Indian Journal of Agricultural Sciences **92** (4): 431–7, April 2022/Review Article
https://doi.org/ 10.56093/ijas.v92i4.123862

Selenium in human and animal nutrition and need for selenium fertilization of crops

RAJENDRA PRASAD[1] and YASHBIR SINGH SHIVAY[1]*

ICAR-Indian Agricultural Research Institute, New Delhi 110 012, India

Received: 04 January 2020; Accepted: 13 January 2022

ABSTRACT

Selenium is an essential micronutrient for humans and animals, required to increase immunity, protect cells from free radical damage and inflammation, and support a healthy metabolism. The typical manifestations of selenium deficiency in humans are loss of appetite, fatigue after even mild exercise, cardiac arrhythmia and palpitations, cardiac insufficiency, cardiomegaly, and congestive heart failure, swelling in the joints of arms and legs in children aged 5–13 years resulting in structural shortening of the fingers and long bones resulting in growth retardation and stunting. Clinical signs of selenium deficiency in cattle include mastitis, perinatal death and abortions, suboptimal fertility in adult cattle and suboptimal milk production, acute nutritional muscular dystrophy in young calves, sudden collapse or death of calves within 2–3 days of birth, stiff-legged gait, weakness and inability to stand or walk in young calves. Being a micronutrient for humans and animals, the margin between deficiency and toxicity of selenium are small and selenium supplementation has to be carefully planned. Agronomic biofortification by fertilizing crops on selenium deficient soils is the safest way and has been successfully tried in China and Finland. It is now practised in Australia and several other countries. However, the research work on selenium in soils, plants, animals and humans is of recent origin in India and needs utmost attention and priority considering its importance in the food chain.

Keywords: Biofortification, Fertilization, Mastitis, Perinatal death, Swelling in knees

Selenium (Se) is one of those few elements in the periodic table which merit a historical consideration to evaluate the uniqueness of its biological effects. From its origin in the earth's crust to various soils, to distribution and accumulation in vegetation, and its subsequent toxicity to mammals through seleniferous foods, it follows an orderly sequence. In India, the first survey of soils and fodders concerning selenium content was reported from Gujarat state in 1970 (Sharma 1984). It was only after the incidence of a mysterious disease in animals in Haryana, that the research on this element gained momentum. While a systematic survey of selenium contents of soils and fodders of state and other related problems is being studied by soil scientists of the Haryana Agricultural University, Hisar and the role of selenium in animal nutrition is being systematically studied by experts at the National Dairy Research Institute, Karnal (Sharma 1984).

India has millions of people below the poverty line (BPL) who struggle with providing two square meals a day (Prasad 2013) and protein-energy deficiency (PED) is rampant in the country (Prasad 2003, Prasad and Shivay 2019). There is hardly any effort for attending to mineral nutrient deficiencies, although some attention to this has been drawn towards Zn and Fe deficiencies (Prasad 2012, Prasad *et al.* 2013, 2014, Shivay and Prasad 2014a, Prasad and Shivay 2020a) and some other minerals (Prasad *et al.* 2016). In this situation, selenium (Se) is a far cry. However, Se nutrition has received considerable attention in the world in recent decade (Rossipal and Tiran 1995, Reilly 1996, Moreno-Reyes *et al.* 1998, Brown and Arthur 2001, Papp *et al.* 2007, Xia 2005, Dharmasena 2014, Saha *et al.* 2017, Prasad and Shivay 2020b) and mineral food supplements in the USA and other countries have Se in them. It is estimated that globally at least a billion people are Se deficient which is up to one in seven people (Jones *et al.* 2016). Using moderate climate-change scenarios for 2080–2099, Jones *et al.* (2016) predicted that changes in climate and soil organic carbon (SOC) content will lead to overall decreased soil Se concentrations, particularly in agricultural areas; these decreases could increase the prevalence of Se deficiency.

Selenium (Se) has not received much attention from agronomists and soil scientists in India, because it is not yet an essential plant nutrient (Prasad 2007, Pilon-Smits 2015, Prasad and Shivay 2021). Nevertheless, certain algae require Se for their growth (Harrison *et al.* 1988, Stadtman 1996) and plants belonging to species *Astragalus, Stanleya, Morinda, Neptunia, Onopsis and Xylorhiza* can accumulate Se (Terry *et al.* 2000). Selenium has many similarities with

[1]ICAR-Indian Agricultural Research Institute, New Delhi.
*Corresponding author email: ysshivay@iari.res.in

sulphur. Both sulphur and selenium belong to the same group in the periodic table and have +4 and +6 active oxidation states as judged by the presence of compounds SO_2, SeO_2, Na_2SO_4, $NaSeO_4$ etc. (Rao 1999). Selenium and sulphur are also closely related elements utilized in nature for a vast array of biochemical reactions (Collins *et al.* 2012). Therefore, Arora (1985) used a mixture of sulphates of magnesium, ferrum, copper, zinc and cobalt for treating Se toxicity in cattle.

