CHEMISTRY OF BORON AND MANAGEMENT IN DIFFERENT CROPS

ABSTRACT

Boron (B) is an important plant micronutrient with a narrower range of deficit to toxicity than any other nutritional element. As a result, comprehending the chemistry of born in soil is crucial. Although B inadequacy and toxicity may be linked to total B levels in the soil, these issues are caused by the chemical forms of B present in the soil, notably its solubility and availability to plants. Solution pH, soil texture, soil moisture, temperature, organic matter, and clay mineralogy all impact B availability and adsorption in soils. Various empirical equations may be used to characterize boron adsorption processes empirically. Boron management has improved thanks to the latest fertilizer technologies that provide better nutrient dissemination, year-round B availability, and a more adjustable application window in diverse crops. This paper reviews about different studies and progress of research in dynamics of boron and its management in different horticulture and agriculture crops.

Key words: Boron, Boron Chemistry, Adsorption-Desorption of B, Management of B

1. INTRODUCTION

B is one of the most important nutrients for crop growth, development, yield, and quality. Boron is more abundant in sedimentary rocks than in igneous rocks. Fundamental minerals like tourmaline and volatile emanations from volcanoes are the main B sources in most soils. Minerals which contain Boron are Kernite ($Na_2B_4O_7$.$4H_2O$), Colemanite ($Ca_2B_6O_{11}$.$5H_2O$), Borax ($Na_2B_4O_7$.$10H_2O$), Ulexite ($NaCaB_5O_9$.$8H_2O$), Tourmaline [$Na(Mg,Fe)_3Al_6$ $(BO_3)_3Si$ $_6O_{18}.(OH)_4$], Kotoite ($Mg_3(BO_3)_2$). Borax and solubor are the two most used B fertilizers [1]. Table 1 shows a list of common fertilizers.

The typical boron concentration in soil is 30 PPM; however this varies substantially depending on the main rock. As a result, plants only require trace amounts of boron; yet, at 2 PPM or above, most plants become toxic [2]. Plants need about 25 PPM of boron in the soil. The subsoil and deeper layers have higher boron [3]. B is mostly found in soil solutions as boric acid and borate [4]. Boron is constantly cycling through the soil. Minerals, adsorbing clay and Fe/Al oxide surfaces, organic matter, and fertilizers provide B to the soil solution. B is the sole essential element that appears in soil solution as a non-ionised molecule (H_3BO_3) [5].

In acidic soils, soluble B appears as non-ionized boric acid, whereas borate anion becomes increasingly prevalent when soil pH rises [6]. Plant B absorption is influenced by factors such as pH, texture, organic matter, temperature, moisture content, and plant type. B deficiency is commonly connected with coarse textured soils that are prone to leaching as a result of heavy rainfall in humid climates [7]. The kind and amount of bio-available B in the soil affects plant B absorption [8]. Water-soluble B concentrations is classified into five categories: very low (2.0 µg/g), low (0.25 - 0.5 µg/g), medium (0.51 - 1.0 µg/g), high (1.1 - 2.0 µg/g), and very high (>2.0 µg/g) [9]. Weathering, mineralization, adsorption-desorption, immobilisation and leaching processes all affect its availability to plants. Boron in soil solution is in equilibrium with adsorbed boron. Humic compounds and clay minerals are responsible for boron adsorption (crystalline or amorphous substances). Boron availability is greater in the pH range of 5.0-7.0, and it rises again at pH 8.5. Boron absorption by plants may be influenced by the types of nitrogen (N) given, since they can affect the pH of the soil solution: ammonium (NH^{+4}) lowers pH, whereas nitrate (NO^{-3}) raises it [4]. 0.0–0.2 PPM is considered low, 0.21–0.6 PPM is considered medium, 0.61–1.1 PPM is considered high, 1.2–3.0 PPM is considered extremely high, and >3.0 PPM is considered dangerous soil boron concentrations [10][11]. The ideal soil boron range was indicated to be 0.5–2.0 PPM, with lower and higher readings indicating insufficiency and toxicity. As a result, boron nutritional problems are extremely frequent [8].

