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Factors Affecting Bioactive Compound Accumulation in Blueberry Fruit

Ze Huang, Minghua Li
Biotechnology Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, China
Corresponding email: ze.huang@cuixi.org
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Abstract Blueberry fruit quality is no longer evaluated only by berry size, bloom, and firmness. In commercial orchards and premium fresh markets, the ability of fruit to accumulate anthocyanins, phenolic compounds, flavonoids, and vitamin C has become an increasingly important indicator of nutritional value and market competitiveness. The accumulation of these bioactive compounds is jointly regulated by cultivar genetic characteristics, light environment, temperature conditions, water availability, soil acidity, and orchard management practices. Even under the same cultivation conditions, significant differences in bioactive compound levels exist among blueberry cultivars. As blueberry is a typical acid-loving crop, unsuitable soil pH can affect nutrient uptake, photosynthesis, and subsequent fruit quality formation. Evidence from Caota town in Zhejiang Province, karst production areas in Guizhou, protected cultivation systems in Liaoning, and high-altitude regions in southwest China indicates that improving blueberry quality requires effective coordination of cultivar selection, environmental conditions, and orchard management. This review systematically analyzes the major factors affecting bioactive compound accumulation in blueberry fruit and proposes future production strategies for commercial orchards, providing references for high-quality fruit production and stable economic returns.
Keywords Blueberry (*Vaccinium corymbosum* L.); Anthocyanins; Polyphenols; Flavonoids; Vitamin C; Fruit quality; Environmental factors; Cultivation management; Commercial production

1 Introduction

Blueberry has developed from a niche berry crop into a high-value fruit with both fresh-market appeal and functional nutritional benefits. With changing consumer demands, blueberry quality evaluation is no longer limited to berry size, bloom, color, and firmness, but increasingly focuses on sugar–acid balance, storage performance, and the content of functional compounds such as anthocyanins. Blueberry fruit contains various phytochemicals, among which anthocyanins are considered one of the major contributors to its nutritional and health-related value. In commercial production, growers need not only stable yields but also improved flavor, firmness, and bioactive compound content through suitable cultivar selection and cultivation management to meet the requirements of premium fresh markets and functional food industries (Kalt et al., 2020).

The main bioactive compounds in blueberry fruit include anthocyanins, total phenolics, flavonoids, proanthocyanidins, phenolic acids, and vitamin C. These compounds influence not only nutritional value and antioxidant capacity but also fruit coloration, flavor development, and postharvest quality. During blueberry ripening, significant changes occur in phytochemical composition. Total phenolic and total flavonoid contents do not always change in parallel with anthocyanin accumulation, indicating that ripening is not a simple process in which all antioxidant compounds increase simultaneously. Instead, different phenolic compounds undergo continuous transformation and redistribution during fruit development. Differences among cultivars, developmental stages, and fruit tissues further indicate that nutritional quality cannot be fully evaluated only based on external fruit color (Moggia et al., 2017).

The accumulation of bioactive compounds in blueberry fruit results from the combined effects of genetic characteristics, fruit development, and cultivation environment. Abscisic acid (ABA) promotes blueberry fruit ripening and anthocyanin accumulation by regulating the expression of structural genes involved in anthocyanin biosynthesis, including chalcone synthase (CHS), chalcone isomerase (CHI), dihydroflavonol 4-reductase (DFR), and anthocyanidin synthase (ANS), as well as transcription factors such as MYB, bHLH, and WD40 (Han et al., 2021; Yang et al., 2023). Under commercial production conditions, cultivar characteristics, light availability, temperature, water supply, soil acidity, fertilization practices, canopy structure, and harvest maturity can all affect the expression of this genetic potential.

This review summarizes the major bioactive compounds involved in blueberry fruit quality formation and analyzes their changes among different ripening stages and cultivars. Based on production practices in major blueberry-growing regions of China, this study further summarizes management strategies for improving bioactive compound accumulation under different ecological conditions and provides scientific references for quality improvement in commercial orchards. Sustainable production of high-quality blueberries requires appropriate matching between cultivars and environmental conditions, coordination between canopy structure and light distribution, adaptation of cultivation substrates to blueberry root physiological requirements, and proper decisions regarding harvest timing and target markets. Only through integrated management can growers consistently produce blueberries with high bioactive compound contents and stable fruit quality.