Selenium in Soils

The concentration of selenium in most soils lies within the range of 0.1 to 2 mg/kg soil. However, concentrations up to 1000 mg/kg soil total and 38 mg/kg soil selenium as water-soluble selenate have been reported in seleniferous soil areas of the world (Anderson *et al.* 1961, Lakin 1972). Seleniferous soils are found in the North American plains, Australia, Israel, Ireland, South Africa, South America, the former Soviet Union, France, Germany, and China (Fleming 1980, Watts 1994). However, a vast region of soils is deficient in Se. In India, Yadav *et al.* (2005) reported that drier lands' where lesser rains were received or where less irrigation water was available in Rajasthan and southern parts of Haryana had above normal soil selenium levels and tended to be seleniferous. These soils were also found to be alkaline. Punjab, Himachal Pradesh and northern parts of Haryana had normal levels of selenium in their soils, although some soils had high Se content. In the seleniferous areas of Punjab, the selenium content of surface (2.12 ± 1.13 mg/kg soil) and subsurface (1.16±0.51 mg/kg soil) layers of soils was 4–5 times higher than that of non-seleniferous areas (Dhillon and Dhillon 1991). In Uttar Pradesh soils, the total and water-soluble selenium ranged between 0.350 mg/kg soil to 0.549 mg/kg soil and 0.029 mg/kg soil to 0.039 mg/kg soil. Red soils had the highest total selenium, but the lowest water-soluble selenium, whereas black soils had the lowest total selenium and the highest water-soluble selenium. Perhaps, this trend could be explained based on organic matter of the soils, rather than on the type of soil. Selenium distribution in 12 soil profiles representing different bioclimatic zones of the Haryana State were studied (Singh and Kumar 1976). The total selenium varied between 1.0–10.5 mg/kg soil and, in many cases, the highest total selenium was accumulated in the second layer or sub-soil, which attributed it to the accumulation of clay in these layers. The higher total selenium in soils was positively correlated with $CaCO_3$, clay and iron content and negatively correlated with soil pH (Singh and Kumar 1976). The total and water-soluble selenium in Gujarat soils varied from 0.142 mg/kg soil to 0.678 mg/kg soil and 0.051 mg/kg soil to 0.121 mg/kg soil with averages of 0.375 mg/kg soil and 0.079 mg/kg soil, respectively (Patel and Mehta 1970). The soils of Gujarat cannot be called high selenium soils, as most of the normal soils in the world fall in the range of 0.1–2.0 mg/kg soil of selenium.

Total Se in soils can be determined using an atomic absorption spectrometer (Briggs and Crock 1986) or a spectrophotometer (Mathew and Narayan 2006) or by Fluorometry (Levesque and Vendette 1971). With regard to bioavailable Se in soils, several extractants are used for determining it. These include ammonium bicarbonate-DTPA, 0.5 M sodium bicarbonate, hot water, 0.1 mono-potassium phosphates, 0.25 M KCl and isotopically exchangeable Se. According to Dhillon *et al.* (2005), hot water-soluble Se can serve as a reliable index of bioavailable Se in alkaline seleniferous soils and it varies from 17–68 μg/kg in Northern India soil. Soils containing >0.5 mg Se/kg soil have been found to produce vegetation containing Se more than the maximum permissible level for animal consumption (Dhillon *et al.* 1992).

Selenium deficiency and toxicity in humans

For humans, Se is a vital mineral to increase immunity, protect cells from free radical damage and inflammation, and support a healthy metabolism. Selenium deficiency or Keshan disease (named after its discovery in Keshan County of western Heilongjiang province in China) had its widespread occurrence in 1935, and it was discovered that selenium deficiency was an important factor in its etiology (Ge and Yang 1993). It was endemic in children aged 2–10 years and in women of childbearing age covering areas from northeast to southwest China. The daily intake was only 3–11 μg Se per day in these areas (Luo *et al.* 1984). The typical manifestations of Keshan disease are loss of appetite, fatigue even after mild exercise, cardiac arrhythmia and palpitations, cardiac insufficiency, cardiomegaly, and congestive heart failure. Another disease associated with Se deficiency reported from China was Kashin-beck disease. The typical symptoms of Kashin-beck disease are swelling in the joints of arms and legs in children aged 5–13 years resulting in structural shortening of the fingers and long bones resulting in growth retardation and stunting (Li *et al.* 1984). The selenium contents of hair and whole blood in Se deficiency is abnormally low and so is the glutathione peroxidase (GSHPx) content in the blood. It may be mentioned that glutathione peroxidase is a selenoprotein (Rotruck *et al.* 1973) containing four Se atoms per molecule (Flohe *et al.* 1973). Selenoproteins have a role in skeletal muscle regeneration, cell maintenance, oxidative homeostasis, thyroid hormone metabolism, and immune responses (Reeves and Hoffman 2009, Castets *et al.* 2012). Selenium fertilization in China reduced Se deficiency from 40% in 1970 to 1% in 1986 (Li *et al.* 1984).

