

## Boron in Indian agriculture – A review

RAJENDRA PRASAD<sup>1</sup>, DINESH KUMAR<sup>2</sup>, Y.S. SHIVAY<sup>3</sup> AND D.S. RANA<sup>4</sup>

ICAR - Indian Agricultural Research Institute, New Delhi 110 012

Received : December 2013; Revised accepted : August 2014

### ABSTRACT

Boron (B) is an essential plant nutrient and its specific deficiency symptoms are well documented in several crops. Boron is essential for the development of reproductive tissues and its deficiency results in low grain set or poor quality seeds and fruits. Adequate B nutrition is reported to reduce incidence of some diseases in plants. About one-third of the cultivated soils, especially in the eastern and north-eastern states of India are deficient in B. Good responses for a number of crops to B have been reported. Borax and boric acid are the common B fertilizers. The average amounts of B removed (g/tonne grain or other economic produce) by some crops are: 21 in wheat [*Triticum aestivum* (L.) emend. Fiori & Paol], 22 in pearl millet [*Pennisetum glaucum* (L.) R. Br. Emend. Stuntz], 36 in sorghum [*Sorghum bicolor* (L.) Moench], 17 in cowpea [*Vigna unguiculata* (L.) Walp], 16 in cotton (*Gossypium* spp.), 21 in cabbage [*Brassica oleracea* (L.) var. *capitata*], 15 in cluster bean (*Cyamopsis tetragonoloba* L.), 14 in castor (*Ricinus communis* L.), 9 in groundnut (*Arachis hypogaea* L.) and potato (*Solanum tuberosum* L.) and 23 in brinjal (*Solanum melongena* L.). Boron, possibly because of its role in lignin formation is able to reduce the incidence of several diseases in plants. High amounts of B in irrigation water could be toxic to crops and irrigation water having < 3 mg B/litre is ideal for B tolerant and semi-tolerant crops.

**Key words:** Abortion of flowers, Boron, Fruit quality, Irrigation water, RNA synthesis

Boron (B) deficiency is one of the major constraints to crop production (Sillanpaa, 1982), and it has been reported in over 80 countries and in 132 crops over the last 60 years (Shorrocks, 1997). Boron deficiency has been realized as the second most important micronutrient constraint in crops after that of zinc (Zn) on global scale (Ahmad *et al.*, 2012). B has emerged as an important micronutrient in Indian agriculture, next only to zinc in the context of the spread of its deficiency (Sathya *et al.*, 2009). About one-third of the cultivated soils in India are deficient in B (Gupta *et al.*, 2008). Sandy, highly leached, calcareous (>15% calcium carbonate), high pH (> 7) and recently limed soils are prone to B deficiency (Borkakati and Takkar, 2000; Alloway, 2008). In India, boron deficiency was initially reported 2% in the year 1980 (Katyral and Vlek, 1985), which has now increased to 52% (Singh, 2012). Its deficiency has been widely found in highly calcareous soils of Bihar, Tamil Nadu, Eastern Uttar Pradesh and Saurashtra, sandy soils of Haryana and Rajasthan, hill and sub-montaneous soils of north Himalayan and NEH States and in red and lateritic soils of Orissa, Karnataka, Andhra Pradesh and Kokan region. Sakal *et al.* (2002)

reported that in calcareous soils of north Bihar about 48% of cultivated soils were deficient in B. The B deficient soils in India are generally in the eastern states of Assam, Bihar, Meghalaya, West Bengal, Jharkhand and Orissa and include acid red and lateritic soils in addition to high pH calcareous soils (Behera *et al.*, 2009).

### Functions of B in plants

Boron as an essential plant nutrient was reported as early as 1923 by Warrington (Tandon, 1995). However, B is neither an enzyme constituent nor does it directly affect enzyme activities (Prasad, 2007). B is relatively immobile in plants and generally B content in plants increases from lower to upper parts (Cripps, 1956). B in anthers, stigmas and ovaries may be twice as high as in stems of plants (Sywortokin, 1958), suggesting its role in pollen formation and quality of flowers and fruits. In plants B is required in the structure of cell wall (O'Neil *et al.*, 2004) and this function is attributed to role of boron in cross-linking of cell wall proteins (Dell and Huang, 1997). B is essential for the development of reproductive tissues and its deficiency results in low grain set or poor quality seeds (Dell *et al.*, 2002). B deficiency may trigger early synthesis of ethylene leading to poor fruit quality (Bell and Dell, 2008). Some recent studies in Geochemistry point out the

<sup>1</sup>Corresponding author Email: rajmua36@gmail.com

<sup>1</sup>Ex-ICAR National Professor (Agronomy); <sup>2,3,4</sup>Principal Scientist, Division of Agronomy, IARI, New Delhi 110 012

importance of B in the synthesis of RNA in the prebiotic era (Periur, 2001; Scorei and Cimpoiasu, 2006). The important functions of B in crop plants can be summarized as:

