{-1}$ Se soil, a substantial decrease (up to 96%) in dry matter yield was recorded for all the crops except potato and cauliflower. Application of 5 $mg \cdot kg^{-1}$ Se to soil proved highly toxic and the complete mortality was observed in case of radish, turnip and brinjal. Other crops like tomato, cauliflower and pea could survive the toxic effect of high Se concentration, but did not bear any fruit. In general, dry matter accumulation in inedible parts of different vegetable crops was greater than that of edible parts. Potato, however, was an exception. Except in case of carrot, garlic and onion, the ratio of inedible to edible portion of different vegetable crops increased with an increase in the level of applied Se.

3.3 Se accumulation

Se accumulation in edible portions of different vegetable crops varied with the level of Se in soil (Fig. 1). At no-Se control, different vegetables absorbed almost similar amount of Se. The differences among vegetables increased as the level of Se in soil increased. The highest amount of Se was accumulated by radish (38 $mg \cdot kg^{-1}$ dry weight) and the lowest by onion (9 $mg \cdot kg^{-1}$ dry weight) at 1.25 $mg \cdot kg^{-1}$ Se soil. The selenium content of edible portions of vegetables further increased with the application of 2.5 $mg \cdot kg^{-1}$ Se to soil, ranging from 16.7 to 80.1 $mg \cdot kg^{-1}$. At all the levels of applied Se, the edible

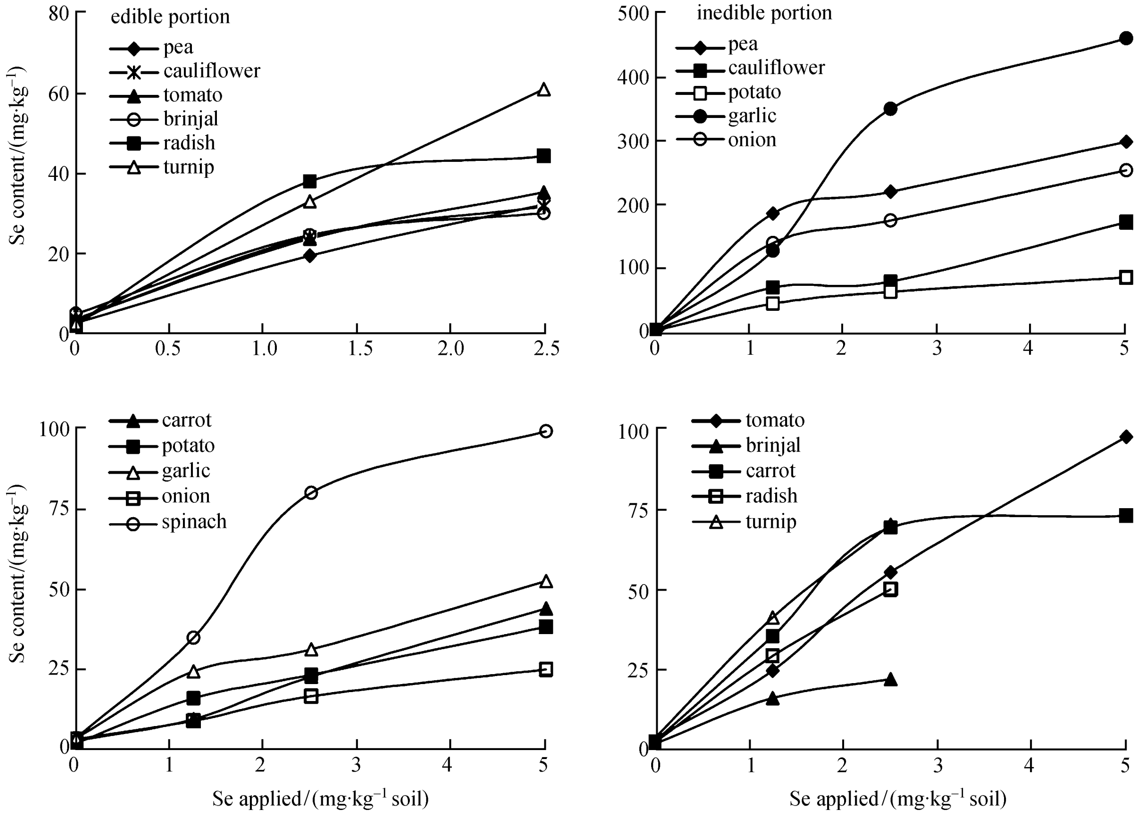

Fig. 1 Selenium accumulation in edible and inedible portion of vegetables in relation to different amounts of Se applied to soil