In some European and Middle East countries, the general approximate values for daily Se intake were: UK 60 μg Se/day; France 64 μg Se/day; Spain 94–107 μg Se/day; Belgium 60 μg Se/day; Italy 56 μg Se/day; Poland 25 μg Se/day; Iran 40 μg Se/day; Jordan 39 μg Se/day and Turkey 30–40 (Stoffaneller and Morse 2015). In Europe, the Finland soils were found to be particularly poor in Selenium and the Finnish Ministry of Agriculture and Forestry of Finland decided to implement selenium biofortification of food through fertilizers to increase the very low concentration of selenium in the nation's food chain in 1984. The program was quite successful in raising the amount of Se in plants and, consequently the human Se intake. The Se content in winter wheat increased from 0.01 mg/kg grain in 1982–1984 to 0.04 mg/kg grain in 1988 and the daily intake per person increased from 25 µg in 1975–1977 to 105 µg in 1988. Today, the amount of selenium added to fertilizers in Finland is 10 mg/kg fertilizer (Eurola *et al.* 1990). Some of the sincere efforts have also been made in India for agronomic biofortification of Zn in major food crops (Shivay *et al.* 2008abc, Shivay *et al.* 2013, Shivay and Prasad 2014b, Shivay *et al.* 2014, Shivay *et al.* 2016), however, biofortification approach is lacking in case of selenium in our country.

South Australians consume inadequate Se to maximise selenoenzyme expression and cancer protection, and Se intake levels have declined around 20% from the 1970s (Lyons *et al.* 2005). Field trials, along with glasshouse and growth chamber studies, were used to investigate the agronomic biofortification of wheat. Selenium applied as sodium selenate at rates of 4–120 g Se/ha increased grain Se concentration progressively up to 133-fold when sprayed on the soil at seeding and up to 20-fold when applied as a foliar spray after flowering. The threshold value of toxicity of around 325 mg Se/kg in leaves of young wheat plants was recorded, which was never reached by Se fertilization (Lyons *et al.* 2005) (Table 1). A meta-analysis confirms the high impact of Se fertilization as an effective Se biofortification strategy (Ros *et al.* 2016); both soil and foliar applications have proved good.

In India fertilization with selenium has yet not started. Some pot-culture studies were made in Punjab and different crops were in the following order in accumulating Se in their forage: raya 1.78–75.25 µg/g, wheat 3.00–4.72 µg/g, maize 1.55–6.63 µg/g and rice 1.26–4.58 µg/g in forage on a dry weight basis; thus rice accumulated the least (Dhillon *et al.* 2005). With regard to Se intake, in South India a low-income vegetarian diet may supply 27.4 µg Se/day, while a low-income non-vegetarian diet may supply 52.5 µg Se/day (Mahalingam 1997). The daily intake of Se by the adult population of Mumbai was reported to be 61.9 µg Se/day, which is adequate (Mahapatra *et al.* 2001). In a study in Punjab, three villages from the selenium-endemic area of Nawan Shahr district and two villages from the non-endemic area of Ludhiana district, Punjab, India, were covered. The daily intake of Se by men in the selenium-endemic area was 632 µg Se/day, while in the non-selenium-endemic area it was only 65 µg Se/day; the values for women were 472 and 52 µg Se/day, respectively (Hira *et al.* 2004). Se content in hair in Se-endemic areas was 255 and 231 µg/100 g in men and women, respectively, while it was only 4.97 and 4.77 µg/100 g in men and women, respectively in a non-endemic area. Thus, Se intake was a problem in Se-endemic areas.

Selenium content in food and Recommended Dietary Allowance (RDA) for humans

Selenium content (µg/100 g) in some grains in India is as follows: rice 5.8–17.6, wheat 6.2–26.3, maize 3.2–17.0, sorghum 9.1–28.7, pearl millet 14.6–39.1, red gram 13.1–

Table 1 Biofortification of some crops by foliar spray of selenium

Country	Crop	Source of Se	Dose of Se (g/ha)	Se (mg/kg)	Reference
Canada (Barley-red clover-potato rotation)	Barley (grain) 1993	Check	0	0.050[c]	MacLeod *et al.* (1998)
		Sodium selenite	10	0.512[b]	
		Sodium selenite	20	1.130[a]	
	Red clover (Ist cut) 1994	Residual applied to barley-1993	0	0.045[b]	MacLeod *et al.* (1998)
			10	0.077[b]	
			20	0.110[a]	
	Potato 1995	Residual applied to barley-1993	0	0.142[a]	MacLeod *et al.* (1998)
			10	0.022[b]	
			20	0.098[ab]	
Slovak Republic	Winter wheat	Check	0	0.032[c]	Ducsay *et al.* (2016)
		Sodium selenite	10	0.051[c]	
		Sodium selenite	20	0.072[b]	
		Sodium selenate	10	0.205[b]	
		Sodium selenate	20	0.445[a]	
China	Buckwheat-grain (2013)	Check	0	0.065[b]	Jiang *et al.* (2015)
		Sodium selenite	5	0.102[ab]	
		Sodium selenite	10	0.111[a]	
USA	Pasture of Rye grass + subterranean clover	Check	0	0.087[d]	Filby *et al.* (2007)
		Sodium selenite	600	1.170[c]	
		Sodium selenite	2240	4.240[b]	
		Sodium selenate	600	8.440[a]	