2 Major Bioactive Compounds Determining Blueberry Fruit Quality

2.1 Anthocyanins and fruit coloration

Anthocyanins are the major pigments responsible for the transition of blueberry fruit from green or reddish immature berries to fully ripened blue-purple fruit. They are also important bioactive compounds determining fruit appearance quality. The distribution of anthocyanins is not uniform among different fruit tissues. The peel is the main accumulation site, which explains why blueberry fruit may show complete external coloration while pigment accumulation inside the fruit is still continuing.

Sun et al. (2018) investigated changes in bioactive compounds during different developmental stages of southern highbush blueberry (*Vaccinium corymbosum* L.). As fruit developed from the green stage to the fully ripe blue stage, total anthocyanin content increased rapidly from 3.43 mg/g FW to 153.39 mg/g FW, representing more than a 40-fold increase. At the same time, anthocyanin levels in the peel of mature fruit were much higher than those in the pulp, indicating that the peel is the main storage tissue for anthocyanins and an important contributor to the strong antioxidant capacity of blueberries. In addition to changes in total content, anthocyanin composition also changed during ripening. The number of detected anthocyanin compounds increased as fruit matured, and malvidin gradually became one of the dominant anthocyanins in ripe blueberry fruit.

2.2 Polyphenols and antioxidant capacity

Polyphenols in blueberry fruit mainly include anthocyanins, flavonols, flavanols, proanthocyanidins, and phenolic acids. Common non-anthocyanin phenolic compounds include chlorogenic acid, quercetin derivatives, myricetin derivatives, catechin, and epicatechin. During fruit development, different polyphenolic compounds do not accumulate at the same rate. Green immature fruit generally contains higher total phenolic content and stronger in vitro antioxidant activity, while total phenolics gradually decrease during fruit enlargement and coloration, accompanied by rapid anthocyanin accumulation at the blue stage. Vasquez-Rojas et al. (2025) compared blueberry fruit from two production seasons and found that total phenolic content, DPPH radical scavenging activity, and FRAP values generally declined as fruit developed from the green and pink stages to the blue stage, whereas anthocyanin content increased markedly in fully ripe fruit. These results indicate that ripening is not simply a process of increasing all antioxidant compounds, but rather involves metabolic rearrangement, with immature fruit dominated by defensive phenolics such as chlorogenic acid and flavanols, while mature fruit shifts toward anthocyanin accumulation associated with coloration and improved eating quality.

The contribution of different phenolic compounds to antioxidant capacity varies according to their chemical structures, hydroxyl groups, and relative abundance. Therefore, blueberry samples with similar total phenolic contents may still show different antioxidant capacities due to differences in anthocyanin, flavonol, and phenolic acid composition. Zheng et al. (2024) reported that preharvest application of 0.5 mmol/L melatonin significantly increased total phenolic and total flavonoid contents in blueberry fruit. Meanwhile, total anthocyanin content increased by 50.38%, and ABTS radical scavenging activity and FRAP values increased by 116.49% and 94.28%, respectively. Metabolomic analysis identified 459 flavonoid-related metabolites, suggesting that improved antioxidant capacity was not controlled by a single compound but resulted from coordinated changes among anthocyanins, flavonols, flavonoids, and flavanols.

2.3 Flavonoids, vitamin C and nutritional quality

In addition to anthocyanins, blueberry fruit contains abundant flavonols, flavanols, and other non-anthocyanin phenolic compounds, which together form an important nutritional foundation of blueberry fruit. The accumulation patterns of different flavonoid compounds are not completely consistent during fruit development. Flavonols and flavanols are generally higher at the immature stage, followed by continuous transformation and redistribution as fruit ripens. Günther et al. (2020) analyzed metabolic changes during different developmental stages of northern highbush and rabbiteye blueberries and found that flavonoid metabolites were mainly accumulated in the skin tissue and showed clear spatial and temporal variation during ripening. The fruit skin maintained high levels of flavonoids and anthocyanins throughout maturation, whereas the corresponding metabolites in the pulp were much lower, which partly explains the stronger antioxidant capacity of blueberry skin.