The regulatory influence on other nutritional elements, production of new cells in meristematic tissue [12], translocation of sugars, starches, phosphorus, and other nutrients [13], cell wall synthesis [14] are all plausible roles of B in crops. As B is important for nitrogen absorption, both legumes and cyanobacteria require it for Nitrogen fixation [15]. Boron is required for glucose transport, metabolism, permeability and stability of cell membranes, and phenol metabolism [16]. A combination of heavy precipitation and high B solubility in soil solution might induce B insufficiency. Its deficit is particularly common in coarse-textured soils with poor organic matter, high pH, and calcium carbonate (CaCO3), resulting in low crop yields [17]. Boron is mobile in plants such as apples, cauliflower, carrots, onions, celery, and grapes, but immobile in plants such as beans, corn, cotton, potato, tomato, sorghum, and wheat. Boron deficiency symptoms emerge initially on stem tips, young leaves, blooms, and buds because it is a less mobile nutrient in plants [18]. B deficiency has been discovered in coarse-textured acidic soils as well as volcanic soils [19]. Boron may be hazardous to plants if it is present in excess levels in the soil [20].

Passive diffusion transports B at high B concentrations, whereas active transport requires the employment of a unique type of protein at low B concentrations [21]. At present, three pathways or mechanisms for B uptake and transport in plants have been identified: passive diffusion through plasma membrane; facilitated transport via channel proteins, such as nodulin 26-like intrinsic proteins (NIPs); and high-affinity active transport reconciled by borate transporters (BOR) under low B availability [22].

Since limited B adsorption occurs on the mineral fraction at low pH values, organic matter is one of the most important sources of B in acid soils [23]. Organic matter in the soil serves as a significant source of B. [24] discovered a higher presence of B in organic matter in soils than in the mineral fraction, as well as a favorable effect of organic fertilization on B absorption. Underground water used for irrigation has been documented to have dangerous quantities of B in many places (Uttar Pradesh, Rajasthan, Haryana, Punjab, and Gujarat) of India [25]; [26], whereas canal and tube well water are two typical sources utilized for irrigation. Groundwater, mining waste, fertilizers, and fossil fuel residues all result in greater B levels in soils. The physical–chemical soil features and B interaction in the soil were taken into account while defining the threshold B concentration in irrigation water for sensitive (0.3 mg/L) and tolerant (2 mg/L) crops [27]. Wood burning, coal and oil-fired power generation, glass production, borate mining and processing, leaching of treated wood/paper, and sewage disposal are all examples of anthropogenic sources [1].

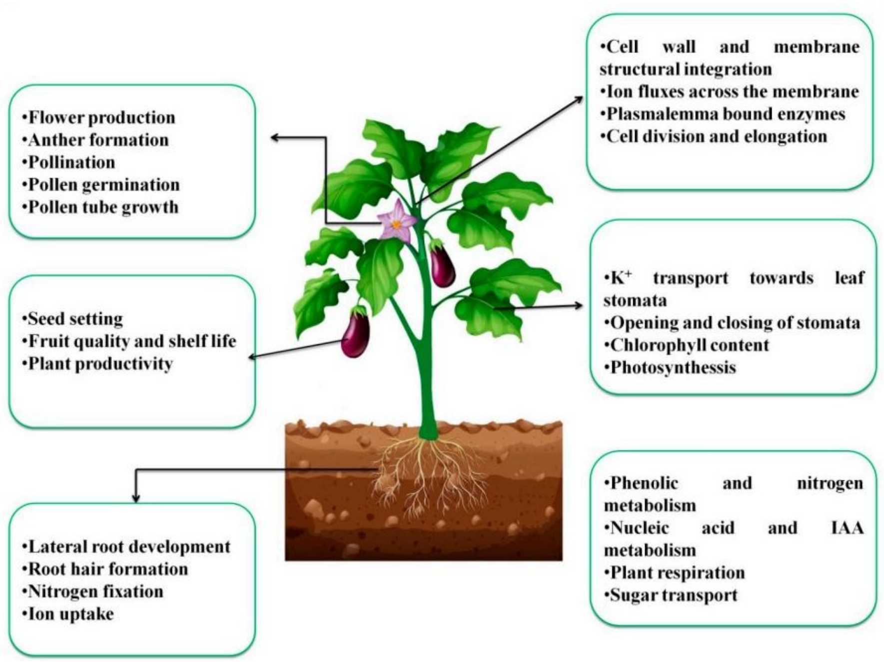
Table 1. Commercially available sources of Boron

