rhizosphere. Boron mainly enters blueberry roots through mass flow, making boron deficiency more likely in coarse-textured soils with low organic matter content. Under such conditions, drip irrigation combined with fertigation is generally more suitable than large-scale soil fertilization for maintaining a stable boron supply. A field study conducted in Oregon by Leon-Chang and Bryla (2024) showed that weekly boron fertigation from April to July was the only approach that increased soil extractable boron concentrations to recommended levels, whereas foliar boron application was more effective in increasing boron concentrations in leaves, roots, and fruits. Irrigation conditions also influence calcium use efficiency because under low transpiration conditions, calcium accumulation in fruits is usually lower than that in leaves, and high root-zone temperatures during later growth stages can further restrict calcium and boron uptake.

Studies on sweet cherry provide additional mechanistic insights. Under boron-deficient soil conditions, calcium allocation to branches, leaves, and edible tissues was reduced, while more calcium remained in roots and seeds, indicating that boron deficiency may impair effective calcium transport and distribution within plants (Bonomelli et al., 2025). Therefore, in blueberry production, calcium and boron nutritional management should consider the interactions between these two elements to achieve synergistic regulation. Rhizosphere chemical conditions determine whether applied calcium and boron can be effectively absorbed and utilized by plants. Blueberry prefers acidic soil conditions; however, excessively low pH and high rainfall conditions generally reduce boron availability, while excessive concentrations of aluminum, iron, and manganese in acidic substrates may also inhibit calcium uptake (Zydlik et al., 2022; Leon-Chang and Bryla, 2024). In soilless cultivation systems, the proportion of ammonium nitrogen and the type of nitrogen fertilizer can also alter nutrient balance. For example, Anwar et al. (2024) found that an NH_4^+:NO_3^- ratio of 50:50 increased leaf calcium content, promoted flowering and fruiting, and enhanced photosynthetic capacity. However, under potted conditions, increasing ammonium sulfate application increased leaf calcium content in some cultivars but reduced leaf boron levels in most cultivars.

The suitable range of soil calcium availability in blueberry is relatively narrow and shows strong site-specific variation. Under commercial production conditions, low-dose soil calcium application increased exchangeable calcium content but did not improve fruit firmness, size, or weight in ‘Duke’ and ‘Legacy’ blueberry (Hirzel, 2023). Optimization of the root-zone environment requires comprehensive consideration of soil pH, nitrogen forms, water supply, soil physical properties, and the nutrient requirements of specific cultivars.

6.3 Application of calcium and boron regulation in quality-oriented production

For blueberry production targeting high quality and high commercial value, the currently more reliable strategy is to implement early precise calcium supplementation combined with boron nutritional management based on boron deficiency risk assessment. Existing studies have shown that calcium has the most significant effects on fruit firmness and storage performance when it can effectively enter fruits and increase fruit calcium levels. For example, in ‘Liberty’ blueberry, early preharvest calcium application increased fruit firmness, reduced polygalacturonase activity, and decreased decay and dehydration, thereby improving postharvest quality (Lobos et al., 2021a). Some foliar fertilizers containing calcium and micronutrients have also been shown to increase blueberry fruit weight, firmness, soluble solids content, and post-storage quality; however, these effects are usually influenced by the combined action of multiple components in the formulations and cannot be fully attributed to calcium alone (Zydlik et al., 2022).

In contrast, boron management plays a more consistent role in maintaining normal reproductive development and can increase soluble solids content in some cultivars through foliar spraying or fertigation (Leon-Chang and Bryla, 2024). Negi and Upadhyay (2024) found in southern highbush blueberry that preharvest $CaCl_2$, boric acid, and their combined treatments all reduced physiological weight loss and decay rate during cold storage, indicating that appropriate calcium–boron combinations have the potential to extend storage life.

Sustainable high-quality blueberry production requires the establishment of an integrated nutrient management system based on cultivar characteristics, tissue nutrient diagnosis, and orchard stress management. Blueberry responses to calcium are highly variable, the optimal range of boron availability is relatively narrow, and the