4.3 Boron deficiency and its impact on blueberry production

Boron deficiency commonly occurs in acidic and high-rainfall cultivation environments. This issue is particularly important in blueberry production because low soil pH reduces boron availability, while strong leaching processes can further accelerate boron loss from the root zone (Reyes-Díaz et al., 2024; Vera-Maldonado et al., 2024). Symptoms of boron deficiency in blueberry mainly include shoot tip necrosis, leaf mottling and chlorosis, leaf curling, shortened internodes, reduced leaf area, and restricted new shoot growth (Arrington and DeVetter, 2017; Meriño-Gergichevich et al., 2017). De Silva et al. (2022) found that with increasing boron deficiency severity, flower buds may fail to open normally, pollen tube growth can be inhibited, seed development may be impaired, and fruit deformation may occur, highlighting the essential role of boron in reproductive tissue development. In various fruit crops, boron deficiency has also been associated with physiological disorders and reduced commercial fruit quality (Álvarez-Herrera et al., 2025).

Both male and female reproductive tissues have relatively high boron requirements, and boron deficiency can reduce pollen production, pollen viability, pollen tube elongation, and the functionality of transmitting tissues (De Silva et al., 2022). However, studies in blueberry have shown that even when tissue boron concentrations are increased, correcting low boron status does not necessarily improve fruit set or yield, indicating that boron availability represents only one of multiple factors limiting production performance (Arrington and DeVetter, 2017; Leon-Chang and Bryla, 2024). The optimal range between boron deficiency and toxicity is relatively narrow and is influenced by cultivar differences, making excessive boron application more likely to exceed suitable levels under intensive fertilization conditions.

Excessive boron supply can inhibit plant growth, reduce photosynthetic efficiency, and subsequently affect yield and fruit quality. Such effects have been demonstrated in blueberry and other fruit crops (Luo et al., 2024; Reyes-Díaz et al., 2024). Therefore, the objective of boron management in blueberry production should be to maintain an appropriate nutritional level. Proper control of boron application rates and timing is essential for maximizing its beneficial effects on fruit development and quality formation while avoiding potential toxicity risks.

5 Synergistic Effects of Calcium and Boron Nutrition on Blueberry Quality

5.1 Interaction between calcium and boron in cell wall formation

Calcium and boron act on different components of fruit cell walls, and their synergistic effects are mainly reflected in pectin stabilization and the maintenance of cell wall structural integrity. Lopes et al. (2026) reported that blueberry fruit texture is highly dependent on cell wall composition, cell membrane integrity, and pectin structures responsible for connecting adjacent cells. Cell wall-bound Ca^{2+} enhances pectin stability and regulates the activities of cell wall degradation-related enzymes. In various fruit systems, both calcium and boron interact with pectin structures and jointly contribute to the stability of cell wall networks. Calcium mainly enhances pectin network stability through the formation of “egg-box” structures between Ca^{2+} and de-esterified pectin, whereas boron improves cell wall adhesion and rigidity by participating in the formation of borate ester bonds associated with RG-II (Figure 3). Du et al. (2025) reported in citrus that combined Ca+B treatment reduced water-soluble pectin content while increasing the proportions of CDTA-soluble pectin and sodium carbonate-soluble protopectin, indicating that this treatment delayed pectin solubilization and enhanced peel structural stability.

Similar mechanisms have been demonstrated in tomato and strawberry. In tomato, boron was found to promote calcium distribution in the symplast and reduce pectin methylesterase activity (Gholamnejad et al., 2023). In strawberry, boron maintained cell wall-bound boron levels and promoted cross-linking interactions between boron and structural components such as pectin, cellulose, and hemicellulose, thereby improving cell wall stability during storage (Zhang et al., 2024).

Calcium and boron also exhibit complementary effects in maintaining fruit firmness. Calcium mainly increases tissue strength by enhancing middle lamella stability and the structural integrity of cell wall polysaccharide networks, whereas boron contributes to firmness preservation by limiting pectin degradation and softening-related