- Carbohydrate metabolism and transport of sugars through membranes
- Nucleic acids (DNA and RNA) and phytohormone syntheses
- Structural integrity of plasma membrane (boric acid is most probably involved in linking of some cell components)
- Tissue development (involvement in a messenger role in plants is suggested)
- Formation of stable complexes with compounds having *cis*-hydroxyl groups
- Formation of B complexes with the constituents of cell walls and plasma membranes

### Boron needs of crops

Plant species differ in their B requirements; the general critical deficiency range is 5-10 mg/kg dry matter (DM) in monocots (wheat, barley etc.) and 20–70 mg/kg dry matter (DM) in dicots (legumes) (Romheld and Marschner, 1991; Gupta, 1993). Differences in the B demand of monocots and dicots are probably related to the amounts of pectic substances present in their cell wall. Only a meager amount of pectic material is present in the cell walls of monocots and such species also have much lower Ca requirements. In a recent study, application of both Ca and B to four cultivars of maize significantly enhanced shoot dry matter production (Kanwal *et al.*, 2008). Excess B concentration can be toxic to plants, the critical toxicity limits (mg/kg DM) are: 100 for corn (*Zea mays* L.), 100-270 for wheat (*Triticum aestivum* L. emend. Fiori & Paol.), 400 for cucumber (*Cucumis sativus*) and 100 for squash (*Cucurbita pepo*). Thus, crops differ in their sensitivity to B deficiency and toxicity. The 3 major categories of plant species in relation to B nutrition are given below (Romheld and Marschner, 1991; Gupta, 1993):

- i. Low sensitivity to B deficiency and less tolerance to B toxicity: Wheat [*Triticum aestivum* (L.) emend. Fiori & Paol], barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench], soybean (*Glycine max* L.), other beans and potato (*Solanum tuberosum* L.).
- ii. Medium sensitivity to B deficiency and medium tolerance to B toxicity: Broccoli (*Brassica oleracea* L. var. *italica*), cabbage (*Brassica oleracea* L. var. *capitata*), carrot (*Daucus carota* L.), lettuce (*Lactuca sativa* L.), radish (*Raphanus sativus* L.), spinach (*Spinacia oleracea* L.), tomato (*Lycopersicon*

*esculentum* Mill), sweet corn (*Zea mays* L. var. *saccharata*).

- iii. High sensitivity to B deficiency and high tolerance to B toxicity: Alfalfa or lucerne (*Medicago sativa* L.), sugarbeet (*Beta vulgaris* L.) and turnip (*Brassica rapa* var. *rapa*).

### Boron deficiency symptoms and critical deficiency level (CDL) in plant tissue

Being a less mobile nutrient in plants, boron deficiency symptoms first appear on stem tips, young leaves, flowers and buds (Dobermann and Fairhurst, 2000). B deficiency symptoms in plants include dark green, leathery, downward cupping of leaves and dieback of shoot tips (Bell, 1997). Abortion of flowers and flower buds, squares in cotton, poorly shaped fruits and malformed seeds, which fetch a much lower price in the market, has the most shocking effect on growers. Some of the known B deficiencies are ‘crown and heart rot’ in sugar beets, ‘tip burn’ in lettuce, ‘cracked stems’ in celery, formation of internal ‘cork like’ material in cauliflower and ‘hollow heart’ in groundnut kernels. All these effects are due to association of B with pectic material in cell walls (Mengel and Kirkby, 1987). B is considered as a fertilizer for quality in fruits. The critical deficiency level (CDL) of B is 5–39 mg/kg DM in mature tissue; the values differ from species to species.

### Total boron content in Indian soils

The total B contents in Indian soils varied from 7 to 630 mg B/kg of soil. Soils in arid and semi-arid tropical regions had the highest contents of B. Satyanarayan (1958) reported the influence of the geology of soil parent materials on the total B content as 7 mg B/kg in granite (gneiss), 22 mg B/kg in lavas, 36 mg B/kg in basalt, 13 mg B/kg in limestone, 62 mg B/kg in alluvium, 44 mg B/kg in slate and 371 mg B/kg in laterite. Certain young calcareous alluvial soils (Calciorthents/Calcifluvents) had B contents of up to 83 mg/kg. Coarse textured, leached soils (Haplustalfs) showed lower B contents and its accumulation was dependent upon the calcium carbonate (CaCO<sub>3</sub>) content in the profile (Sakal and Singh, 1995). On the other hand, Vertisol and Alfisol soils of the Deccan trap formed from granite, basalt, shale, slate and limestone had 28–57 mg B/kg. Raychaudhari and Datta Biswas (1964) found that Xerochrepts developed on granite and crystalline gneiss contained 8.5 mg B/kg, but lateritic (Alfisol) soils from more or less similar geologic parent materials contained 25 mg B/kg.