Flavonoids contribute not only to antioxidant capacity but also to fruit flavor formation and quality differences among cultivars. Even when different cultivars have similar total flavonoid contents, their specific flavonoid compositions may vary considerably, resulting in differences in antioxidant activity and sensory characteristics. Li et al. (2023) used combined metabolomic and transcriptomic analyses to investigate flavonoid metabolism during fruit ripening among different blueberry cultivars. The results showed significant differences in flavonoid metabolic pathways among cultivars, and some flavonol compounds were closely associated with fruit coloration and ripening regulation. Therefore, blueberry nutritional quality should not be evaluated only based on total flavonoid or total anthocyanin content, but should also consider the combined effects of different flavonoid components.

Although vitamin C content in blueberry is generally lower than that of anthocyanins and other phenolic compounds, it remains an important indicator of fruit nutritional quality. Vitamin C contributes to antioxidant activity and works together with phenolic compounds to maintain the stability of the fruit antioxidant system. Significant differences in vitamin C content exist among cultivars and developmental stages, and its accumulation pattern is jointly regulated by genetic background and environmental conditions. Therefore, vitamin C, together with flavonoids and phenolic compounds, should be considered as an important component of comprehensive blueberry quality evaluation.

3 Environmental Factors Affecting Bioactive Compound Accumulation in Blueberry Fruit

3.1 Variety and genetic background

Genetic background is one of the most stable and important factors determining bioactive compound accumulation in blueberry fruit and provides the basis for fruit quality formation. Compared with environmental factors such as light, temperature, and water availability, genotype determines the potential accumulation capacity of anthocyanins, phenolics, flavonoids, and vitamin C, while environmental conditions and cultivation practices mainly regulate the expression of this genetic potential. Even under the same ecological conditions and management practices, significant differences in nutritional quality can still be observed among blueberry cultivars. Therefore, appropriate cultivar selection has become the first step in high-quality blueberry production.

Liu et al. (2025) evaluated 26 highbush blueberry cultivars (*Vaccinium corymbosum* L.) grown in the same orchard in Shandong Province under uniform management conditions and compared their fruit quality and bioactive compound profiles. The results showed significant differences among cultivars in soluble solids content, titratable acidity, vitamin C content, anthocyanin composition, and antioxidant capacity. Among them, ‘Sunrise’, ‘Bluegold’, ‘Elliott’, ‘Amblue’, and ‘Briteblue’ showed better overall performance, with higher sugar accumulation, stronger antioxidant activity, and richer anthocyanin profiles. In contrast, some cultivars with relatively high yield did not necessarily have higher functional compound levels. These findings indicate that fruit quality is not determined only by cultivation management but is also strongly controlled by cultivar genetic characteristics, and different cultivars have different potentials for quality formation (Liu et al., 2025).

3.2 Light conditions

Light is not only the energy source for blueberry photosynthesis but also an important environmental signal regulating the synthesis of anthocyanins and other bioactive compounds. Light intensity, spectral composition, and duration can influence related metabolic pathways, thereby affecting the accumulation of anthocyanins, phenolics, and vitamin C in blueberry fruit. Wei et al. (2023) investigated the effects of different LED light qualities on blueberry fruit and found that blue light significantly promoted the expression of anthocyanin biosynthesis-related genes and increased anthocyanin content (Figure 1). Yellow light, however, was more effective in enhancing ascorbic acid (vitamin C), glutathione, and total phenolic contents. In addition, blue and white light treatments promoted fruit enlargement and increased single fruit weight, suggesting that different light qualities regulate blueberry fruit development and nutritional quality through different mechanisms.