Rye grass-*Lolium perenne*; Subterranean clover-*Trifolium subterraneum*; Barley-*Hordeum vulgare*; Red clover-*Trifolium pratense*; potato-*Solanum tuberosum*; winter wheat-*Triticum aestivum*; Buckwheat-*Fagopyrum esculentum.*

37.6, chickpea 9.4–23.5, green gram 2.8–15.0, black gram 6.8–28.5, lentil 14.6–39.1 (Kumar and Krisnaswamy 2003); pulses, in general, have more Se because it is generally attached to proteins (Jaiswal *et al.* 2015). This is why non-vegetarian food is richer in Se. The richest source is oysters, cooked 100 g yields 154 µg of selenium. Tuna fish when cooked can provide 108.2 µg of Se. One hundred grams of other meats provide lean tenderloin of pork 51.6 µg of Se, lean beef 44.8 µg of Se and chicken leg or roasted breast 37.8 µg of Se.

The RDA for Se is 15 µg for infants 0–6 months; 20 µg for 7–12 months; 20 µg for children 1–3 years; 30 µg for children 4–8 years; 40 mg for children 9–13 years; 55 µg for adolescents and adults; 60 µg in women while pregnant and 70 µg while lactating women (Institute of Medicine 2000). The upper limits for Se intake are 40–60 µg/day for infants, 90 µg/day for children 1–3 years, 150 µg/day for children 4–8 years, 150–280 µg/day for children 9–13 years and 400 µg/day for 14 years onwards. However, a diet containing 1 mg Se/kg dry weight can lead to chronic poisoning in humans and animals and one-time ingestion of plant material containing 1000 mg Se/kg dry weight can be lethal (Wilber 1980). Excessive selenium causes hair loss, deformed and brittle nails, sloughing off of nails, tooth decay, mottled or discoloured skin, fatigue, irritability, listlessness, reduced mental alertness, hand tremors, tingling or loss of sensation in the arms or legs, reduced blood pressure and unconsciousness (MacFarquhar *et al.* 2010).

Selenium toxicity and deficiency in animals

Interest in Se in the USA started with its toxicity in grazing animals. It was first recognized in animals grazing on certain plants grown in seleniferous soils, which developed a peculiar condition called alkali disease, or blind staggers (McLester 1943). The typical symptoms were: hair loss, lameness pain, sloughing of joints of hooves, liver cirrhosis and anaemia. The disease could lead to mortality in animals. It was soon found that excess Se led to fatty infiltration and necrosis of the liver and Se was thus considered related to vitamin E (Williams 1973). Selenium toxicity has also been reported from Ireland, where the main visible symptoms are lameness, horizontal grooves or cracks in the hooves; occasional sloughing of hooves; reluctance to move and hair loss, especially from the tail and from India, where gangrene of distal extremities (below the tarsus or carpus, tips of ears, muzzle, the tip of tail or tongue) also occurs (Rogers *et al.* 1990). In India, Se poisoning in cattle may arise within 10–42 days of feeding rice straw, lucerne or berseem with Se levels 0.50–6.7 mg/kg dry matter. The problem soils have Se levels of 1.0–10.5 mg/kg (Arora *et al.* 1975).

It was soon discovered that, in general, many areas in the USA (Van Metre and Callan 2001), England (Ndiweni *et al.* 1991), Scotland (Arthur *et al.* 1979), Ireland (Cullerton *et al.* 1997), New Zealand (Davies and Watkinson 1966) and several other countries had Se deficiency. Clinical signs of selenium deficiency in cattle include mastitis, perinatal death and abortions, suboptimal fertility in adult cattle and suboptimal milk production, acute nutritional muscular dystrophy in young calves, sudden collapse or death of calves within 2–3 days of birth, stiff-legged gait, weakness and inability to stand or walk in young calves (Eulogio *et al.* 2012; Ran *et al.* 2010; Mehdi and Dufrasne 2016). Typical deficiency symptoms of Se deficiency in sheep include tiff gait, arched back, apparent lameness, reluctance to move, poor growth, reduced wool production, reduced ewe fertility, white muscle disease and sudden deaths (Kahn 2005, Caple *et al.* 1980, Hefnawy and Tórtora-Pérez 2010). Rotruck *et al.* (1973) found that Se deficiency resulted in oxidative damage to red blood cells, which was related to decreased activity of the enzyme glutathione peroxidase (GSHPx).