Source	Formula	B%
Borax	$Na_2B_4O_7 .10H_2O$	11
Boric acid	H_3BO_3	17
Colemanite	$Ca_2B_6O_{11} .5H_2O$	10-16
Sodium pentaborate	$Na_2B_{10}O_{16} .10H_2O$	18
Sodium tetraborate (Fertibor, Granubar)	$Na_2B_4O_7 .5H_2O$	14-15
Sodium octaborate (Solubor)	$Na_2B_8O_{13} .4H_2O$	20-21

2. ROLE OF BORON IN PLANTS

Boron (B) is involved in the production of cell walls, membrane integrity, sugar transport, and the metabolism of phenol, glucose, nucleic acid, and IAA (indol acetic acid). In addition to its role in different metabolic processes, B impacts the development of reproductive structures, including microsporogenesis, pollen germination, and seed formation [28]. B increases fruit setting and seed formation during pollen tube expansion and germination, resulting in increased crop yield. B has a role in the cell membrane's protein and enzymatic functions, resulting in increased membrane integrity [12]. The increased demand for B in early developing tissues demonstrates its importance in cell division and elongation [29]. B has a role in phenolic metabolism, and phenol aggregation is a common symptom of B deficiency. B is important in nitrogen (N) metabolism because it increases nitrate levels while decreasing nitrate reductase activity when B levels are low [30]. B has an impact on the availability and absorption of other soil nutrients by plants. After B treatment, there was an apparent increase in the absorption and translocation of P, N, K, Zn, Fe, and Cu in cotton leaves, buds, and seeds [31].

Figure 1. Functions of Boron in plants [44]



1. DEFICIENCY OF BORON

On a worldwide basis, boron shortage has been identified as the second most significant micronutrient limitation in crops, behind zinc (Zn) [31]. Since B is a unique nutrient with extremely narrow deficiency and toxicity thresholds, it frequently causes deficiency or toxicity. Plants show a variety of deficiency symptoms depending on their age and species, such as stunted root growth, restricted apical meristem growth, brittle leaves, reduced chlorophyll content and photosynthetic activity, ion transport disruption, increased phenolic and lignin content, and reduced crop yield [12]. B deficiency signs such as poor fruit production and fewer seeds are seen mainly during the reproductive period of crops. Although plants display uniform deficient symptoms on whole leaves, but sometimes in the form of isolated patches, the prevalence of symptoms is dependent on the severity of the B-deficiency condition. Because B is immobile, it tends to accumulate in older leaves, but new leaves do not acquire enough B to develop properly. Young leaves show deficient signs such as thick, twisted, and brittle leaves with restricted leaf expansion; corky veins; interveinal chlorosis; yellow water-soaked areas on lamina; and a short internodal distance, resulting in a bushy plant appearance [32].

Boron requirements are generally higher during a plant's reproductive phase of life. As a result, under field conditions, the yield can be significantly reduced without any visible signs of deficiency. Male sterility is the most typical result of insufficiency throughout the reproductive period [29]. Root growth is inhibited when cell division in the apical meristem stops due to boron shortage. Internodes are reduced and necrotic patches form on leaves in severe and persistent deficit [33]. Mango fruit pitting problem is thought to be linked to boron and calcium insufficiency [34].