portion of onion absorbed the lowest amount of Se and that of spinach absorbed the highest. The selenium content in inedible parts of vegetables increased consistently as the level of Se increased in soil. At the no-Se control treatment, the Se concentration in inedible portion of different crops varied from 2.0 to 4.8 mg·kg^{-1} dry weight, with the lowest in potato and the highest in garlic. Compared to control, an appreciable increase in Se concentration of inedible part of different crops was observed with application of 1.25 mg·kg^{-1} Se to soil. The highest amount of Se was absorbed by peas (186.1 mg·kg^{-1}) and the lowest by brinjal (16.2 mg·kg^{-1}). The differences in Se content were, however, non-significant between carrot and turnip, potato and turnip, and radish and tomato. At levels of 2.5 and 5.0 mg·kg^{-1} Se application, garlic accumulated the largest amount of Se followed by peas, onion and cauliflower (Fig. 1). When the level of applied Se increased from no-Se control to 1.25 mg·kg^{-1} Se soil, a relative increase in the amount of Se absorbed by the edible as well as inedible part of vegetables was greater than that when level of applied Se further increased from 1.25 to 2.5 mg·kg^{-1} Se.

Total Se uptake is a function of biomass accumulation and the concentration of Se in plant tissues. In the no-Se control treatment, Se uptake by edible portions of different vegetable crops varied from 3.2 to 54.4 μg·pot^{-1}. At 1.25 mg·kg^{-1} Se application level, Se uptake by edible parts of all the vegetable crops varied from 7 to 485 μg·pot^{-1} and thereafter it continued to decrease as the level of Se increased up to 5 mg·kg^{-1} Se in soil. Since application of Se at higher levels was relatively less detrimental to biomass accumulation of inedible portions than the edible portions, uptake of Se in the inedible portions of vegetables was 5 to 10 times higher than that in the edible portions.

4 Discussion

Toxic effects of selenate-Se, in the present investigation, were mainly expressed as restriction in plant growth, burning of leaf margins and complete mortality at the highest level of Se applied to soil. Advanced senescence, yellowing of leaves and significant reduction in dry matter accumulation by different plant tissues of tomato was recorded by Pezzarossa et al. (1999), but complete mortality was not observed even with the application of 10 mg·kg^{-1} selenate-Se to soil. It was possibly due to the fact that tomato plants were grown in peat soil. In the present study, vegetables were grown in the soil containing only 0.3% organic matter. Addition of polysaccharides reduced the absorption of Se significantly by lettuce (Ferri et al., 2003) and thereby reduced the toxic effects of Se on its growth. Banuelos and Meek (1989) did not observe any significant differences in dry matter yield of different vegetables grown in peat soil mixture with $5\,\mathrm{mg\cdot kg^{-1}}$. Selenium was added in selenate form using the modified Hoagland solution containing $0.5\,\mathrm{mg\cdot L^{-1}}$ Se throughout the growing season until a total of $5\,\mathrm{mg\cdot kg^{-1}}$ Se was achieved. Significant reduction in the plant growth of *L. sativa* was observed with the application of $1.5\,\mathrm{mg\cdot kg^{-1}}$ Se as selenate-Se to the alkaline sandy soil (Pezzarossa et al., 2007). Selenium uptake by spinach and mustard crops grown in selenite-Se treated soil adversely affected the contents of total protein, vitamin C and crude fiber of both vegetables (Sagoo et al., 2004). Vegetable crops differ in their sensitivity to the form and amount of Se in soil. Different Se metabolism mechanisms should be involved in different vegetable plants. According to Brown and Shrift (1981), Se-accumulating plants could tolerate large amounts of Se due to a mechanism responsible for excluding Se from incorporation into proteins. None of the vegetable plants seems to possess this mechanism in spite of the fact that three of these belong to the Brassicaceae family (radish, cauliflower and turnip) and two to the Alliaceae family (onion and garlic). Both families possess several secondary accumulator members which can grow on soil with low to medium Se content and can accumulate up to $1000\,\mathrm{mg\cdot kg^{-1}}$ Se (Brown and Shrift, 1982). Possibly, the toxic Se effects in the present investigation were observed due to interference with sulphur metabolism. Selenium can substitute for S leading to the formation of Se analogues of S organic compounds in plants. Similarity of Se-aminoacids to their S-analogues of cysteine and methionine can disrupt the normal biochemical reactions and enzyme functions within cells (Anderson and Scarf, 1983). The incorporation of Se into proteins can result in the alteration of the protein structure, the inactivation of the proteins, the eventual poisoning of plants and leading to toxicity symptoms (Shamberger, 1985).