### Available boron contents in Indian soils

The contents of ‘available’ (hot water soluble – HWS)

B in Indian soils ranged from 0.75 to 8.0 mg B/kg (Singh, 2001). Availability of soil B to plants is often related to the total B content as well as other properties such as pH, CaCO<sub>3</sub> and organic matter contents, nutrient interactions, plant type or variety and environmental factors, which strongly influence the emergence of B deficiency or toxicity in plants (Sakal *et al.*, 1996; Saha and Singh, 1997). Deficiencies of B in Indian soils ranged from 2% in alluvial soils (Ustipsammments) of Gujarat, to 68% in red soils (Calciorthhents, Haplustalfs) in Bihar, with a mean of 33% for the whole country (Singh, 1999; Singh 2006). A maximum occurrence of B deficiency (54–86%) was recorded in Alfisol soils of Asom and West Bengal, due to a decrease in water soluble B with increase in rainfall (Sakal and Singh, 1995). A significant negative correlation exists between soluble B and CaCO<sub>3</sub> content (Saha and Singh, 1997). An increase in organic carbon (OC) content from 0.50 to 0.75% enhances the fixation of B in soils by 48–60%. Thus, association of B with OC prevents its leaching and thereby ensures its higher availability to crop plants (Katyal and Vlek, 1985). High concentrations of B were recorded in the saline soils of the Indo-Gangetic plain and moderate level in Vertic Ustochrepts of Rajasthan and Madhya Pradesh (Mathur *et al.*, 1964; Saha *et al.*, 1998).

#### **Boron critical deficiency levels (CDL) in soils**

In India, hot water extractable B (Berger and Troug, 1939) is the accepted procedure for determining available B in soils and the general CDL is 0.5 mg/kg soil (or 0.5 ppm) (Rattan *et al.*, 2008), although different values have been reported by researchers in different States of India. These include 0.35–0.36 mg/kg in Punjab (Singh and Randhawa, 1977), 0.52–0.53 mg/kg in Bihar (Sakal *et al.*, 1996) and Uttar Pradesh (Takkar *et al.*, 1997). Based on large number of field trials data on crop response to B fertilization, Singh (2007) however, reported hot water extractable B concentration of <0.25, 0.25–0.50, 0.50–0.75, 0.75–1.00 and >1.00 mg/kg for categorizing very low, low, medium, adequate and high B fertility soils, respectively. As a contrast to other plant nutrients, B in soil solution is present in non-ionic form as boric acid [H<sub>3</sub>BO<sub>3</sub>] or B(OH)<sub>3</sub> and is generally taken up in this form (Bingham *et al.*, 1970). Based on solubility criteria the average concentration of H<sub>3</sub>BO<sub>3</sub> in soil solution is approximately 10<sup>-5.5</sup> M (Lindsay, 1991).

#### **Boron toxicity symptoms and critical toxic level in plant tissue**

Boron toxicity is noticed in some limited geographical areas and mostly in sensitive crops. The most prominent symptoms of B toxicity are the yellowing of the leaf tip or leaflets followed by browning and scorching or gradual

necrosis of the tips and leaf margins (Gowarikar, 2009). This renders the plants stunted and bushy, with a few thinly branched leaves supporting small, curled-up and discoloured leaflets. Older leaves develop brown spots which make the leaf appear dried up and brittle (Gowarikar, 2009). Excess accumulation of B above 3.0 mg B/kg soil induces leaf necrosis; reduces leaf area to the extent which significantly reduces the photosynthesis, yield, quality of produce of common crops (Shorrocks, 1997).

#### **Soil factors affecting B availability**

A number of soil factors affect B availability in soils; some of these are discussed here:

*Soil solution pH:* Soil solution pH is the most important factor affecting B availability (Takkar *et al.*, 1989). B availability is the least below pH 5.0 and between 7.2 and 8.7. That is why application of lime to acid soils, in excessive amounts, can sometimes render plants deficient in B. This is in contrast to Fe, whose availability decreases as the pH increases and Mo, whose availability increases as the pH increases.

*Soil organic matter (SOM):* Boron associated with humic colloids is the principal B pool for plant growth in most of the agricultural soils (Jones, 2003) and a positive correlation between levels of SOM and the amount of hot water-soluble B has been reported (Chang *et al.*, 1983; Takkar *et al.*, 1989; Shafiq *et al.*, 2008).

*Soil moisture:* Boron bioavailability decreases under drought conditions because of reduced mobility of B in soil by mass flow to roots (Barber, 1995). Lack of moisture in soil also reduces transpiration rate, which reduces B transport to shoots (Lovatt, 1985). Soil moisture stress is reported to reduce B uptake and increase B deficiency in crops as reported by Miley and Woodall (1967) in cotton and by Faust and Shear (1968) in apple. This would also partly explain reports of B deficiency in groundnut, which is generally grown under rainfed or dryland agriculture conditions.

*Soil texture:* Coarse-textured soils often contain less available B than fine-textured soils (Takkar *et al.*, 1989), primarily due to lower levels of soil organic matter. This could be the reasons for B deficiencies in crop plants in sandy soils (Gupta, 1968).