Besides visible light, ultraviolet-B (UV-B) radiation is also an important environmental factor promoting anthocyanin accumulation. Recent studies have shown that UV-B acts as a developmental signal and activates anthocyanin biosynthesis through the UVR8-COP1-HY5-MYB regulatory pathway. Song et al. (2023) identified several MYB transcription factors involved in UV-B-induced anthocyanin accumulation in blueberry, while Li et al. (2021) reported that long-term preharvest UV-B exposure not only promoted fruit ripening and sugar accumulation but also regulated anthocyanin metabolism at different developmental stages. Therefore, shading nets, greenhouse films, or excessively dense canopies in modern production systems may reduce UV-B penetration or canopy light availability, potentially limiting anthocyanin accumulation and nutritional quality development.

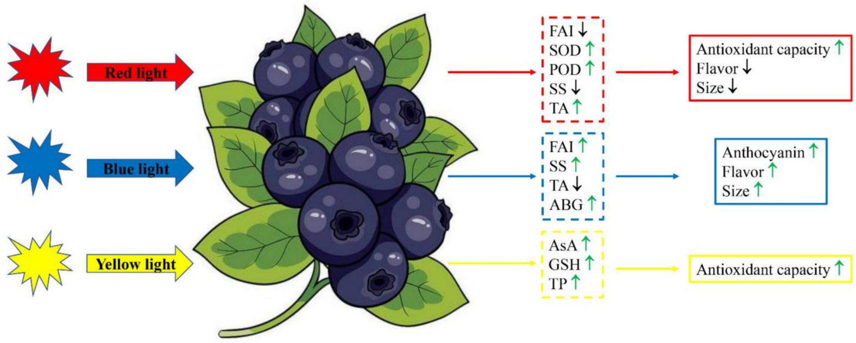

Figure 1 Possible mechanism of regulating fruit quality and anthocyanin content in blueberry via different light wavelengths. The green up-arrow indicates a significant increase, and the black down-arrow indicates a significant decrease. FAI, fruit appearance indexes; SOD, superoxide dismutase; POD, peroxidase; SS, soluble solids; TA, total acid; ABG, anthocyanin biosynthesis genes; AsA, ascorbic acid; GSH, glutathione; TP, total phenol (Adopted from Wei et al., 2023)

3.3 Temperature and climate conditions

Temperature is a major climatic factor affecting blueberry fruit quality formation. It regulates bioactive compound accumulation through its effects on sugar accumulation, organic acid metabolism, enzyme activity, and plant stress responses. Prolonged high temperatures during summer can accelerate fruit respiration, increase carbon consumption, and reduce anthocyanin accumulation and fruit coloration. In contrast, environments with moderate daytime temperatures and cooler nights generally favor sugar accumulation, acid retention, and anthocyanin biosynthesis. Temperature and light are among the most important environmental factors controlling anthocyanin formation, and they can interact with plant hormone pathways to influence fruit quality.

Field observations from different production regions further demonstrate the importance of climate conditions. Blueberries grown at higher altitudes generally show higher soluble solids content, total flavonoids, total phenolics, proanthocyanidins, and anthocyanins, together with higher sweetness scores compared with fruit produced at lower altitudes. Altitude is positively associated with flavonoid content, total phenolics, proanthocyanidins, anthocyanins, and fruit sweetness. These results suggest that low temperatures, larger day–night temperature differences, and unique light conditions associated with high-altitude environments jointly promote bioactive compound accumulation, making climate an important determinant of final blueberry fruit quality.

3.4 Water availability

Blueberry has a shallow root system and relatively limited water uptake capacity, making it highly sensitive to changes in soil moisture. Both prolonged drought and excessive irrigation can negatively affect fruit development and bioactive compound accumulation. However, moderate water regulation does not always reduce fruit quality and may improve certain quality traits under specific environmental conditions. Ordóñez-Díaz et al. (2020) conducted a field experiment in southwest Spain and found that moderate deficit irrigation did not significantly reduce major blueberry fruit quality parameters but increased fruit firmness. This indicates that under Mediterranean climatic conditions, precisely controlled irrigation reduction can save water while maintaining or even improving commercial fruit quality.