Selenium requirement by ruminants is 0.1–0.3 mg/kg body weight (NRC 1996). Pastures and forages in areas with adequate Se contain up to 0.2 mg/kg dry weight, while in areas with Se deficiency contain 0.05 mg/kg dry weight or less (Underwood 1981). According to Dargatz and Ross (1996), the rate of adequate selenium in the blood of cattle is between 0.08 and 0.16 mg/L and between 51 and 85 µg/L in the plasma (Villard *et al.* 2002). To achieve this adequate rate, an additional dietary intake of 0.5 mg/kg dry matter may be enough (NRC 1996). The rations high in fermentable carbohydrates, nitrates, sulfates, and calcium or hydrogen cyanide negatively influence the organism's use of the selenium contained in the diet (Mehdi and Dufrasne 2016).

Conclusion

Since selenium is emerging as an important element in human and animals nutrition throughout the world, we have not started a detailed study of this nutrient in India. It is high time that soil and plant research on selenium is being started in the country. ICAR-Indian Institute of Soil Science, Bhopal, India should take a lead in this research area and a detailed study on selenium in the soil-plants-animal-humans continuum can be initiated across the country at the earliest to address the issues related to its deficiency and toxicity.

REFERENCES

Anderson M S, Lakin H W, Beeson K C, Smith F F and Thacker E. 1961. Selenium in Agriculture. *USDA. Agricultural Research Service, Agriculture Handbook No* **200**: 1–65.

Arora S P, Parvinder K, Khirwar S S, Chopra R C and Ludri R S. 1975. Se levels in fodders and its relationship with Degnala Disease. *Indian Journal of Dairy Science* **28**: 249–53.

Arora S P. 1985. Livestock problems related to geochemistry in India include selenium toxicity and goitre. *Proceedings 1st International Symposium on Geochemistry and Health, London,* pp 164–80.

Arthur J R, Price J and Mills C F. 1979. Observations on the selenium status of cattle in the northeast of Scotland. *The Veterinary Record* **104**(15): 340–41.

Briggs P H and Crock J G. 1986. Automated determination of total selenium in rocks, soils, and plants. Geological Survey, US Department of Interior, Report 86.

Brown K M and Arthur J R. 2001. Selenium, selenoproteins and human health: a review. *Public Health Nutrition* **4**(2b): 593–99.

Caple L W, Andrewartha K A, Edwards S J A and Halpin C G. 1980. An examination of the selenium nutrition of sheep in Victoria. *Australian Veterinary Journal* **56**: 160–67.

Castets P, Lescure A, Guicheney P and Allamand V. 2012. Selenoprotein N in skeletal muscle: from diseases to function. *Journal of Molecular Medicine (Berl)* **90**(10): 1095–1107.

Collins R, Johansson AL, Karlberg T, Markova N, van den Berg S, Olesen K, Hammarström M, Flores A, Schuler H, Schiavone L H, Brzezinski P, Arner E S L and Högbom, M. Collins R, Johansson AL, Karlberg T, Markova N, van den Berg S, Olesen K, Hammarström M, Flores A, Schuler H, Schiavone L H, Brzezinski P, Arner E S L and Hogbom,o M. 2012. Biochemical discrimination between selenium and sulfur 1: A single residue provides selenium specificity to human selenocysteine lyase. *PLoS One* **7**(1): e30581.

Cullerton N, Parle P, Murphy W and Murphy J. 1997. Selenium supplementation for dairy cows. *Irish Journal of Agricultural and Food Research* **36**(1): 23–29.

Dargatz D A and Ross P F. 1996. Blood selenium concentrations in cows and heifers on 253 cow-calf operations in 18 states. *Journal of Animal Science* **74**: 2891–95.

Davies E B and Watkinson J H. 1966 Uptake of native and applied selenium by pasture species. *New Zealand Journal of Agricultural Research* **9**: 317–24.

Dharmasena A. 2014. Selenium supplementation in thyroid associated ophthalmopathy: an update. *International Journal of Ophthalmology* **7**(2): 365–75.

Dhillon K and Dhillon S K. 1991. Selenium toxicity in soils, plants and animals in some parts of Punjab, India. *International Journal of Environmental Studies* **37**(1–2): 15–24.

Dhillon K S, Bawa S S and Dhillon S K. 1992. Selenium toxicity in some plants and soils of Punjab. *Journal of the Indian Society of Soil Science* **40**: 132–36.

Dhillon K S, Neeraj Rani and Dhillon S K. 2005. Evaluation of different extractants for the estimation of bioavailable selenium in seleniferous soils of Northwest India. *Australian Journal of Soil Research* **43**: 639–45.

Ducsay L, Lozek L, Marcek M, Varenyiova M, Hozlar P and Losak T. 2016. Possibility of selenium biofortification of winter wheat grain. *Plant, Soil and Environment* **62**(8): 379–83.

