REVIEW ARTICLE

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Calcium-boron Interactions in Plant Nutrition: From Molecular Mechanisms to Agricultural Applications: A Review

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ABSTRACT

Ca-B interactions in crop plants are essential in crop productivity, quality and stress-tolerance in a variety of agro-climatic conditions. This review discusses the complex processes behind Ca-B nutrition in plants, both at the molecular interaction level and in the field. Calcium ionically bridges with the pectin compounds at the cellular level and boron forms borate crosslinking with rhamnogalacturonan II (RG-II). The resulting B-RG-II complex that involves two molecules of boric acid and two Ca^{2+} ions is important to retain the cell wall integrity. The effect of these nutrients during the plant development is synergistic and when there is deficiency of boron, it leads to increased cytosolic Ca^{2+} and also calcium-regulated gene expression. Physicochemical properties of soil play a great role in Ca-B dynamics. Boron adsorption on clay minerals is enhanced as pH rises reaching a peak of about pH 9.0 in alkaline environment. The arable land of the world is estimated at around 50% of the global land, with 50% of this area being acid in nature making the availability of the two nutrients to be limited and thus requires strategic interventions. Optimised Ca-B nutrition leads to significant increases in yield of major crops. This can only be achieved through combined methods of soil testing, precise fertilisation and environmental concerns to facilitate good management. Nutrient management strategies are being transformed with the new technologies such as genomics, metabolomics, precision agriculture, mycorrhizal associations and machine learning algorithms. New areas of research should be directed towards new decision support systems, molecular level interventions, sustainable boron recovery of waste streams and mycorrhizal-mediated nutrient interactions.

Key words: Decision support systems, Foliar applications, Nano-fertilisation, Precision agriculture, Stress tolerance.

Calcium and boron are vital nutrients which have a significant impact on crop growth, development and yield in all the agricultural systems in the world. Calcium is a component of structure of cell walls and membranes as well as a key secondary messenger in a variety of signal transduction pathways. Though it is needed in lesser amounts, Boron is essential in cell wall synthesis, membrane integrity and reproductive development. The synergistic effect of these nutrients has also proven to be a defining factor in the attainment of optimal crop productivity, quality parameters and stress resilience.

Ca-B interactions have agricultural importance that is highlighted by the overall deficits in crop productivity in the world. In the world, the problem of the lack of boron is observed on about 132 million hectares of agricultural land and the issue of calcium imbalance is observed on almost half of arable lands of acidic soils (Vera-Maldonado *et al*., 2024). Although the work on calcium and boron has continued since the 1930s, recent developments in molecular biology, the omics technologies and precision agriculture transformed the concept of these interactions. Recent tools in the field of analysis, such as genomics, transcriptomics and metabolomics have helped to discover previously unknown molecular processes related to the uptake, transport and signalling of nutrients (Chen *et al*., 2024; Lin *et al*., 2024).

The recent research has highlighted the idea that the lack of boron contributes not only to a weaker cell wall but also to a wide range of developmental delay factors and calcium tends to replace boron as a biochemical reserve (Vera-Maldonado *et al*., 2024). Boron deficiency initiates calcium levels in the cell and changes the expression of the calcium-regulated genes (Camacho-Cristobal *et al*., 2013; Gonzalez-Fontes *et al*., 2014). Fluctuations in boron may alter the levels of Ca^{2+} and reactive oxygen species (ROS) production, both of which are central messengers in the plant signalling networks (Long and Peng, 2023). The joint effects of the two nutrients are critical to plant reproductive success and the fruit trees subjected to combined treatments attain better fruit set than using one nutrient treatment (Bonilla *et al*., 2004; Shah *et al*., 2024).

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Ca-B nutrition has to be managed by appropriate soil testing procedures and combined fertilization techniques. The vulnerabilities posed by climate change and soil erosion coupled with the lack of available resources pose increasing burdens on agricultural production systems and demand the optimised Ca-B nutritional management strategy to improve the system resilience.