White necrotic streaks and the youngest developing leaves in rice do not unfurl and remain trapped in the subtending leaf. In wheat, chlorotic flecks with a vivid orange yellow tint in the centre of the lamina can be seen in older leaves. In ear-producing tillers, inflorescence and grain setting are limited. Older leaves of barley plants develop dark brown necrotic patches along the tips and edges after around 7 weeks of growth. Internodes become shorter, and nodes frequently expand. Plant leaves in mustard at the pre-flowering stage become thick, leathery, and pale to brownish green in colour, with searing symptoms at the developing tips. At maturity, there was also slowed growth and the production of unfilled grains. Boron deficiency manifests as in cotton after 4 weeks of development, with noticeable signs appearing 45-50 days later with chlorotic patches of brittle young leaves. At the same time, the cupping of the central leaves is inward. In the carrot Rough, tiny roots with a longitudinal fracture and a conspicuous white core are formed. 'Brown-head,' 'Hollow stem,' and delayed curd development occur in cauliflower. The developing tip of the tomato stem has a blackened look, reduced development, curling, and yellowing. Fruits may have corky regions and ripen unevenly [5].

2. TOXICITY OF BORON

Boron toxicity manifests differently in species with restricted and substantial phloem mobility. Foliar symptoms in barley and wheat include chlorosis and necrosis extending from the leaf tips, as well as brown lesions that start on the edges and spread throughout the leaf surface. The condition affects the plant's oldest leaves first, and then spreads to the top of the plant. Brown lesions can be found on leaf sheaths, stems, spikes, and awns in severe instances [33]. When boron content rises with soil depth, symptoms appear later and yield is lowered less [35].

Excess boron has no effect on the area, breadth, or length of the leaves [36]. Excess boron reduces emergence in maize, tomato, carrot, and alfalfa [37]. For phloem-mobile Prunus, Malus, and Pyrus species, young shoot tip cessation, leaf axil gumming, brown corky lesions along stems and petioles, and bud abscission have been described [33] Chlorosis and necrosis at leaf tips on older leaves, delayed emergence and foliation, reduced development of lateral roots, distorted leaves, leaf axil gumming, and bud abcission are the most common boron toxic symptoms.

3. CHEMISTRY OF BORON IN SOIL

5.1. Availability of B

Several variables influence the bioavailability and concentration of B in soils. Many parameters influence B retention in soil, including soil B content, pH, texture, organic matter, cation exchange capacity, exchangeable ion composition, and clay type and mineral coatings on clays [38]. Solution pH, soil texture, soil moisture, temperature, organic matter, and clay mineralogy are all factors that influence B availability and adsorption in soils [39]. Aluminium and iron oxides, magnesium hydroxide, clay minerals, calcium carbonate, and organic matter are all boron adsorbing surfaces in soils [40].Soils derived from marine shale-rich parent material frequently have high B contents. Volcanic ash and soils enriched in aluminium (Al) oxides contribute to lower B bioavailability in soils [40]. They discovered a strong link between accessible B content, EC, pH, and organic carbon concentration [41]. In the pH range of 3 to 9, boron adsorption by soils increased, but in the pH range of 10 to 11.5, it declined [42] [43] observed that B adsorption was influenced by soil qualities such as organic matter, clay, and aluminium oxide content, and that it was reliant on and increased as a function of pH. The impact of organic matter on the availability of B in soils is magnified as the pH and clay content of the soil rise. Microbes are mostly responsible for the release of B in suitable form in organic substances [44]. In addition to the pH of the soil solution, the amount of B absorbed by the soil is strongly determined by soil texture. It rises in proportion to the amount of clay in the soil [23]. Illite is by far the most reactive with B of the clays, while montmorillonite is only reactive at higher pH and kaolinite is the least reactive on a mass basis [45].

Wetting and drying cycles enhanced the quantity of B fixation, and the drying impact became more noticeable as the amount of B added increased. Organic matter has a significant impact on the availability of

B. The results showed that soil B has a positive relationship with matter, and that as the matter content of the soil increased, so did the B concentration. This increase could be due to the decomposition of organic matter which produces acids such as tartaric, oxalic, citric, acetic, formic, and humic acid, which solubilized the unavailable fixed B in clay or $CaCO_3$. Furthermore, some B gets complexed or chealeted with organic mattercontent and this B is released into the soil solution as the organic matter decomposes [42].Because minimal B adsorption on the mineral fraction occurs at low pH values, organic matter is one of the most important sources of B in acid soils [23].