#### **Response of crops to boron and its methods of application**

A large number of crops have responded to B fertilization. Precise B fertilization is important for the normal growth, yields and quality of produce due to very narrow range of boron (B) deficiency and toxicity in soils and plants (Singh and Goswami, 2013). The range of response

(t/ha) and mean (t/ha) for some crops were: wheat [0.03-1.17, mean 0.39], rice [0.01-1.67, mean 0.32], maize [0.17-1.05, mean 0.57], chickpea [0.09-0.90, mean 0.35], lentil [0.04-0.49, mean 0.24], pigeonpea [0.03-0.32, mean 0.19], groundnut [0.05-0.42, mean 0.12], linseed [0.24-0.17, mean 0.09], sunflower [0.03-0.85, mean 0.55], mustard [0.12-0.50, mean 0.27], onion [3.87-7.30, mean 4.47] and cotton [0.06-0.45, mean 0.26] (Singh, 1999). Boron application @ 0.75 kg and 1.5 kg/ha in spring sunflower was effective and the crop responded well up to the second dose, and the higher (1.5 kg/ha) level gave the highest seed yield (2.01 t/ha), which was 13.5 and 6.3% more than that of the control and 0.75 kg B/ha respectively (Shekhawat and Shivay, 2008).

Dwivedi *et al.* (1990) reported that soil application of 20 kg sodium tetraborate (14% B) to supply 2.8 kg B/ha or two foliar sprays with 0.2% solution of this salt proved equally effective in increasing soybean grain yield. The residual effect of soil applied B on subsequent wheat crop was significantly higher as compared with direct foliar B application. As B undergoes less leaching in fine-textured soils, soil application may produce residual effect. In view of very sharp and narrow difference between optimum and toxic levels of B, more precaution is needed in its repeat application, particularly in medium- to fine-textured soils. Boron deficiency is also invariably corrected by its soil application depending upon soil type (Arora *et al.*, 1985; Sakal *et al.*, 1988; Ali and Monoranjan, 1989). In calcareous soils of Bihar, the rate varying between 1.0 to 2.5 kg B/ha has been found to be optimum for different crops (Sakal *et al.*, 1988; Sinha *et al.*, 1991).

Mondal *et al.* (2012) concluded that foliar application of 0.2% boron at flowering along with three irrigations at branching, pre-flowering and pod development stages are optimum for realizing optimum yield of summer mungbean on a sandy loam alluvial soil in West Bengal.

The highest yield, oil and protein content of rapeseed was recorded when NPK (80:40:40 kg/ha) was combined with soil application of B at 0.5 kg/ha as calbor and organic manure at 5 tonnes/ha (Mandal and Das, 2011). Ansari *et al.* (2013) concluded that both soil and foliar applied boron have positive effect on growth and yield attributes as well as pod yield of groundnut. They clearly demonstrated that solubor as soil application @ 10 kg/ha can be applied to achieve better land utilization, high yield as well as productivity and profitability than other treatments under rainfed sandy loam soils. Generally 5–10 kg borax (11% B)/ha is applied to soil or a 0.1–0.3% boric acid (16.5% B) solution is sprayed on foliage to overcome the B deficiency. Solubor (sodium borate) is also used for foliar spray. Boronated super phosphate (0.18% B) (Takkar, 1996) and recently boronated NPK (0.3% B) have been introduced in the Indian market (Sarkar *et al.*, 2006). In established field crops and in grapes B can be top-dressed (Boswell *et al.*, 1980).

Frequency of application depends upon doses of B applied and the nature of the crop. Studies showed that application 0.8 kg B/ha to each crop, or 1.6 kg B/ha to alternate crops gave higher yields in rice–wheat, maize–wheat and sesame–chickpea cropping systems and were found optimum for sustaining higher productivity (Table 1). Regular applications of more than 2 kg B/ha caused adverse effects on the growth and yield of crops. Therefore, one should apply the optimum dose of B at the desired frequency (Singh, 2006).

Crop species and their cultivars differ significantly in their relative response to B, so its fertilisation has to be practiced accordingly. Sakal and Singh (1995) reported the tolerance of sesame cultivars to B stress in the order: RT-54 > OMT-11-63 > OMT-11-6-5 = Krishna > TC 25 and that of mustard cultivars as: Pusa Bold > RH-30 > = Kranti > RAURD = BR-40 = Varuna in B-deficient

**Table 1.** Cumulative response (grain yield) of different crops as influenced by rates and frequency of boron application in three cropping cycles in calcareous soil (Singh, 2006)