Calcium-boron interactions molecular mechanisms

In plant physiology, the functions of calcium and boron do not occur in isolation but are complementary. Calcium ionically crosslinks pectic polysaccharide and boron borate esters rhamnogalacturonan II (RG-II) chains in cell wall construction (O'Neill *et al*., 1996; Vera-Maldonado *et al*., 2024). The resultant borate-RG-II dimer as found in the higher plants has two molecules of boric acid, two Ca^{2+} ions and two chains of RG-II and the calcium strengthens the boron bridges (Kobayashi *et al*., 1999; Matoh and Kobayashi, 1998). Radish root experiments demonstrated that cell wall disintegration was caused by removal of 96% of the calcium in the B-RG-II complex by chelating agents (Matoh and Kobayashi, 1998).

These elements do not simply have a structural association. The lack of boron increases the levels of cytosolic Ca^{2+} and activates calcium-regulated genes (Camacho-Cristobal *et al*., 2013; Gonzalez-Fontes *et al*., 2014). As both Ca^{2+} and ROS are considered core messengers, the changes in the availability of boron can control the downstream gene expression *via* these messengers (Long and Peng, 2023). The nutrients always regulate the reproductive processes such as pollen germination, tube growth and fertilization (Bonilla *et al*., 2004; Sathya *et al*., 2009; Shah *et al*., 2024).

When there is adequate calcium in roots, the plants are buffered to avoid toxicity caused by boron and the membrane integrity and transport efficiency are maintained (Siddiqui *et al*., 2012). Hydroponic experiments revealed that an insufficiency of either nutrient lead to a decrease of biomass and root systems through a change in wall compounds and structure (Liu *et al*., 2019). The recent developments in the discovery of genes/proteins related to calcium-boron transportation suggest that in the future, the control of nutrients may become more finely adjusted (Shi *et al*., 2017; Long and Peng, 2023).

Chemical dynamics of soil and biogeochemistry

Calcium and boron interaction is affected by the physicochemical characteristics of soil, particularly soil pH (Fig 1) and is occasionally not predictable. The geochemical modelling of multi-surface has shown that most soils have 68% or greater reactive boron in the solution phase and iron and aluminium oxides are the main adsorbing minerals in tropical soils whereas solid organic matter is the primary adsorbing mineral in temperate soils (Van Eynde *et al*., 2020a). The recent experimental work on boron adsorption to ferrihydrite indicated that boron adsorbs to the inner-sphere bidentate complex of the iron oxides to give mechanistic insights of surface speciation in soils (Van Eynde *et al*., 2020b; Jayara *et al*., 2023).

Calcium carbonate ($CaCO_3$) occupies the binding sites of boron and makes complexes with boron which are inaccessible to plants (Arora and Chahal, 2010). In limestone soils, this chemistry may lead to laboratory assays to reveal that there is sufficient boron in the soil and yet plants are deficient. The mineral properties of attracting soils have a substantial impact on the adsorption capacity toward boron and short-range order minerals constitute the major binding surfaces (Terraza-Pira *et al*., 2023). Studies of clay minerals (kaolinite, montmorillonite, gibbsite) show that the adsorption capacity of boron also grows to a proportion of cation exchange capacity and the maximum adsorption capacity is observed in alkaline environments because magnesium-borate ion pairs are well fixed on negatively charged surface sites (Ulatowska *et al*., 2024).

Soil organic matter may enhance the availability of boron in the form of chelation complexes that change the movement of nutrients in soil (Goldberg, 1997). Bioavailability and speciation studies affirm that the levels of soil organic carbon content show a significant correlation

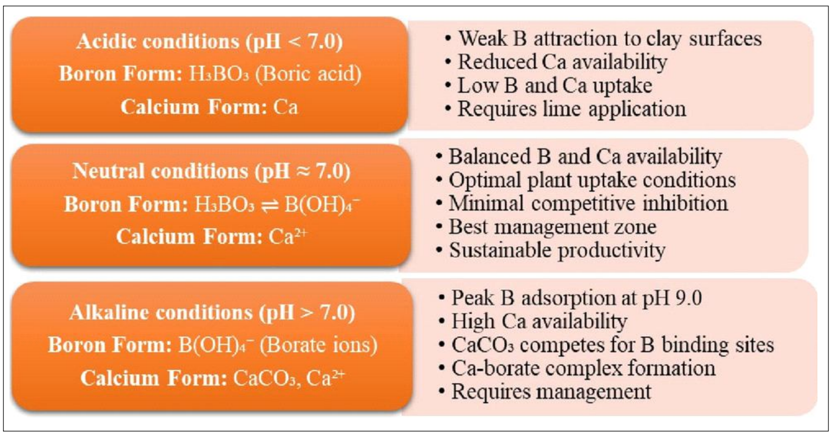

Fig 1: Calcium and boron transformation with soil pH.

with the patterns of micronutrient availability such as boron (Rahman and Schoenau, 2022). The interactive effects of boron and organic amendments on plant-soil microbial interactions show that the additions of organic matter can alter the availability of boron both by direct complexation and indirectly by affecting the activity of microorganisms (Vera *et al*., 2021).