Chakraborty (1999)[46] investigated the interaction impact of B and sulphur on B availability in mustard-growing soils and found that the amount of periodic fluctuations in B content in soils increased dramatically with sulphur treatment, peaking at 60 kg ha^{-1} application. Because sulphate and phosphate anions compete with B, B has favourable interactions with sulphur and phosphorus. After the crop was harvested, researchers discovered that soil treated with calcium or magnesium sulphates had lower levels of hot-water-soluble B than soil treated with calcium or magnesium carbonates. Cotton yields responded positively to B fertilisation when combined with potassium treatments in long-term studies [1]. P was observed to boost the release of available B when used alone. The addition of Zn reduced the concentration of HWS-B in the absence of phosphorus [47]. Supplemental zinc, according to [20], has the potential and practical value of controlling B absorption and toxicity in soils where plants are cultivated under zinc deficit and B toxicity.

5.2. Fractions of B

For plant nutrition, the distribution of B between the solid and liquid phases is critical. Between the soil solution and the adsorbed B, there is a state of equilibrium [48]. Acknowledging the chemistry of B in soils and the possible contribution of these fractions to plant absorption of B requires fractionation as well as knowledge of its chemistry. The types of B contained in soil can be used to determine B status and possible availability to plants [49]. Plants receive B from the soil solution, and the adsorbed pool of B controls buffering against sudden fluctuations in the amount of B in the soil solution [50]. The evaluation of various forms in soils aids in the comprehension of their dynamics in soils. In soil layers of various depths, the concentration of B and its forms is widely dispersed [51].

Soil B comes in a variety of forms, each of which is in a state of dynamic equilibrium with the others. These forms include freely soluble B, specifically adsorbed B, oxide-bound B, organically bound B, and residual [52]. The most labile fraction of B in soil is readily soluble B which constitutes solution B along with non-specifically adsorbed B which is found on the clay edges and other variable charge surfaces by displacement by anion exchange and mass reaction [1]. The amount of water-soluble B usually ranges from 7 to 80 mg/g [39]. The specifically adsorbed boron percentage is mostly determined by the clay composition of the soil and may be selectively adsorbed onto clay surfaces or connected with organic matter in soil [53]. 0.01–0.61 percent of total soil B is found in this pool [54]. Tightly bound B at non-crystalline and some crystalline of Fe and Al is included in oxide-bound B. Adsorption sites for B are amorphous Al_2O_3 and Fe_2O_3 [1]. This pool accounts for around 3% of total boron [55]. Organically bound boron is inextricably linked to organic materials. Organic material adsorbs B, rendering it inaccessible to plants. Total boron is made up of 2–8% of organically bound boron [55]. Residual B can be found in mineral formations that are both primary and secondary, such as tourmaline and clay mica [1].

5.3. Adsorption and Desorption of B

Boron availability is affected by adsorption–desorption processes, which are impacted by numerous physico-chemical features of soils [56] [57]. The pH of the soil solution, the mineral content of the soil, and the texture of the soil determines the adsorption of boron [58]. Many soil variables influence the release of adsorbed boron from soil, including pH, EC, clay, and organic matter concentration [40].Various adsorption equations have been used to describe boron adsorption processes on oxides, clay minerals, and soil materials [59]. B adsorption on aluminium and iron oxides, clay minerals, calcite, humic acids, and soils was most typically described using the Langmuir or Freundlich equations [60]. The Langmuir equation has also been proven to accurately predict B adsorption by a variety of soils, including amorphous soils with adsorption maxima ranging from 10 to 100 g B g^{-1}[61]. Because it is based on basic first-order kinetics, the Langmuir equation has significant limitations, but it can provide useful quantitative information on which to draw inferences about the nature of adsorption. This isotherm has the benefit of being able to offer both intensity and a capacity factor. Freundlich isotherms are used to express boron desorption data for all of soils studied by [62].

The adsorption of boron in Tamil Nadu soils followed both the Langmuir and Freundlich adsorption isotherms, with the Freundlich adsorption isotherm fitting the entire data well. The Freundlich K values for boron adsorption in 11 Tamil Nadu soils range from 0.18 to 1.96 mg kg^{-1}[63]. In Haplaquepts, the Freundlich constant (1/n) varied from 0.703 to 1.230, whereas Fluvaquepts of Assam had values ranging from 0.611 to 0.703 [64]. The adsorption of added boron (B) in 12 soils representing diverse agro-ecological areas of India was found to be in the following order: Vertisols>Inceptisols>Alfisols. Freundlich and Langmuir equations explained the adsorption behavior of the soils, however based on prediction coefficients (R2), Freundlich seemed to be the best fit for Vertisols and Inceptisols, and Langmuir for Alfisols with the lowest B adsorption [6].