Eulogio G L J, Hugo C V, Antonio C N, Alejandro C I and Juan M Q. 2012. Effects of the selenium and vitamin E in the production, physicochemical composition and somatic cell count in milk of Ayrshire cows. *Journal of Animal & Veterinary Advances* **11**: 687–91.

Eurola M, Ekholm P, Ylinen M, Koivistoinen P and Varo P. 1990. Effects of selenium fertilization on the selenium content of cereal grains, flour, and bread produced in Finland. *Cereal Chemistry* **67**(4): 334–37.

Filby S J, Peters A, Bourska C, Pirelli G and Oldfield J. 2007. Selenium fertilization of pastures for improved forage selenium content. *The Professional Animal Scientist* **23**: 144–47.

Fleming G A. 1980. Essential micronutrients. II. Iodine and selenium. *Applied Soil Trace Elements*, pp 199–234. Davis B E (Ed), New York, John Wiley & Sons.

Flohe L, Gunzler W A and Shock H H. 1973. Glutathione peroxidase-A selenoenzyme. *FEBS Letters* **32**: 132–34.

Ge K and Yang G. 1993. The epidemiology of selenium deficiency in the etiological study of endemic diseases in China. *American Journal of Clinical Nutrition,* (*Supplement)* **57**: 259S–63S

Harrison S J, Yu P W, Thompson P A, Price N M and Phillips D J. 1988. Survey of selenium requirements in marine phytoplankton. *Marine Ecology Progress Series* **47**: 89–96.

Hefnawy A E G and Tortora-Perez J L. 2010. The importance of selenium and the effects of its deficiency in animal health. *Small Ruminant Research* **89**: 185–92.

Hira C K, Partal K and Dhillon K S. 2004. Dietary selenium intake by men and women in high and low selenium areas of Punjab. *Public Health Nutrition* **7**(1): 39–43

Institute of Medicine. 2000. *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids.* Institute of Medicine, National Academy Press. Washington, DC, USA.

Jaiswal S K, Prakash R and Nagaraja T P. 2015. Selenium in storage proteins of wheat cultivated in selenium impacted soils of Punjab, India. *Acta Alimantaria* **44**(2): 235–41.

Jiang Y, Zeng Z H, Bu Y *et al.* 2015. Effects of selenium fertilizer on grain yield, Se uptake and distribution in common buckwheat (*Fagopyrum esculentum*). *Plant, Soil and Environment* **61**(8): 371–77.

Jones G D, Droz B, Greve P, Gottschalk P, Poffet D, McGrath S P, Seneviratne S I, Smith P and Winkel L H E. 2016. Selenium deficiency risk predicted to increase under future climate change. PANS Early Edition: 1–6. (www.pnas.org/cgi/doi/10.1073/pnas.1611576114)

Kahn C M. 2005. *Merck Veterinary Manual*. 9th edn. Merck & Co., Inc., Kenilworth, NJ, USA.

Kumar A and Krishnaswamy K. 2003. Selenium in human health. *Nutrition News* **24**(2): 3–5.

Lakin H W I. 1972. Selenium accumulation in soils and its absorption by plants and animals. *Geological Society of America Bulletin* **83**: 181–89.

Levesque M and Vendette E D. 1971. Selenium determination in soil and plant materials. *Canadian Journal of Soil Science* **51**(1): 85–93.

Li J Y, Ren S X, Cheng D Z, Wan H J, Liang S T, Zhang F J and Gao F M. 1984. Distribution of selenium in the microenvironment related to Kashin-Beck disease. *Selenium in Biology and Medicine,* pp 911–25. Combs G F, Spallholz J E, Levander O E and Oldfield J E (Eds) New York, AVI Van Nostrand.

Luo X M, Yang C L, Wei H J, Liu X and Qixo C H. 1984. Selenium intake and metabolic balance in 10 men consuming self-selected diets in a selenium-deficient area of Hebei Province, PR China. *FASEB Journal* **43**: 1097.

Lyons G H, Judson G J, Ortiz-Monasterio I, Genc Y, Stangoulis J C and Graham R D. 2005. Selenium in Australia: Selenium status and biofortification of wheat for better health. *Journal of Trace Elements and Medicinal Biology* **19**(1): 75–82.

MacFarquhar J K, Broussard D L, Melstrom P, Hutchinson R, Wolkin A, Martin C, Burk R F, Dunn J R, Green A L, Hammond R, Schaffner W and Jones T F. 2010. Acute selenium toxicity associated with a dietary supplement. *Archives of Internal Medicine* **170**(3): 256–61.

MacLeod J A, Gupta U C, Milburn P and Sanderson J B. 1998. Selenium concentration in plant material, drainage and surface water as influenced by Se applied to barley foliage in a barley–red clover–potato rotation. *Canadian Journal of Soil Science* **78**: 685–88.