Clay mineralogy is very different in Ca-B dynamics, where 2:1 types of minerals tend to bind more calcium and boron as compared to the 1:1 type in some situations under the influence of chemicals (Goldberg, 1997). Although much attention is given to chemistry, the biological component is becoming known as a critical one. The interactions between the soil properties and microbial communities are the core of the nutrient cycling (Philippot *et al*., 2023). The microbiome functions and the soil structure of agroecosystems are interconnected, microbial communities help to maintain Ca-B availability by the breakdown of organic matter, mineral weathering and general biogeochemical cycles (Hartmann and Six, 2023).

Plant uptake, transport and translocation

Transport of calcium and boron through the vascular system is influenced by a complex of interacting transport systems that may act cooperatively or independently. A major part of the process begins at the root membrane, where specific transporters define the elements that get in and its rates. The forms of B in acidic soils are the boric acid (H_3BO_3) whereas, in neutral to alkaline soils, the form changes to the tetrahydroxy borate $[B(OH)_4]^-$. Calcium is transported *via* specific Ca^{2+} channels and transport proteins (Miwa and Fujiwara, 2010). In the case of boron, two families of transporters have been found, including BOR transporters that act as exporters and nodulin-26-like intrinsic proteins (NIPs) that act as channels through which boric acid could traverse (Takano *et al*., 2002). There is still research on the complicated interplay between this system and conditions in real field scenarios. BOR1 was initially identified in Arabidopsis and is required in efficient xylem transport especially in translocation of younger parts of the plant (Takano *et al*., 2002).

The translocation of the two nutrients through the xylem greatly relies on the chemical forms and the environments. The level of calcium plays a significant role in the transport and distribution of boron within the plant systems. The majority of crops lack the ability to translocate boron in vegetative tissues to the growing meristematic tissues including shoots, root tips, flowers, seeds, or fruits (Brown and Shelp, 1997). Rather, the boron movement is primarily by the xylem due to the process of transpiration. High-air humidity and low soil moisture are environmental conditions which lower transpiration that negatively affects the xylem movement of boron (Pujari and Latha, 2017). Prolonged droughts hinder uptake of boron by decrease in root development, decrease of supplies of organic reserves and lower diffusion to root surfaces. In the case of deficiency of boron, the use of light energy that is captured during photosynthesis is minimally decreased, which results in surplus energy that can contribute to the possibility of leaf damage. Normal distributions patterns could be restored through sufficient calcium supplementation (Camacho-Cristobal *et al*., 2013). Boron also has significant functions in mycorrhizal fungi and plant root associations and helps in uptake of phosphorus among other nutrients by roots.

Growth, development and yield response of crop

Vegetative growth

Boron is actively involved in the cell wall construction in vegetative tissues, particularly by Borate ester connections with rhamnogalacturonan II that are necessary to regulate the wall porosity and elasticity (Funakawa and Miwa, 2015). Calcium on the other hand serves to ionically crosslink the pectic polysaccharides, which in effect strengthens the same wall framework that boron is forming. Adequate boron nutrition can be shown to increase phosphorus and potassium uptake into the root, which is at least partially due to the preservation of ATPase activity and the integrity of root membranes (Goldbach *et al*., 2007). Calcium-boron nutrition combination promotes cell division mechanisms and studies have shown that the two nutrients are critical in the proper formation of cell walls and stability of membranes when the cells are growing and developing.

Responses to calcium-boron interactions with regards to leaf growth and photosynthetic capacity are high and the responses are known to affect total plant productivity. Field experiment on soybean revealed that foliar calcium application with boron raised net photosynthetic rate by 25%, stomatal conductance by 18%, leaf protein content by 12% and Rubisco activity by 54% over untreated plants (Galeriani *et al*., 2022). There was also an improvement in water use efficiency and carboxylation efficiency (Çoksu and Özyazıcı, 2025). Balanced Ca-B nutritional plants are better lodging resistance and environmental tolerance (enhanced lignification and structural carbohydrate development in vascular tissues) under a condition of coordinated availability of calcium and boron (Fig 2) (Goldbach *et al*., 2007).