Adsorption–desorption of B had been investigated using four surface soil samples from the arid and semi-arid zones of Punjab state, two from each. It is concluded that the clay content and CEC of the soil were the key determinants of boron adsorption [40]. The Langmuir adsorption equation was used to calculate the boron adsorption data. When the curves were resolved into two linear sections, the fit of data in the Langmuir adsorption isotherm was curvilinear and substantial and good. The adsorption maxima for fine-textured soils were substantially greater than for coarse-textured soils. This is mostly owing to the soil's high clay and organic matter concentration, as well as its CEC. When boron was adsorbed on Assam soils, CEC, clay, and organic matter content of the soils were positively and substantially linked with b1 [65]. Several investigations have shown that the mechanism of B adsorption on soil materials, such as clay, sesquioxides, and organic matter, is ligand exchange [66]. In Assam soil types, boron adsorption maxima were substantially linked with organic carbon (r = 0.96) [64]. As the fineness of soil texture is increased the maximum adsorption capacity of soils seemed to rise [67]. These findings indicated that in sandy soils poor in organic matter, supplemental B fertilizer should be easily available to plants due to the soil's inability to adsorb high levels of B. Because of the high adsorption capacity and bonding energy of fine-textured soils with high clay content or high levels of organic carbon, huge amounts of B might be added without being harmful to plants. Boron adsorption reduced with increasing temperature from 10 to 40 °C, according to [68]. As per [69], boron emissions increased as the temperature rose.

Hysteresis is common in B desorption reactions [70]. At a given equilibrium solution concentration in the soils, the quantity of boron sorbed by the soil was consistently larger during desorption than during adsorption [71]. Desorption of B rose when soil pH increased, but reduced as organic C, clay, and CEC levels increased [72]. The fact that both free Fe and Al oxide levels in soil decreased with an increase in soil pH might explain the positive association between B desorption and soil pH. It may be deduced that B adsorbed on sesquioxides at lower pH was attached more firmly than B adsorbed on soil elements other than sesquioxides at higher pH. Soil characteristics, such as CEC, clay, CaCO3, pH, and organic C, have a significant impact on B absorption and desorption in soil [60]. In comparison to fine-textured soils, coarse-textured soils desorb more boron. These findings indicated that soils with higher boron adsorption slowly release boron into the soil solution and vice versa [73]. The sequence of desorption of added B was Inceptisols>Vertisols>Alfisols. Desorption of B rose when soil pH increased, but reduced as organic C, clay, and CEC levels increased [60].

6. MANAGEMENT OF BORON

Boron is a vital element that has a variety of roles in plant development and metabolism. Multi-nutrient deficit has been recorded in various soils for crop production as a result of intensive cropping systems and greater crop productivity. Crop residue recycling, proper irrigation management, and micronutrient fertilizer, including boron application, should be made along with major nutrient fertilization wherever sub-optimal supplies are suspected for imparting sustainability to crops and cropping systems at the highest potential yield levels. Boron is the scarcest nutrient, especially in fruit crops, impacting crop productivity and quality. In boron-deficient environments, efficient boron use by plants is an essential management technique. Many studies have been conducted to improve boron management in agricultural productivity. Different boron application methods and nutrient combinations have been studied in order to determine the most effective application method and dose. As seen in the table below, various plant species require varied quantities of boron fertilization. When recommending boron fertilizer, all plant and soil parameters that influence boron availability should be taken into account. Due to the relatively limited range of B deficiency and toxicity in soils and plants, optimizing B fertilizer input in B deficient soils is critical for normal development, yields, and quality of food. The frequency of B application is determined by the dosages used and the crop's characteristics.