Seleniferous soils are sporadically distributed in north-western India (Dhillon and Dhillon, 2003). Vegetable crops growing under field conditions in the seleniferous region did not exhibit any sign depicting toxic Se effects on plants. The selenium content in toxic soils and edible portions of vegetables ranged from 0.23 to $4.55\,\mathrm{mg\cdot kg^{-1}}$ and 0.9 to $36\,\mathrm{mg\cdot kg^{-1}}$ dry weight in the seleniferous region. Possibly under field conditions, readily available Se is not provided to plants at a level high enough to cause toxicity symptoms

Increase in dry matter yield of inedible portions by 10%–21% at $1.25\,\mathrm{mg\cdot kg^{-1}}$ selenate-Se soil demonstrated the beneficial biological role of Se in the case of potato, radish and cauliflower plants in the present investigation. Similar growth promoting the role of Se has been observed in ryegrass (Hartikainen et al., 2000) and lettuce (Xue et al., 2001). Essentiality of Se for higher plants is still under debate, but its metabolic significance in plant development has recently been associated especially with increasing the tolerance of plants to oxidative stress, delaying senescence, promoting the growth of ageing seedlings and regulating the water status of plants under drought conditions (Germ and Stibilj, 2007).

All the vegetable crops readily accumulated Se from the selenate-Se treated soil. Selenate-Se is actively absorbed by plants following the transport path, followed by sulphate (Epstein, 1955) that is reduced to selenite-Se in the leaf before its incorporation into various organic seleno-compounds (Brown and Shrift, 1982). Since the selenate reduction and subsequent incorporation into organic compounds take place in the leaf, it may explain higher Se accumulation in the vegetative portion than other parts of vegetable crops as observed in the present investigation. Edible portions of all the vegetable crops accumulated Se many folds greater than the critical level of $5\,\mathrm{mg\cdot kg^{-1}}$ Se diet as suggested by the US Food and Nutrition Board (2000). Among vegetables grown on on-farm locations in the seleniferous region of Punjab where selenate-Se is the dominant form, except carrot and potato, all the vegetables could absorb 2–10 times more Se than its critical level in diet (Dhillon and Dhillon, 1991). Vegetables grown in the selenate-Se treated soil resulted in significantly greater concentrations of Se than the plants grown in soil treated with selenite-Se; the highest concentration of Se was recorded in broccoli (*B. oleracea* var. *botrytis*) floret ($1382\,\mathrm{mg\cdot kg^{-1}}$ Se dry matter) and ranged from 398 to $735\,\mathrm{mg\cdot kg^{-1}}$ Se in leaf tissues of different vegetables (Banuelos and Meek, 1989). In edible portions of vegetables grown at farmer's fields in the seleniferous region of Punjab, the Se content ranged between 0.9 (potato) and 50.9 (brinjal) $\mathrm{mg\cdot kg^{-1}}$ dry matter (Dhillon and Dhillon, 1991). On the other hand, the Se content of edible tissues of different vegetable crops grown in the western side of San Joaquin Valley ranged from 0.11 to $1.25\,\mathrm{mg\cdot kg^{-1}}$ (Bureau et al., 1988). Significant differences in Se content of vegetable in both situations may be due to the differences in Se species and chemical characteristics of seleniferous soils. Tomato plants accumulated Se in the selenate treated soil about 14 times more than that from the selenite treated soil (Pezzarossa et al., 2007). Although onion also belongs to the Alliaceae family as garlic, yet it absorbed relatively less Se ($28\,\mathrm{mg\cdot kg^{-1}}$ dry matter) than garlic (110 to $150\,\mathrm{mg\cdot kg^{-1}}$ Se) (Ip and Lisk, 1994). From the soil treated with $25\,\mathrm{mg\cdot kg^{-1}}$ selenite-Se, mustard and spinach tops absorbed 31.6 and $32.6\,\mathrm{mg\cdot kg^{-1}}$ Se, respectively (Sagoo et al., 2004). At a similar level of selenite-Se application, raya (*Brassica juncea* L. Czern) plants absorbed $136.9\,\mathrm{mg\cdot kg^{-1}}$ Se dry matter (Rani et al., 2005).