Reproductive development

Reproductive development is especially sensitive to interactions of calcium-boron as the processes which are important determinants of reproductive success in plants. Boron is vital to such reproductive organs as the formation of the pollen tubes and calcium is vital to fertilization signal transduction (Rashid *et al*., 2004). Scientific evidence is that the deficiency of boron leads to flower bud abortion, panicle sterility and delayed flowering in rice and the deficiency of boron in wheat causes a substantial decrease in grain yield through sterile grains (Rehman *et al*., 2018).

Research on rice has established that the application of boron has a significant influence on reproductive development that leads to less panicle sterility and larger panicles. It was found that the fertilization of flowers with boron improved the yield of high-quality rice by an average of 25-34%, which was explained by the number of panicles per plant and by the rate of filled grains (Siangliw *et al*., 2024). The research also determined that the use of boron stimulated rates of fertilized grains and a decrease in the percentage of unfertilized grains and thus the concentration of boron in all the parts of the plant.

Calcium-boron interactions are also important in the fruit set stage because these interactions mediate the process of fertilization success. A study conducted on mango on varied locations resulted in the finding that the treatment of calcium and boron increased the yield and the quality of the fruits to the level to be sold in the export markets (Nascimento *et al*., 2023). Intriguingly, the highest yields were realized not by simple application of the nutrient but when foliar sprays were applied with a combination of water-soluble calcium and boron with amino acids and algae extract. The research connected with the quality parameters of seeds, strongly points at the fact that distribution of calcium and boron in balance, leads to protein synthesis and storage metabolism in the growing seeds occurring more effectively, which is reflected in terms of improved viability and increased germination potential (Domingos *et al*., 2021).

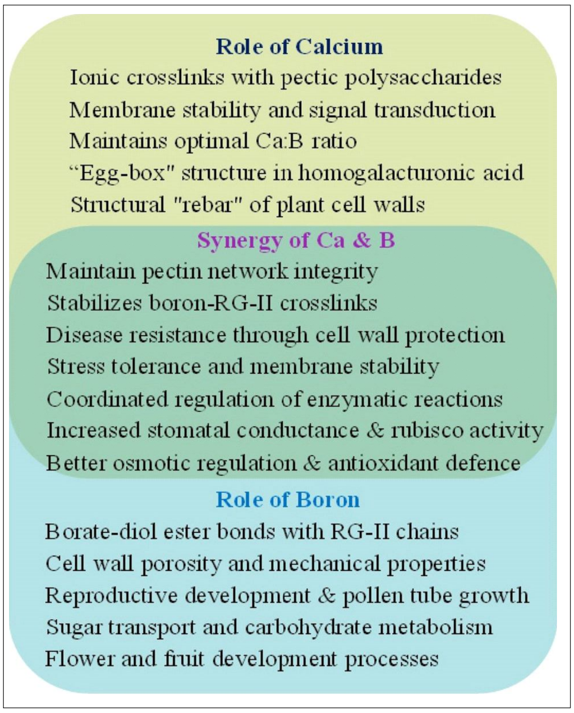

Fig 2: Functions of Ca-B and its synergetic effect in plants.

Stress responses and environmental resilience

Calcium-boron interactions have also been recognized to have a critical contribution to the enhancement of plant resilience to different environmental stresses (Fig 3). Research has revealed that plants that experience deficiencies of boron are more vulnerable to damage caused by high level of light that comes along with long, hot and sunny days. In that case, photosynthesis cannot be effectively performed with high light energy and the remaining energy leads to photodamage. A sufficient amount of boron and adequate calcium concentration can help to alleviate these effects (Goldbach *et al*., 2007; Vera-Maldonado *et al*., 2024). Oxidative damage, which is recently found as one of the key triggers of cell death, seems to be the critical issue of B deficiency (Koshiba *et al*., 2009). These results are very strong indications of balanced Ca-B nutrition in maintaining plants under environmental stress in physiological state.