B rate (kg/ha) and use frequency	Total B added (kg/ha)	Rice–wheat (3 + 3 = 6 crops)			Maize–mustard (3 + 3 = 6 crops)			Sesame–chickpea (3 + 3 = 6 crops)		
		kg			kg			kg		
		kg/ha	kg/kg B	%	kg/ha	kg/kg B	%	kg/ha	kg/kg B	%
0.8 A	2.4	2,710	1,129	14.2	1,590	663	13.2	377	157	7.2
0.8 C	4.8	3,380	704	17.8	2,650	553	22.1	955	199	18.1
1.6 A	4.8	4,130	860	21.7	2,730	569	22.7	1,162	242	22.1
1.6 C	9.6	2,540	265	13.3	2,530	264	21.1	1,117	116	21.2
32 I, 8C	72	2,850	39	15.0	2,310	32	19.2	719	10	13.6
F.S. 2	9.0	1,330	147	7.0	1,520	168	12.7	555	62	10.5
LSD (P=0.05)	-	378	-	-	469	-	-	182	-	-

B added I=Once to first crop, A=Alternate, C=All crops, F.S. = Foliar spray of 0.25% H<sub>3</sub>BO<sub>3</sub>

Psamment soils in Bihar. Among the various sources of B, the efficacy of borax, Granubor-II and boric acid was found to be almost equal in increasing the productivity of groundnuts, soybeans, rice, cauliflower, chickpea, and maize. Basal application of B, through broadcasting, gave the best response. However, if a basal application is missed, foliar sprays of 2.0–2.5 g/litre of boric acid or Solubor can be used for correcting the B deficiency quite efficiently.

### Interaction with other nutrients

A significant positive interaction of B exists with N and K. Smithson and Herthcote (1976) reported that for good yields of cotton adequate B needs to be applied with high rates of N. Similarly, Woodruff *et al.* (1987) reported that high rates of K also require higher B application in corn for yield maximization. On the other hand B has a negative interaction with Zn and high rates of Zn application can reduce B uptake, which in a way can help in reducing B toxicity in plants (Pilbeam and Kirkby, 1983). Data on these aspects are not yet available from India. Sinha *et al.* (2003) reported that interaction of P × B occurs when low P level interferes with B metabolism, aggravating both the deficiency or excess symptoms of B. Shekhawat and Shivay (2008) reported that the total uptake of B was higher due to various treatments of N, S and B. Also, positive interaction of B was recorded with N and S in their study on spring sunflower.

### Boron and irrigation water

B is the unique element in the sense that there is a narrow range between its deficient and toxic levels, < 0.5 mg B/kg and > 5 mg B/kg, respectively (Reddy, 2000). Irrigation water having 5–10 mg B/litre is suitable only for semi-tolerant crops. Irrigation water having < 3 mg B/litre is ideal for B tolerant and semi-tolerant crops. Underground water used for irrigation purpose has been reported to contain toxic amounts of B in several parts of Uttar Pradesh, Rajasthan, Haryana, Punjab, and Gujarat (Chauhan and Asthana, 1981).

### Boron and disease/pest resistance in plants

Boron, possibly because of its role in lignin formation (Graham *et al.*, 1987) is able to reduce the incidence of several diseases in plants. Some of these are: clubrot (*Plasmodiphora brassicae*) in crucifers (Dixon and Webster, 1988), *Rhizocantania solani* in peas, cowpea and mungbean (Kataria and Grover, 1987), *Rhizoctonia bataticola* in groundnut (Murgesan and Mahadevan, 1987), *Fusarium solani* in bean (*Phaseolus vulgaris*) (Guerra and Anderson, 1985), and tomato leafcurl in tomato (Zaher, 1985). Application of B to soil is also re-

ported to reduce mite (*Petrobia latens*) population in wheat (Singh, 1986).

### CONCLUSION

It is concluded that B plays an important role in plant life and adequate B fertilization is a must for successful crop production on B deficient soils, especially Bihar, Jharkhand, West Bengal, Orissa and north-eastern states. Plant species differ in their sensitivity to B deficiency and toxicity. Hence, needful and careful B fertilization is the key for sustainable production of crops in intensive cropping systems in India.