Mahalingam T R, Vijayalakshni S, Krishna and Prabhu R. 1997. Studies on some trace and minor elements in blood. A survey of the Kalpakkan (India) population. Part III: Studies on dietary intake and its correlation to blood levels. *Biological Trace Element Research* **57**: 223–38.

Mahapatra S, Tripathi R M, Raghunath R and Sadasivan S. 2001. Daily intake of selenium by the adult population of Mumbai, India. *Science of Total Environment* **277**(1–3): 217–23.

Mathew M and Narayan B. 2006. An easy spectrophotometric determination of selenium using azure B as a chromogenic reagent. *Indian Journal of Chemical Technology* **13**: 455–58.

McLester J S. 1943. *Nutrition and diet in health and disease,* 4th edn, pp 128–29. WB Saunders, Philadelphia. PA, USA.

Mehdi Y and Dufrasne I. 2016. Selenium in Cattle: A Review. *Molecules* **21**(5): 545–59.

Moreno-Reyes R, Suetens C, Mathieu F, Begaux F, Zhu D, Rivera M T, Boelaert M, Nève J, Perlmutter N and Vanderpas J. 1998. Kashin–Beck osteoarthropathy in rural Tibet in relation to selenium and iodine status. *New England Journal of Medicine* **339**(16): 1112–20.

Ndiweni N, Field T R, Williams M R, Booth J M and Finch J M. 1991. Studies on the incidence of clinical mastitis and blood levels of vitamin E and selenium in dairy herds in England. *The Veterinary Record* **129**(5): 86–88.

NRC. 1996. *Nutrient Requirements of Beef Cattle,* 7th edn, (Update 2000); National Research Council, National Academy Press, Washington, DC, USA,

Papp L V, Lu J, Holmgren A and Khanna K K. 2007. From selenium to selenoproteins: synthesis, identity, and their role in human health. *Antioxidants & Redox Signaling* **9**(7): 775–806.

Patel C A and Mehta B V. 1970. Se status of soils and common fodders in Gujarat. *Indian Journal of Agricultural Sciences* **40**: 389–99.

Pilon-Smits E A H. 2015. *Progress in Botany 76*. Luttge U and Beyschlag W (Eds), Springer International Publishing Switzerland (DOI 10.1007/978-3-319-08807-5).

Prasad R and Shivay Y S. 2019. Fertilizer nitrogen and global warming – A review. *Indian Journal of Agricultural Sciences* **89**(9): 1401–06.

Prasad R and Shivay Y S. 2020a. Agronomic biofortification of plant foods with minerals, vitamins and metabolites with chemical fertilizers and liming. *Journal of Plant Nutrition* **43**(10): 1534–54.

Prasad R and Shivay Y S. 2020b. Selenium fertilization of crops for sustenance of human and animal nutrition and health. *Indian Journal of Fertilisers* **16**(10): 1034–39.

Prasad R and Shivay Y S. 2021. *Soil Fertility and Plant Nutrient Management*. 201 p. ISBN: 978-93-90512-27-0. Published by New India Publishing Agency, New Delhi.

Prasad R, Majumdar K, Shivay Y S and Kapil U. 2016. *Minerals in Plant and Human Nutrition and Health*. International Plant Nutrition Institute, Peachtree Corners, GA, USA, 80 p.

Prasad R, Shivay Y S and Kumar D. 2013. Zinc fertilization of cereals for increased production and alleviation of zinc malnutrition in India. *Agricultural Research* **2**(2): 111–18.

Prasad R, Shivay Y S and Kumar D. 2014. Agronomic biofortification of cereal grains with iron and zinc. *Advances in Agronomy* **125**: 55–91.

Prasad R. 2003. Protein-energy malnutrition and fertilizer use in India. *Fertilizer News* **48**(8): 13–26.

Prasad R. 2007. *Crop Nutrition-Principles and Practices*, New Delhi, New Vishal Publications. 272 p.

Prasad R. 2012. Micro-mineral nutrient deficiencies in humans, animals, plants and their amelioration. *Proceedings National Academy of Sciences, India* **82** B: 225–33.

Prasad R. 2013. Population growth, food shortages and ways to alleviate hunger. *Current Science* **105**(1): 32–36.

Ran L, Wu X, Shen X, Zhang K, Ren F and Huang K. 2010. Effects of selenium form on blood and milk selenium concentrations, milk component and milk fatty acid composition in dairy cows. *Journal of Science of Food and Agriculture* **90**: 2214–19

Rao C N R. 1999. *Understanding Chemistry*. University Press (India) Ltd, Hyderabad.

Reeves M A and Hoffmann P R. 2009. The human selenoproteome: recent insights into functions and regulation. *Cellular and Molecular Life Sciences* **66**(15): 2457–78.

Reilly C. 1996. *Selenium in Food and Health*. London, Blackie Academic and Professional.