Sodium/potassium ratio can be enhanced to a balanced state with calcium supplementation, which

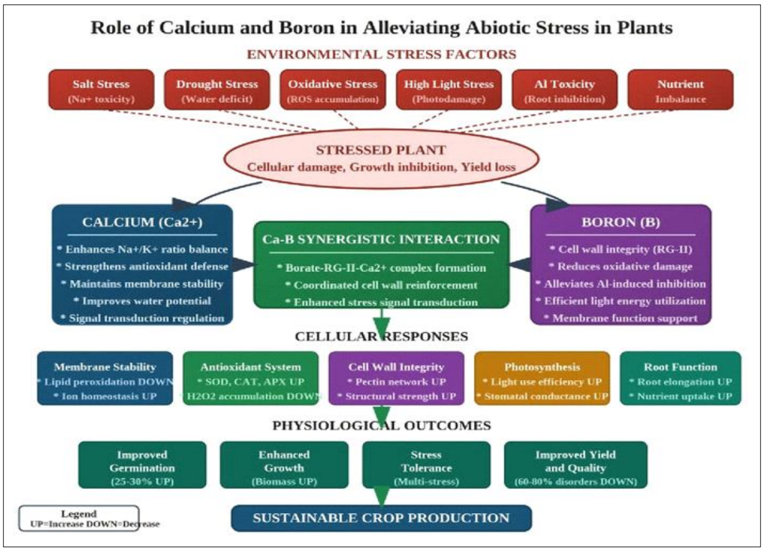

Fig 3: Schematic representation of calcium-boron (Ca-B) interactions in alleviating abiotic stress in plants.

enhances antioxidant protection of stressed plants (Rahman *et al*., 2016). Ca-B use under salt stress conditions enhances seed germination and seedling development at an earlier stage than that achieved by using either one nutrient separately (Bonilla *et al*., 2004; Vera-Maldonado *et al*., 2024).

The results of comparing calcium, boron and zinc application to tomato showed that Ca-B treatment enhanced the yields and quality of fruits and prevented physiological disorders (Shah *et al*., 2024). Conditions of drought and other environmental factors that cause a decrease in transpiration, negatively affect the calcium and boron transport in plants (Brown and Shelp, 1997; Vera-Maldonado *et al*., 2024). Nonetheless, it has been found that the two nutrients with proper supply can be used to maintain membrane stability and general cellular performance in the levels of water stress. The new research findings indicated that the presence of boron can reduce the aluminium-induced inhibitory effect of root elongation and when acting in cooperation with calcium, a more wide-ranging physiological resilience can be observed (Vera-Maldonado *et al*., 2024). They play a key role in the maintenance of productivity, quality and stress tolerance in diverse crops and under various conditions (Long and Peng, 2023; Shah *et al*., 2024).

Management strategies and crop specific applications

The proper management of Ca-B in agricultural systems depends on the extensive testing of the soils and diagnostic methods. The majority of crops retain sufficient levels of boron between 25-75 ppm in dry leaf materials. Soil application is advisable when the crops such as alfalfa, sugar beet, potato, sunflower, soybean or canola have a level below 25 ppm (Goldbach *et al*., 2007). There are strong positive linear relationships between the content of boron in plants and the extractable boron in soil when comparing wheat (R^2 = 0.509) and cotton (R^2 = 0.525) and extractable soil boron presents linear relationships with the yields of crops (Rashid *et al*., 2013).

The fertilizer systems based on nanotechnology are very promising, with the nano-calcium and nano-boron fertilizers showing a high level of bioavailability related to the controlled-release quality that minimizes the loss of nutrients through leaching (Vera-Maldonado *et al*., 2024; Raliya *et al*., 2018). Early foliar application of calcium nitrate (10-15 lbs/acre) or calcium chloride (5-8 lbs/acre) during the early fruit development improves the photosynthetic capacity, water potential and stomatal conductivity and decreases hydrogen peroxide accumulation (Naeem *et al*., 2018). The interaction between Ca-B is also an important concept to understand, where the presence of elevated levels of calcium in the soil may cause reduced absorption of boron as a result of the formation of calcium borate complexes (Kumar and Singh, 2019; Long and Peng, 2023). A more recent incorporation of sodium borates and calcium borates into a dual-release system with immediate release (sodium) and prolonged release (calcium) is better in nutrient delivery, with the ideal soil pH being 6.0-6.8.