Table 2. Requirement of Boron for different crops

Low Requirement	Moderate Requirement	High Requirement
Alfalfa	Apple	Barley
Apple	Carrot	Beans
Cabbage	Grapes	Citrus
Cauliflower	Lettuce	Cucumber
Cotton	Tomato	Corn
Peanut	Radish	Potato
Sugar beet	Pears	Rice
Sunflower	Peaches	Sorghum
Turnip	Spinach	Wheat,oats

6.1. Management of Boron in Horticultural crops

Among the various levels of boron, the maximum concentration of all boron components in soil was reported at a rate of 2 kg B ha^{-1}for cauliflower, cowpea, and okra crops at different crop growth phases. With crop ageing, there was a gradual drop in the level of all boron components. A boron concentration of 2 kg B ha^{-1} was shown to be effective in enhancing yield in all crops. He also reported the contributions of different boron fractions to crop output that is oxide bound boron was found to be the biggest contributor to cauliflower yield, residual boron to cowpea yield, and organic bound boron fraction to okra yield [74].

The importance of calcium and boron in the formation and maintenance of structural characteristics is well understood. Effect of boron and calcium on yield characteristics of grapes is well established. The number of bunches/vines (22 to 31 no's), yield/vine (5.32 to 6.13 kg/vine), and yield per hectare (21.7 t ha^{-1}) were all favorably improved by calcium and boron treatments. TSS (17.9 to 15.9 Brix), juice pH (3.92 to 3.75), titrable acidity (0.91 to 1.19 percent), total solids (1.32 to 1.07 percent), berry hardness (11.9 to 7.95 N), and total sugars (15.6 to 11.2 percent) were all positively affected. They concluded that foliar spray of 0.5 percent calcium nitrate and 0.2 percent boric acid applied twice at 45 and 55 days after pruning boosted production by 11.1 percent while also improving quality metrics in the Paneer grape variety [75].

Spraying guava plants twice with a foliar solution of Borax @ 0.6 percent solution and $ZnSo_4$ @ 0.75 percent solution, first before first flowering and again after fruit setting, is favorable to getting a larger yield of quality fruits from the winter season crop. This method outperformed other foliar nutrient administration practices in terms of flowering, fruit set, fruit retention, fruit size, weight, volume, yield per plant, and fruit quality metrics such as total sugar, TSS, and Ascorbic acid [76].

Boron sources should be administered to coconut palms if foliar and soil levels of B fall below established critical values (7.50–13.27 mg B kg^{-1} for leaf boron concentration and 0.46–0.83 mg B kg^{-1} for soil boron concentration for acidic sandy soils of Kerala). To improve boron usage efficiency, the ideal dose of 160 g of borax per palm (i.e., 16 g of boron per palm) can be administered in four split doses together with husk burial in coconut cultivating soils [77].

In Citrus orchards, B inadequacy is common, and it causes production loss and poor fruit quality [78]. Citrus plants growing in excess B may benefit from the use of fertilizers including Si, Ca, and Zn [79].

B fertilization enhances tuber number and yield greatly. It is recommended that three sprays with 0.1 percent boric acid (40, 50, and 60 days after planting) resulted in the highest quantity and production of tubers, as well as increased B absorption in potato tuber (85.8%), haulm (182.0%), and total plant (169.8%) above control. The same dosage resulted in the highest net return and benefit-to-cost ratio. The availability of N and B in post-harvest soil was significantly influenced by B fertilizer. The findings imply that improving tuber output and B-use efficiency for processing grade potatoes requires the correct dose and method of B treatment [80]

Boron (as disodium octaborate tetrahydrate) foliar sprays at 0.10 percent were most beneficial in enhancing the amount of B in the leaves (149.64 %) and fruits (120.14 %) of the 'Dashehari' cultivar. Overall, foliar application outperformed soil application in terms of increasing yield and reducing internal necrosis and fruit cracking disorders. In the 'Dashehari' cultivar, the internal necrosis disorder exacerbated the occurrence of fruit cracking. The results of this study showed that foliar boron application at 0.10 percent was the most effective for managing the above disorders and maintaining proper level of B in the leaves and fruits of ‘Dashehari’ [81].