Although moderate water stress may have beneficial effects within a certain range, prolonged or severe drought significantly reduces blueberry quality. Continuous water deficiency suppresses photosynthesis, reduces chlorophyll content, and affects carbon assimilation and nutrient transport, ultimately limiting fruit development and bioactive compound accumulation. Moderate abiotic stress may activate antioxidant systems and increase some bioactive compounds, but this positive effect occurs only within a limited stress range (Krishna et al., 2023). Once water stress exceeds the plant tolerance threshold, vegetative growth, canopy function, and fruit enlargement are severely affected, and the negative effects become greater than the potential benefits from increased secondary metabolites.

3.5 Soil properties

Soil conditions are fundamental factors affecting blueberry growth and fruit quality formation, among which soil pH is particularly important. Blueberry is a typical acid-loving fruit crop and grows best in acidic soils with high organic matter content, good drainage, and sufficient aeration. Ochmian et al. (2021) reported that the suitable soil pH range for blueberry cultivation is approximately 3.8–5.5 and compared different soil amendment methods. Sulfur application effectively reduced soil pH and improved soil suitability for blueberry growth, while some soil types, such as silty loam soils, remained difficult to adjust even after amendment. This indicates that not all soils are equally suitable for blueberry production.

Unsuitable soil pH directly affects blueberry physiological functions. Yang et al. (2022) found that high-pH stress significantly reduced leaf SPAD values, net photosynthetic rate, transpiration rate, and stomatal conductance, while also altering osmotic regulation and antioxidant systems. As a result, different cultivars showed varying degrees of growth inhibition under alkaline conditions. High soil pH not only reduces blueberry yield but also weakens fruit quality and nutritional value by restricting nutrient uptake and disrupting normal physiological processes. Therefore, maintaining an appropriate acidic root-zone environment is a fundamental requirement for stable blueberry production and high-quality fruit formation.

4 Production Management Practices for Improving Blueberry Fruit Quality

4.1 Fertilization management strategies

Fertilization is an important production practice affecting blueberry fruit quality. Its role is not only to promote plant growth and increase yield but also to directly regulate the accumulation of bioactive compounds such as anthocyanins and phenolics. Blueberry has a shallow root system and is highly sensitive to nutrient availability. Insufficient fertilization can limit plant growth and fruit development, while excessive fertilization, especially excessive nitrogen supply, may promote excessive vegetative growth, increase competition between shoots and fruits for assimilates, and reduce the accumulation of bioactive compounds.

Mecozzi et al. (2026) investigated the effects of different nutrient supply levels on fruit quality of ‘Duke’ blueberry (*Vaccinium corymbosum* L.) grown under soilless conditions in Italy. The results showed that lower nutrient supply favored higher anthocyanin content and antioxidant capacity, while increased nutrient availability promoted vegetative growth, yield, and some phenolic compounds but did not further enhance anthocyanin accumulation. These findings indicate that high yield does not always correspond to high fruit quality, and excessive nutrient input beyond plant requirements may not be converted into quality advantages. For commercial orchards, fertilization programs should therefore be optimized according to fruit quality formation, maintaining a balance between vegetative growth and reproductive development while avoiding excessive late-season nutrient supply.

4.2 Pruning and canopy management

A well-structured canopy improves orchard ventilation and light penetration, increases effective light exposure of fruiting branches, enhances leaf photosynthetic efficiency, and optimizes the leaf-to-fruit balance, thereby creating a favorable microenvironment for the accumulation of anthocyanins, phenolics, and other bioactive compounds. In contrast, overly dense canopies reduce the exposure of fruit to blue light and UV-B radiation, limiting anthocyanin formation. However, excessive pruning or an overly open canopy may expose fruit to excessive heat and strong radiation, increasing the risk of sunburn, water loss, and quality deterioration.

Canopy management strategies should be adjusted according to cultivation systems. In protected cultivation, canopy structure should be combined with appropriate covering materials, supplemental lighting, and shading management to optimize the light environment and avoid reduced light availability caused by greenhouse coverings. In open-field orchards, winter pruning, renewal of fruiting branches, and removal of overly dense shoots can improve internal canopy light conditions and maintain productive fruiting wood. Proper canopy management not only improves fruit coloration and appearance uniformity but also promotes the accumulation of anthocyanins and phenolic compounds, thereby enhancing fruit flavor, nutritional quality, and commercial value.