### REFERENCES

- Ahmad, W., Zia, M.H., Malhi, S.S. Niaz, A. and Saifullah. 2012. Boron deficiency in soils and crops: A review. In: *Crop Plant* (Goyal, A., ed.). DOI:10.5772/36702.
- Ali, S.J. and Monoranjan, R. 1989. Effect of NPK and micronutrient in controlling sterility in wheat. *Fertilizer News* **34**: 35–36.
- Alloway, B.J (ed.). 2008. Micronutrient Deficiencies in Global Crop Production (B.J. Alloway, ed.), Springer, Dordrecht. pp 127–48.
- Ansari, M.A., Prakash, N., Singh, I.M., Sharma, P.K. and Punitha, P. 2013. Efficacy of boron sources on productivity, profitability and energy use efficiency of groundnut (*Arachis hypogaea*) under north east hill regions. *Indian Journal of Agricultural Sciences* **83**(9): 959–63.
- Arora, C.L., Singh, B. and Takkar, P.N. 1985. Secondary and micronutrient deficiency in crops. *Progressive Farming* **21**(8): 139.
- Barber, S.A. 1995. Soil Nutrient Bioavailability: A Mechanistic Approach. John Wiley and Sons, New York, NY, U.S.A.
- Behera, S.K., Singh, M.V., and Lakaria, B.L. 2009. Micronutrient deficiencies in Indian Soils and their amelioration through fertilization. *Indian Farming* **59**(2): 28–31.
- Bell, D.W. and Dell, B. 2008. Micronutrients for sustainable food, feed, fibre and bioenergy production. *International Fertilizer Industry Association*, Paris. pp. 175.
- Bell, R.W. 1997. Diagnosis and prediction of boron deficiency for plant production. *Plant and Soil* **193**: 149–68.
- Berger, K.C. and Troug, E. 1939. Boron determination in soils and plants. *Industrial and Engineering Chemistry Analytical Edition* **11**: 540–45.
- Bingham, F.T., Elseewi, A. and Oertli, J. 1970. Characteristics of B adsorption by excised barley roots. *Soil Science Society of America Journal* **34**: 613–17.
- Borkakati, K. and Takkar, P.N. 2000. Forms of boron in acid alluvial and lateritic soils in relation to ecosystem and rainfall distribution. (In) *Proceedings of the International Conference on Managing Resources for Sustainable Agricultural Production in the 21<sup>st</sup> Century. Better Crops* **2**: 127–28.
- Boswell, F.C., Lane, R.P. and Okhi, K. 1980. Field studies with B on Muscadine grapes. *Communications in Soil Science and Plant Analysis* **11**: 201–07.
- Chang, S.S., Hu, N.H., Chen, C.C. and Chu, T.F. 1983. Diagnosis criteria of boron deficiency in papaya and the soil boron status of Taitung area (Taiwan). *Chinese Journal of Soil Science* **32**: 238–52.