Large variations have been observed in human responses to Se supplementation in diet. Se intake ranging from 50 to $200\,\mathrm{\mu g\cdot d^{-1}}$ has been suggested as safe and adequate for adults. Sakurai and Tsuchiya (1975) proposed a maximum acceptable intake of $500\,\mathrm{\mu g\cdot d^{-1}}$

Se. Longnecker et al. (1991) did not observe any evidence of Se toxicity in the subjects residing in seleniferous areas of South Dakota whose Se intake was as high as 724 μg·d^{-1}. Daily consumption of vegetables may vary from 50 to 60 g·d^{-1} per person on dry weight basis (250 to 300 g·d^{-1} per person on fresh weight basis). Thus daily consumption of 5 to 20 g (dry weight) of potato, carrot or onion and 5 to 10 g (dry weight) of other vegetables grown in the soil treated with 1.25 mg·kg^{-1} Se are sufficient to meet the daily requirement of 50–200 μg Se. Even consumption of Se 3 times more than this may not prove harmful to humans (Sakurai and Tsuchiya, 1975).

Producing Se-rich foodstuffs either by growing in seleniferous regions or in the soils treated with Se, can also be an effective way to supplement diet with Se. Beneficial effects of Se are mainly dependent upon its chemical form in the diet and the most readily assimilated form of Se has been reported as selenomethionine (SeMeth) (Patrick, 2004). Supplementation of diet with yeast containing SeMeth can result in a significant reduction in the occurrence of prostate cancer (Duffield-Lillico et al., 2003). Cancer protection effect of Se in Se-rich broccoli (3 mg kg^{-1}) extends to mammary cancer and colon cancer (Finley et al., 2001). Supplementation of diet with 1 to 2 mg·kg^{-1} Se from high Se garlic can produce 56%–75% reduction in total tumor yield (Ip and Lisk, 1994). The evidences indicate that the methylated forms of Se are the active species against tumors and these methylated Se compounds are produced in greatest amount with excess Se intakes (Rayman and Clark, 2000).

5 Conclusions

Vegetable crops exhibited distinct differences in their Se accumulation capacity, particularly when grown in the soil containing high levels of selenate-Se. The greatest amount of Se was absorbed by the edible portion of radish and the lowest by onion bulb. Potato and spinach were tolerant whereas radish, turnip and brinjal were sensitive to high levels of selenate-Se in soil. Edible portions of vegetable crops grown in more than 1.25 mg·kg^{-1} selenate-Se soil will contain enough Se to cause toxicity symptoms and yield reduction. All the vegetable crops except carrot, potato and onion could absorb 20–40 mg·kg^{-1} Se by edible portions (dry weight) in 1.25 mg·kg^{-1} selenate-Se soil and hence they are potentially suitable for use as Se supplementation in the diet of humans in regions with Se deficiency. The results obtained in the present study need to be further confirmed by field experiments.