Field crop research shows that considerable levels of Ca-B responses are experienced in different systems. In the rice-wheat system of the Tarai North-West Indian area, alternate soil application of 1.5 kg B/ha as borax boosted system rice equivalent yield by 6.7% and brought 9.73 t/ha yields with enhanced sustainable yield index (Pachauri *et al*., 2024; Singh *et al*., 2024). Positive Ca-B synergy in applying foliar $CaCl_2$ + H_3BO_3 on tropical acidic soils (3.5-6.5) during flowering and pod filling enhanced soybean water use efficiency by 34% and carboxylation efficiency by 35% (Galeriani *et al*., 2022). The joint use of Ca-B in drought-stressed durum wheat led to a 52-60 per cent improvement in the grain calcium level and an improvement in drought tolerance (Kizilgeci *et al*., 2022).

Vegetable crops are very responsive to balanced Ca-B nutrition. Ca-Mg-B (30 kg/ha) mixtures of micronutrients increased the yield of cabbage (164.7 per cent higher than controls) with increased root development (Jacob *et al*., 2023). The addition of B (0.5 mg/L) + Ca (100 mg/L) enhanced pea seed germination by 25-30 per cent and nodulation in the presence of salt stress (50-100 mM NaCl) and cell wall integrity (Bonilla *et al*., 2004). It was necessary that high Ca-B ratios were required in the symbiosis of the Rhizobium-pea to fix nitrogen in the presence of salt stress (El-Hamdaoui *et al*., 2003). Cassava planted on acidic sandy soils (pH 4.2-5.5) treated with combined Ca + B (500-1000 kg $CaCO_3$/ha + 1.5-3.0 kg B/ha foliar) exhibited 23-35 per cent higher tuberous root yield (Khamkure *et al*., 2023).

Ca-B management of fruits yields a significant number of advantages. Pomegranate had optimum fruit production of 38.3 kg/tree following the application of 2% foliar spray of calcium nitrate, which decreased the fruit cracking and sunburn, enhancing quality parameters (Patel *et al*., 2023). In apple, Ca-B combinations led to enhanced firmness of fruits and less bitter pit occurrence and boron aided in the movement of calcium to fruit tissues (Wojcik *et al*., 2019). Ca-B combined reduced tomato blossom-end rot by 60-80% as a result of the improved calcium movement (Shah *et al*., 2024). A study of 15-42 years of Indian soils showed that the integrated nutrient management (NPK + FYM) ensured sufficient soil boron after 42 years, with the $CaCO_3$ level of soil negatively linked with boron availability (Shukla *et al*., 2019).

Emerging research approaches and technologies

Genomics and transcriptomics

Genetic regions have been discovered to be linked with the level of efficacy of boron in crops such as wheat, rice and Brassica species through genome-wide association studies (GWAS) and quantitative trait locus (QTL) mapping (Miwa and Fujiwara, 2010; Zhang *et al*., 2018). These studies have identified genomic regions that determine the expression and the operation of the boron transporters, which are the targets of breeding programs that develop boron-effective varieties to grown on low-B soils. Single cell RNA sequencing in pea and *Arabidopsis* has given a previously unseen insight into cell-type-specific boron stress responses and identified previously concealed heterogeneity in nutrient stress responses (Chen *et al*., 2024).

The patterns of expression of key genes involved in the transport of boron (BOR1, BOR2, NIP5;1) and calcium channels are coordinated to sustain Ca-B homeostasis. The K63-linked polyubiquitination of BOR1 is induced by high boron concentration conditions and it is a transceptor, which can directly measure the concentration of boron to control the degradation of itself (Uraguchi *et al*., 2021). This complex homeostasis of boron facilitates the homeostasis of this mineral in different soil regimes. Integrative transcriptome-proteome analysis has shown that there are complex molecular regulation mechanisms during boron deficiency, which involve simultaneous up-regulation of NIP5;1-BORs module and related signalling pathways (Lin *et al*., 2024). Recent studies have shown that the calcium-dependent protein kinase CPK10 is essential to bridge the calcium signalling and regulating boron movements, which makes this enzyme molecular targets to be genetically improved to enhance the efficiency of nutrient utilization (Huang *et al*., 2024).

Metabolomics approaches

Metabolomics has shown that the lack of boron attracts a massive metabolic rearrangement, including primary metabolism, cell wall biosynthesis pathways and antioxidant synthesis (Wu *et al*., 2023). Such metabolic changes can be used as biomarkers to identify Ca-B disturbances at an early stage before their manifestations become observed. Research on pear trees showed that the effects of boron application are cascading and change the level of nitrogen, phosphorus, calcium and magnesium in various plant organs (Du *et al*., 2024).