- Chauhan, R.P.S. and Asthana, A.K. 1981. Tolerance of lentil, barley and oats to boron in irrigation water. *Journal of Agricultural Science* **97**: 75–78.
- Cripps, E.G. 1956. Boron nutrition of hops. *Journal of Horticultural Science* **31**: 25–34.
- Dell, B. and Huang, L. 1997. Physiological response of plants to low boron. *Plant and Soil* **193**: 103–20.
- Dell, B., Brown, P.H. and Bell, R.W. 2002. Boron in soils and plants: reviews. Kluwer, Dordrecht.
- Dixon, G.R. and Webster, M.A. 1988. Antagonistic effects of B, Ca and pH on the pathogenesis caused *Plasmadiaphora brassicae* Woronin (club rot)—A review of recent work. *Crop Research* **28**: 83–95.
- Dobermann, A. and Fairhurst, T. 2000. Nutritional disorders and nutrient management, International Rice Research Institute, Los Banos, Philippines. pp. 132–34.
- Dwivedi, G.K., Dwivedi, M. and Pal, S.S. 1990. Mode of application of micronutrients in soybean–wheat crop sequence. *Journal of the Indian Society of Soil Science* **38**: 458–63.
- Faust, N. and Shear, C.B. 1968. Corking disorders of apples: A physiological and biochemical review. *Botanical Reviews* **34**: 441–69.
- Gowariker, V. 2009. The Fertilizer Encyclopedia, John Wiley & Sons, Inc. pp. 861.
- Graham, R.D., Welch, R.M., Grunes, D.L., Cary, E.E. and Norwell, W.A. 1987. Effect of Zn deficiency on the accumulation of B and other mineral nutrients in barley. *Soil Science Society of America Journal* **52**: 652–57.
- Guerra, D., and Anderson, A.J. 1985. The effect of Fe and B amendments on infection of bean by *Fusarium solani*. *Phytopathology Zeit schrift* **30**: 112–15.
- Gupta, S.P., Singh, M.V. and Dixit, M.L. 2008. Deficiency and management of micronutrients. *Indian Journal of Fertilizers* **3(5)**: 57–60.
- Gupta, U.C. 1968. Relationship of total and hot-water soluble boron and fixation of added boron, to properties of Podzol soils. *Soil Science Society of America Proceedings* **32**: 45–48.
- Gupta, U.C. 1993. Deficiency, sufficiency and toxicity levels of B in crops. (In) Boron and its Role in Crop Production (U.C. Gupta, ed.), CRC, Boca Raton, USA. pp. 137–45.
- Jones, J. B. Jr. 2003. Plant mineral nutrition. pp. 325 (In) *Agronomic handbook: Management of crops, soils and their fertility*, CRC Press, Boca Raton, FL, U.S.A.
- Kanwal, S., Rahmatullah, Aziz, T., Maqsood, M. A. and Abbas, N. 2008. Critical ratio of calcium and boron in maize shoot for optimum growth. *Journal of Plant Nutrition* **31**: 1535–42.
- Kataria, H.R. and Grover, R.K. 1987. Influence of soil factors, fertilizers and manures on pathogenicity of *Rhizoctonia solani* on *Vigna* species. *Plant and Soil* **103**: 57–66.
- Katyal, J.C. and Vlek, P.L.G. 1995. Micronutrient problem in tropical Asia. *Fertilizer Research* **7**: 69–94.
- Lindsay, W.L. 1991. Inorganic equilibria affecting micronutrients in soils. (In) *Micronutrients in Agriculture* 2nd edition (J.J. Mortvedt, F.R. Cox, L.M. Schuman, R.M. Welch, eds.) *Soil Science Society of America*, Madison, USA. pp. 89–223.
- Lovatt, C.J. 1985. Evolution of xylem resulted in a requirement of boron in the apical meristems of vascular plants. *New Phytologist* **99**: 509–23.
- Mandal, M. and Das, D.K. 2011. Effect of boron management on yield of rape (*Brassica campestris*) and its mobility in soil and plant. *Indian Journal of Agricultural Sciences* **81(12)**: 1180–83.
- Mathur, C.M., Moghe, V.B. and Talati, M.R. 1964. Distribution of boron in soils of western Rajasthan irrigated with high boron waters. *Journal of the Indian Society of Soil Science* **12**: 319–24.
- Mengel, K. and Kirkby, E.A. 1987. Principles of plant nutrition. Panima Educational Book Agency, New Delhi.
- Miley, W.N. and Woodall, W.E. 1967. Boron for cotton. University of Arkansas Cooperative Extension Service Leaflet 349.
- Mondal, C., Bandopadhyay, P., Alipatra, A. and Banerjee, H. 2012. Performance of summer mungbean [*Vigna radiata* (L.) Wilczek] under different irrigation regimes and boron levels. *Journal of Food Legumes* **25(1)**: 37–40.
- Murgesan, K. and Mahadevan, A. 1987. Control of *Rhizoctonia bataticola* of groundnut by trace elements. *International Journal of Tropical Plant Diseases* **5**: 43–57.
- O’Neil, M.A., Ishi, T., Albersheim, P. and Darvill, A.G. 2004. Rhamnogalacturonan II: Structure and functions of a borate cross-linked cell wall pectic saccharide. *Annual Review of Plant Biology* **55**: 109–39.
- Periur, B.F. 2001. Etude de l’activite’ pre’biotiquepotentielle de l’activiteborique. *Comptes Rendue de Academie de Science et Chimie* **4**: 667–70.
- Pilbeam, D.J. and Kirkby, E.A. 1983. The physiological role of B in plants. *Journal of Plant Nutrition* **6**: 563–82.
- Prasad, R. 2007. Crop Nutrition-Principles and Practices, New Vishal Pub, New Delhi. pp. 272.
- Rattan, R.K., Datta, S.P. and Katyal, J.C. 2008. Micronutrient management—research achievements and future challenges. *Indian Journal of Fertilizers* **4(12)**: 93–118.
- Raychaudhari, S.P. and Datta Biswas, N.R. 1964. Trace elements status of Indian soils. *Journal of the Indian Society of Soil Science* **12**: 207–214.
- Reddy, S.R. 2000. Principles of Crop Production. Kalyani Publisher, Ludhiana. pp. 428.
- Romheld, V. and Marschner, H. 1991. Functions of micronutrients in soils. (In) *Micronutrients in Agriculture*, 2<sup>nd</sup> edition (J.J. Mortvedt, F.R. Cox, L.M. Schuman and R.M. Welch, eds.) *Soil Science Society of America*, Madison, USA. pp. 297–28.
- Saha, J.K. and Singh, M.V. 1997. Effect of CaCO<sub>3</sub> on the adsorption and desorption of boron in swell-shrink soils in Madhya Pradesh. *Journal of the Indian Society of Soil Science* **45**: 57–61.
- Saha, J.K., Singh, M.V. and Sharma, B.L. 1998. Available boron status in major soils of Madhya Pradesh. *Journal of the Indian Society of Soil Science* **46**: 478–79.
- Sakal, R. and Singh, A.P. 1995. Boron research and agricultural production. (In) *Micronutrient Research and Agricultural Production*, (Tandon, H.L.S., ed.), FDCO, New Delhi, India. pp. 1-31.
- Sakal, R., Singh, A.P. and Sinha, R.B. 2002. Evaluation of rate and frequency of B application in cropping systems. *Fertiliser News* **47(10)**: 37–41.
- Sakal, R., Singh, A.P., Sinha, R.B. and Bhogal, N.S. 1988. Annual progress reports. ICAR All India Coordinated Scheme of Micro-and Secondary Nutrients in Soils and Crops of Bihar, *Research Bulletin, Department of Soil Science*, RAU, Samastipur, Bihar, India.