References

Anderson J W, Scarf A R (1983). Selenium and plant metabolism. In: Robb D A, Pierpoint W S, eds. Metals and Micronutrient: Uptake and Utilization by Plants. New York: Academic Press, 241–275

Arvy M P (1993). Selenate and selenite uptake and translocation in bean plants (*Phaseolusvulgaris* L.). Journal of Experimental Botany, 44: 1083–1087

Asher C J, Butler G W, Peterson P J (1977). Selenium transport in root system of tomato. Journal of Experimental Botany, 28: 279–291

Banuelos G S, Meek D W (1989). Selenium accumulation in selected vegetables. Journal of Plant Nutrition, 12: 1255–1272

Brown T A, Shrift A (1981). Exclusion of selenium from protein of selenium-tolerant *Astragalus* species. Plant Physiology, 67: 1051–1053

Brown T A, Shrift A (1982). Selenium: toxicity and tolerance in higher plants. Biological Reviews, 57: 59–84

Bureau R G, McDonald A, Jacobson A, May D, Grattan S, Shenan C, Swanton B, Sherer D, Abrams M, Epstein E, Rendig V (1988). Selenium in tissues of crops sampled from the west side of the San Joaquin valley, California. In: Tanji K K, Valoppi L, Woodring R C, eds. Selenium contents in animal and human food crops grown in California, USA Publication number 3330, University of California, and Oakland, USA, 61–66

Cantor A H, Scott M L, Naguchi T (1975). Biological availability of selenium in feedstuffs and selenium compounds for prevention of exudative diathesis in chicks. Journal of Nutrition, 105: 96–101

Cartes P, Gianfreda L, Mora M L (2005). Uptake of selenium and its antioxidant activity in ryegrass when applied as selenate and selenite forms. Plant and Soil, 276: 359–367

Dhillon K S, Dhillon S K (1991). Selenium toxicity in soils, plants and animals in some parts of Punjab, India. International Journal of Environmental Studies, 37: 15–24

Dhillon K S, Dhillon S K (1997). Distribution of seleniferous soils in north-west India and associated toxicity problems in the soil-plant-animal-human continuum. Land Contamination and Reclamation, 5: 313–322

Dhillon K S, Dhillon S K (2003). Distribution and management of seleniferous soils. Advances in Agronomy, 79: 119–184

Duffield-Lillico A J, Dalkin B L, Reid M E (2003). Selenium supplementation, baseline plasma selenium status and incidence of prostate cancer: An analysis of the complete treatment period of the Nutritional Prevention of Cancer Trial. BJU International, 91: 608–612

Epstein E (1955). Passive permeation and active transport of ions in plant roots. Plant Physiology, 30: 529–535

Ferri T, Petruzelli G, Pezzarossa B, Santaroni P, Brunori C, Morabito R (2003). Study of the influence of carboxymethylcellulose on the absorption of selenium (and selected metals) in a target plant. Microchemical Journal, 74: 257–265

Finley J W, Ip C, Lisk D J, Davis C D, Hintze K J, Whanger P D (2001). Cancer protective properties of high-selenium broccoli. Journal of Agriculture and Food Chemistry, 49: 2679–2683

Food and Nutrition Board, Institute of Medicine (2000). Selenium-Dietary Reference Intakes Vitamin C, Vitamin E, Selenium and Carotenoids. Washington, DC: National Academy Press, 284–324

Furr A K, Parkinson T F, Gutenmann W H, Pakkala I S, Lisk D J (1978). Elemental content of vegetables, grains, and forages field-grown on fly ash amended soil. Journal of Agriculture and Food Chemistry, 26: 357–359

Germ M, Stibilj V (2007). Selenium and plants. Acta Agricultura Slovenica, 89: 65–71

Hambuckers A, Dotreppe O, Hornick J, Istasse L, Dufrasne I (2008). Soil-applied selenium effects on tissue selenium concentrations in cultivated and adventitious grassland and pasture plant species. Communications in Soil Science and Plant Analysis, 39: 800–811