6.2. Management of Boron in Agricultural crops

Effect of boron on the nutritional content of FCV tobacco (*Nicotiana tabacum L.*) had been investigated in two varieties i.e., TM-2008 and Speight G-28. The yield of tobacco crops increased at 1 kg B ha^{-1} and subsequently dropped sequentially in both kinds, according to the findings. The amount of boron supplied had a substantial impact on the amounts of N and P. Potassium levels were also raised, which is a favorable sign that the tobacco crop would be of higher quality. Boron application raised the concentrations of boron nutrients ratios such as K/B, Cl/B, and Mn/Fe, whereas K/Cl and Zn/Cu ratios rose at lower boron levels but declined at higher boron levels [82].

In mustard (*Brassica juncea L.*) number of siliqua/plant, length of siliqua, number of seeds/siliqua, seed yield, and oil content were found to rise when boron was treated at 1.5 kg B ha^{-1}, whereas protein content was reported to increase at 1.75 kg B ha^{-1}. According to the findings, applying 1.5 kg B ha^{-1} resulted in a 36 percent rise in seed output and a 52 percent increase in oil yield. It also considerably boosted B absorption by seed and stover compared to the control. As a result, its use in insufficient regions is advised to boost mustard yield in the region. [83]

Applying boron (8 kg B ha^{-1}) and molybdenum (1 kg Mo ha^{-1}) to medium black calcareous soils in the south Saurashtra region of Gujarat increased growth parameters, yield attributes, yield, nutrient content, uptake, and quality parameters of summer groundnut (*Arachis hypogaea L.*) and post-harvest soil fertility [84].

At crucial growth phases of black gram (*Vigna mungo*), STCR-based N, P_2O_5, and K_2O, as well as soil application of boron @ 1.5 kg ha^{-1} and foliar application of borax @ 0.25 percent, produced the maximum plant height, root dry weight, number of root nodules, and grain yield. Boron should be used to improve the productivity of black gram in calcareous soil [85].

Increasing levels of boron increased seed cotton yield and its attributing characters (plant height, number of sympodial and monopodial branches, boll weight, and number of boll per plant) and root biomass significantly over the control up to 1.0 mg B kg^{-1}, but then became non-significant with higher levels of soil-applied boron [86].

7. Conclusion

It may be inferred from this review that boron is an essential plant nutrient that plays a vital role in a variety of plant physiological activities. Boron is required for plant reproduction, cell wall and membrane structural integration, ion fluxes across membranes, fruit and seed establishment, primary metabolic pathways, and root growth. For successful control of B in crop production, adequate knowledge of B chemistry and its components is required. Boron deficiency and toxicity can be reduced by adjusting pH, temperature, moisture, and organic matter, all of which affect boron availability in plants. Foliar application of B has a direct influence on crop development, according to studies, but soil treatment can have a residual effect. When fertilizing with boron, the adsorption and desorption of B should be taken into account since it is a significant factor that might alter the availability of B to plants.

8. Future aspects

When dealing with B in soils in different geographical and climatic zones, site-specific and crop-specific nutrient management should be considered. Surface complexation models must be incorporated into transport models in order to anticipate B adsorption-desorption reactions in soil and during reclamation operations. More information on the hysteresis effect should be investigated. It is possible to employ advanced experimental techniques to disclose typical characteristics of B-organic matter and B-clay complexes in the soil environment. Boron status of places is being delineated and reassessed, as well as soil fertility maps being updated. Micronutrient research on fruits and vegetable crops is dispersed and limited; nonetheless, there is plenty of room for micronutrients to improve quality and productivity in these crops. Incorporating vesicular arbuscular mycorrhizal (VAM) fungus into integrated fertilizer supply systems has the ability to alleviate deficiencies in soils that aren't significantly deficient. It is necessary to investigate how to optimize the B requirements of diverse crops and cropping systems under varied soil conditions. Boron biofortification in several crops benefits human health dramatically. Boron shortages in crops and cropping systems (including horticultural crops) must be addressed in order to improve fertilizer usage efficiency. Basic research on the emergence and characterization of Boron deficiency/toxicity symptoms, as well as the effects of continuous Boron treatment on crop physiology and soil quality, is urgently needed.

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