- Sakal, R., Singh, A.P., Sinha, R.B. and Bhogal, N.S. 1996. Twenty-five years of research on micro and secondary nutrients in soils of Bihar, Rajendra Agricultural University, Pusa Bihar. pp. 208.
- Sarkar, D., Mandal, B., Sarkar, A.K., Singh, S., Jena, D., Patra, D.P. and Phillips, M. 2006. Response of boronated NPK in B deficient soils. *Indian Journal of Fertilisers* **1**(12): 57–59.
- Sathya, S., Pitchai, G.J. and Indirani, R. 2009. Boron nutrition of crops in relation to yield and quality—a review. *Agricultural Reviews* **30**(2): 139–44.
- Satyanarayan, Y. 1958. Trace element status of cotton soils of Gujarat. *Indian Cotton Cong. Rev.* **12**: 138–141.
- Scorei, R. and Cimpoiasu, V.M. 2006. Boron enhances the thermo stability of carbohydrates. *Origin of Life and Evolution of Biosphere* **36**: 1–11.
- Shafiq, M., Ranjha, A.M., Yaseen, M., Mehdi, S.M. and Hannan, A. 2008. Comparison of Freundlich and Langmuir adsorption equations for boron adsorption on calcareous soils. *Journal of Agricultural Research* **46**: 141–48.
- Shekhawat, K. and Shivay, Y.S. 2008. Effect of nitrogen sources, sulphur and boron levels on productivity, nutrient uptake and quality of sunflower (*Helianthus annuus*). *Indian Journal of Agronomy* **53**(2): 129–34.
- Shorrocks, V.M. 1997. The occurrence and correction of boron deficiency. *Plant and Soil* **193**: 121–48.
- Sillanpaa, M. 1982. Micronutrients and nutrient status of soils, a global study. (In) *FAO Soil Bulletin No. 48*, Rome, Italy.
- Singh, A.P. 1986. Effect of soil nutrients and varietal reactions to the population buildup of brown wheat mite *Pretobia latens* Muller on wheat. *Entomon* **11**: 115–20.
- Singh, B. and Randhawa, N.S. 1977. Distribution of boron in soil, water and plant samples of Malerkotla block of Sangrur district (Punjab). *Journal of the Indian Society of Soil Science* **25**: 47–53.
- Singh, M.V. 1999. Experiences of AICRP on micro and secondary nutrients and pollutant elements in soils and plants. *Fertiliser News* **44**(4): 63–82.
- Singh, M.V. 2001. Evaluation of micronutrient status in different agroecological zones of India. *Fertiliser News* **46**(2): 25–42.
- Singh, M.V. 2006. Micro and secondary nutrients and pollutant elements research in India. Progress report, IISS, Bhopal, pp. 1–110.
- Singh, M.V. 2007. Micro and secondary and pollutant element research in India. AICRP Micro and Secondary and Pollutant Elements in Soils and Plants, IISS, Bhopal **31**: 1–112.
- Singh, M.V. 2012. Spread of micro-nutrient deficiencies specially boron in India and response of field crops. “Brain storming workshop on soil test based nutrients including boron and other micro nutrients” Organized by ICRISAT - Agriculture Directorate, Karnataka -Rio Tinto India at Bangaluru, India.
- Singh, M.V. and Goswami, V. 2013. Efficiency of boron fortified NPK fertilizer in correcting boron deficiency in some cereal and oilseeds crops in India. *17<sup>th</sup> International Plant Nutrient Colloquium* 17–18 August, Istanbul, Turkey.
- Sinha, P., Dube, B.K. and Chatterjee, C. 2003. Phosphorus stress alters boron metabolism of mustard. *Communications in Soil Science and Plant Analysis* **34**(3 and 4): 315–26.
- Sinha, R.B., Sakal, R., Singh, A.P. and Bhogal, N.S. 1991. Response of some field crops to boron application in calcareous soils. *Journal of Indian Society of Soil Science* **39**: 342–45.
- Smithson, J.B. and Herthcote, R.G. 1976. A new recommendation for application of boronated superphosphate to cotton in northeastern Beune plateau stats. *Samarau Agricultural Newsletter* **18**: 59–63.
- Sywortokin, G.S. 1958. The B content of plants with a latex system. *Supplement der Landwirtschaft, Akademie-Verlag*, Berlin. pp. 283–88.
- Takkar, P.N. 1996. Micronutrient research and sustainable agricultural productivity in India. *Journal of the Indian Society of Soil Science* **44**: 562–65.
- Takkar, P.N., Chibba, I.M. and Mehta, S.K. 1989. Twenty years of coordinated research on micronutrient in soils and plants. *Bulletin 314. Indian Institute of Soil Science*, Bhopal, India. 81.
- Takkar, P.N., Singh, M.V. and Ganeshmurthy, A.N. 1997. (In) *Plant nutrient supply needs, efficiency and policy issues* (J.S. Kanwar and J.C. Katyal, eds.), National Academy of Agricultural Sciences, New Delhi. pp. 238–64.
- Tandon, H.L.S. (ed.). 1995. *Micronutrient Research and Agricultural Production*. FDCO, New Delhi. pp. 164.
- Woodruff, J.R., Moore, F.W. and Munsen, H.L. 1987. Potassium, B, N and lime effects on corn yield and ear leaf concentrations. *Agronomy Journal* **79**: 520–24.
- Zaher, N.A.M. 1985. Response of tomato leaf curl virus diseased plants to spraying with some microelements. *Egyptian Journal of Phytopathology* **17**: 73–82.