Hamilton J W, Beath O A (1964). Amount and chemical form of selenium in vegetable plants. Journal of Agriculture and Food Chemistry, 12: 371–374

Hartikainen H, Xue T, Piironen V (2000). Selenium as an antioxidant and pro-oxidant in ryegrass. Plant and Soil, 225: 193–200

Hopper J L, Parker D R (1999). Plant availability of selenite and selenate as influenced by the competing ions phosphate and sulphate. Plant and Soil, 210: 199–207

Ip C, Lisk D J (1994). Enrichment of selenium in allium vegetables for cancer prevention. Carcinogenesis, 15: 1881–1885

Jump R K, Sabey B R (1989). Soil test extractants for predicting selenium in plants. In: Jacobs L W, ed. Selenium in Agriculture and the Environment. Special Publication No. 23, Soil Science Society of America, Madison, WI, USA, 95–105

Levesque M, Vandette E D (1971). Selenium determination in soil and plant materials. Canadian Journal of Soil Science, 51: 85–93

Longnecker M P, Taylor P R, Levander O A, Howe S M, Veillon C, McAdam P A, Patterson K Y, Holden J M, Stampfer M, Morris J S, Willett W C (1991). Selenium in diet, blood, and toenails in relation to human health in a seleniferous area. American Journal of Clinical Nutrition, 53: 1288–1294

Mian Z P (1998). Status of selenium in food and population of Lahore city and cantonment area–Correlation of selenium level with heart and cancer diseases. Dissertation for the Doctoral Degree. Lahore: University of the Punjab

Patrick L (2004). Selenium biochemistry and cancer: A review of the literature. Alternative Medicine Reviews, 9: 239–258

Pezzarossa B, Malorgio F, Tonutti P (1999). Effects of selenium uptake by tomato plants on senescence, ripening and ethylene evolution. In: Kanellis A K, Chang C, Klee H, Bleeker A B, Pech J C, Grierson D, eds. Biology and Biotechnology of the Plant Hormone Ethylene II. Dordrecht: Kluwer Academic Publishers, 275–276

Pezzarossa B, Petruzelli G, Petacco F, Malorgio F, Ferri T (2007). Absorption of selenium by *Lactuca sativa* as affected by carboxymethylcellulose. Chemosphere, 67: 322–329

Rani N, Dhillon K S, Dhillon S K (2005). Critical levels of selenium in different crops grown in an alkaline silty loam soil treated with selenite-Se. Plant and Soil, 277: 367–374

Rayman M P, Clark L C (2000). Selenium in cancer prevention. In: Roussel A M, ed. Trace Elements in Man and Animals. New York: Plenum Press, 575–580

Saggoo M I S, Dhillon K S, Dhillon S K, Kour J (2004). Evaluation of consumability potentials of leafy vegetables harvested from selenium rich soil. Environmental Information Archives, 2: 479–489

Sakurai H, Tsuchiya K A (1975). A tentative recommendation for the maximum daily intake of selenium. Environmental Physiology and Biochemistry, 5: 107–118

Shamberger R J (1985). The genotoxicity of selenium. Mut Res, 154: 29–48.

Wang Z, Gao Y (2001). Biogeochemical cycling of selenium in Chinese environments. Applied Geochemistry, 16: 1345–1351

Warman P R, Muizelaar T, Termeer W C (1995). Bioavailability of As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Se and Zn from biosolids amended compost. Compost Science and Utilization, 3: 40–50

Wu L, Huang Z Z, Bureau R G (1988). Selenium accumulation and selenium-salt cotolerance in five grass species. Crop Science, 28: 517–522

Xue T, Hartikainen H, Piironen V (2001). Antioxidative and growth-promoting effect of selenium on senescing lettuce. Plant and Soil, 237: 55–61

Yang G Q, Wang S Z, Zhou R H, Sun S Z (1983). Endemic selenium intoxication of humans in China. American Journal of Clinical Nutrition, 37: 872–881