Rogers P, Arora S P, Fleming G A, Crinon R A P and McLaughlin J G. 1990. Selenium toxicity in farm animals: treatment and prevention. *Irish Veterinary Journal* **43**: 151–53.

Ros G H, van Rotterdam A M D, Bussink D W and Bindraban P S. 2016. Selenium fertilization strategies for bio-fortification of food: an agro-ecosystem approach. *Plant and Soil* **404**(1–2): 99–112.

Rossipal E and Tiran B. 1995. Selenium and glutathione peroxidase levels in healthy infants and children in Austria and the influence of nutrition regimens on these levels. *Nutrition* **11**(5 suppl): 573–75.

Rotruck J T, Pope A L, Ganther H E, Swanson A B, Hateman D G and Hoekstra W G. 1973. Selenium: Biochemical role as a component of glutathione peroxidase. *Science* **179**: 588–90.

Saha U, Fayiga A, Biswas B K and Sonon L. 2017. Selenium in soil–crop–animal system: A holistic perspective to manage animal and human health. *International Journal of Applied Agricultural Science* **3**(3): 51–66.

Sharma S. 1984. Selenium research in India. *International Journal of Environmental Studies* **22**(3-4): 231–39.

Shivay Y S and Prasad R 2014b. Effect of source and methods of zinc application on corn productivity, nitrogen and zinc concentrations and uptake by high quality protein corn (*Zea mays*). *Egyptian Journal of Biology* **16**(1): 72–78.

Shivay Y S and Prasad R. 2014a. Zinc deficiency in humans and its amelioration. *Indian Journal of Community Health* **27**: Supp S1.

Shivay Y S, Kumar D and Prasad R. 2008b. Effect of zinc-enriched urea on productivity, zinc uptake and efficiency of an aromatic rice-wheat cropping system. *Nutrient Cycling in Agroecosystems* **81**(3): 229–43.

Shivay Y S, Kumar D, Prasad R and Ahlawat I P S. 2008a. Relative yield and zinc uptake by rice from zinc sulphate and zinc oxide coatings onto urea. *Nutrient Cycling in Agroecosystems* **80**(2): 181–88.

Shivay Y S, Prasad R and Pal M. 2013. Zinc fortification of oats grain through zinc fertilisation. *Agricultural Research* **2**(4): 375–81.

Shivay Y S, Prasad R and Pal M. 2014. Effect of variety and zinc application on yield, profitability, protein content and zinc and nitrogen uptake by chickpea (*Cicer arietinum*). *Indian Journal of Agronomy* **59**(2): 317–21.

Shivay Y S, Prasad R and Rahal A. 2008c. Relative efficiency of zinc oxide and zinc sulphate-enriched urea for spring wheat. *Nutrient Cycling in Agroecosystems* **82**: 259–64.

Shivay Y S, Prasad R, Kaur R and Pal M. 2016. Relative efficiency of zinc sulphate and chelated zinc on zinc biofortification of rice grains and zinc use-efficiency in *Basmati* rice. *Proceedings of the National Academy of Sciences, India, Section B Biological Sciences* **86**(4): 973–84.

Singh M and Kumar P. 1976. Se distribution in soils of bioclimatic zones of Haryana. *Journal of the Indian Society of Soil Science* **24**(1): 62–67.

Stadtman T C. 1996. Selenocysteine. *Annual Review of*

Biochemistry **65**: 83–100.
Stoffaneller R and Morse M L. 2015. A review of dietary selenium intake and selenium status in Europe and the Middle East. *Nutrients* **7**(3): 1494–1537.
Terry N, Zayed A M, deSouza M P and Tarun A S. 2000. Selenium in higher plants. *Annual Review of Plant Physiology* **51**: 401–32.
Underwood E J. 1981. The Mineral Nutrition of Livestock, 2nd edn. Commonwealth Agricultural Bureau, Slough, UK.
Van Metre D C and Callan R J. 2001. Selenium and vitamin E. *The Veterinary Clinics of North America. Food Animal Practice* **17**(2): 373–402.
Villard D, Arthur J R, Gonzalez J M and Pallares F J. 2002. Selenium status in cattle: Interpretation of laboratory results. *Bovine Practice* **36**: 73–80.
Watts D L. 1994. The nutritional relationships of selenium. *The Journal of Orthomolecular Medicine* **9**(2): 111–17.
Wilber C G. 1980. Toxicology of selenium-A review. *Clinical Toxicology* **17**: 171–230.
Williams S R. 1973. *Nutrition and diet therapy,* 2nd edn. Mosby, St Louis M, USA.
Xia Y, Hill K E, Byrne D W, Xu J and Burk R F. 2005. Effectiveness of selenium supplements in a low-selenium area of China. *The American Journal of Clinical Nutrition* **81**(4): 829–34.
Yadav S K, Singh I, Singh D and Han S D. 2005. Selenium status in soils of northern districts of India. *Journal of Environmental Management* **75**(2): 129–32.