Combining metabolomics with calcium signalling research reveals that the Ca-B interactions regulate the carbohydrate metabolism, amino acid synthesis and the synthesis of secondary metabolites (Katam *et al*., 2022). This knowledge of such metabolic signatures may facilitate establishment of specific management practices to maximise nutrient supply during critical periods of growth.

Horticultural remote sensing and precision agriculture

Multispectral and hyperspectral imaging technologies can be used as remote sensing instruments to identify the symptoms of Ca-B deficiency at an early stage of its development (Samreen *et al*., 2022; Chivasa *et al*., 2023). About one-third of the analysed soil samples exhibits the deficiency of boron, which demonstrates the importance of nutrient management site-specifically. The application systems with GPS guidance and variable rates allow delivering Ca-B accurately at the field with an accurate delivery on the base of the prescription maps. Grains, pomegranates and tomatoes have shown a high yield as well as quality when the use of Ca-B is precise (Shah *et al*., 2024; Patel *et al*., 2023). Proximal sensors and camera drones mounted on sensors offer real time information to be used in in-season management (Sishodia *et al*., 2024).

Mycorrhizal fungi and pathogenic microorganisms

Arbuscular mycorrhizal fungi (AMF) establish symbiotic relationships with about 80 species of land plants, which boost nutrient uptake of not only calcium but also boron (Wahab *et al*., 2023). Field study meta-analysis shows that AMF inoculation leads to a mean way up of plant biomass as well as boosted uptake of boron, phosphorus, copper and molybdenum (Wu *et al*., 2024). Studies prove that AMF compatibility is related to an increase in concentrations of boron, copper and phosphorus in field-grown maize (Sawers *et al*., 2023). The AMF inoculation has the potential to boost the biomass of the plants and lead to a decrease in the shoot boron levels in the case of toxicity.

Decision support systems (DSS) and machine learning

The machine learning models such as neural networks, XGBoost and random forest algorithm can be able to predict the optimal Ca-B application rates that are more precise than the conventional recommendation systems that are based on the generalized soil test correlations (Tanaka *et al*., 2024). These models combine soil test and weather predictions with crop growth models and past yield information to produce site specific recommendations that consider the interaction of different environmental factors.

The precision rates of XGBoost and random forest algorithms reach above 99% when the algorithms are trained on all-encompassing datasets on a wide range of the soil types and management activities (Saha *et al*., 2024; Musanase *et al*., 2023). DSS that includes these algorithms creates site-specific, real-time recommendations that take into consideration the stage of crop growth, weather predictions and soil moisture (Taneja *et al*., 2023). These tools are becoming available to farmers with different degrees of technical knowledge through user-friendly mobile applications and enabling them to adopt large-scale use of precision nutrient management techniques and minimize the environmental impact and input expenses.

CONCLUSION AND FUTURE PERSPECTIVES

The calcium-boron relationship is one of the most critical interactions in plant physiological process concerning mineral nutrition, which has impact on agricultural productivity, quality parameters and stress tolerance mechanism in varying crop production systems. Recent molecular methods such as genomics, transcriptomics and metabolomics have revealed novel details about Ca B interactions, not only in the discovery of essential transporter genes (BOR1, NIP5) but also in metabolic networks that react to nutrient stress. The RNA sequencing of single cells has shown cell-type-specific responses that were not obvious when examining entire tissues.

The roles of mycorrhizal fungi in Ca-B nutrition have become one of the important research frontiers. AMF associations can promote the uptake of calcium and boron *via* prolonged hyphae systems, which provide viable solutions to the nutrient management. Such technologies as remote sensing and variable rate application are also called precision agriculture and allow managing nutrients in a much more efficient way depending on the specifics of the locations.

Future studies must focus on the design of integrated decision support systems that can incorporate machine learning algorithms to make real-time recommendations. The identification of molecular biomarkers to detect the deficiencies of Ca-B in the plant tissue early before they manifest any symptoms. These intricate Ca-B interactions offer principles upon which sustainable efforts to intensify food security in the world can be directed.

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Informed consent

Not applicable.

Conflict of interest

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