4.3 Mulching management

Mulching improves blueberry growth and fruit quality mainly by regulating root-zone temperature, soil moisture, and weed competition. Because blueberry has a shallow root system with limited root hairs, most roots are distributed in the surface soil layer and are highly sensitive to high temperature, drought, and rapid changes in soil moisture. Organic mulches such as pine bark and wood chips can reduce soil water evaporation and gradually increase soil organic matter during decomposition, while geotextile mulch provides effective weed control and has a longer service life. However, the effects of different mulching materials vary depending on soil properties, climatic conditions, irrigation management, and cultivar characteristics.

Retamal-Salgado et al. (2022) compared the effects of no mulch, pine bark mulch, and geotextile mulch in a commercial blueberry orchard in Chile using rabbiteye blueberry 'Ochlockonee' (Vaccinium virgatum Aiton) and highbush blueberry 'Legacy' (*Vaccinium corymbosum* L.) over two growing seasons. Both pine bark and geotextile mulches reduced daily soil temperature fluctuations, maintained a more suitable root-zone temperature, and improved afternoon photosystem II photochemical efficiency. In 'Legacy', fruit firmness under pine bark and geotextile mulch reached 73 and 75 gf·mm^{-1}, respectively, compared with 67 gf·mm^{-1} in the non-mulched treatment. Both mulching treatments also increased yield in this cultivar, whereas the yield response was not significant in 'Ochlockonee'. These results indicate that mulching can improve root-zone conditions and fruit quality, but its effects are strongly dependent on cultivar characteristics and production environments.

4.4 Harvest maturity and postharvest management

Although complete fruit coloration is commonly considered an important indicator of blueberry maturity, biochemical changes continue after the peel turns blue. During this stage, blueberries continue to accumulate sugars, anthocyanins, and other bioactive compounds. Early harvesting improves transportability and storage performance but reduces fruit flavor and nutritional value. Extending fruit development on the plant can increase anthocyanin accumulation, improve sugar–acid balance, and enhance commercial quality. Therefore, high-quality fresh blueberry production often adopts selective harvesting to ensure that fruits at different maturity stages reach optimal harvest quality.

After harvest, blueberry fruit maintains high respiration and metabolic activity. Improper control of temperature, humidity, or transportation conditions can lead to water loss, softening, and degradation of nutritional compounds, resulting in reductions in anthocyanins, phenolics, and vitamin C content and shortening shelf life. Rapid precooling, continuous cold-chain transportation, and suitable storage conditions have therefore become essential components of commercial blueberry production. These practices help preserve the quality formed during orchard production and maintain fruit market value during distribution.

Postharvest elicitation treatments have recently attracted increasing attention as a strategy for blueberry preservation. Varaldo et al. (2024) reported that an appropriate low-dose UV-B treatment promoted the accumulation of anthocyanins and phenolic compounds in postharvest ‘Cargo’ blueberry (*Vaccinium corymbosum* L.), reduced fruit weight loss, delayed quality deterioration, and improved nutritional preservation during storage. In addition, edible coatings, modified atmosphere packaging, and other green preservation technologies are increasingly applied in blueberry postharvest management (Lopes et al., 2026) (Figure 2). By reducing respiration activity and water loss, these approaches help minimize nutrient degradation and extend fruit shelf life.

Figure 2 Benefits of edible coatings for blueberry fruit preservation (Adopted from Lopes et al., 2026)

5 Field Evidence from Major Blueberry Production Regions in China

5.1 Caota town, Zhejiang province

Caota Town in Zhuji City, Zhejiang Province, is a representative blueberry production area in eastern China and one of the earlier regions in the Yangtze River Delta to develop large-scale blueberry cultivation. In a multi-location comparison of blueberry production areas in China, Zeng et al. (2020) selected Caota Town as a representative low- to medium-altitude site and evaluated fruit quality of the same rabbiteye blueberry cultivar ‘Brightwell’ (Vaccinium virgatum Aiton). Located at approximately 199 m altitude, blueberries from Caota Town showed a soluble solids content (TSS) of 10.3%, titratable acidity (TA) of 0.52%, TSS/TA ratio of 20.0, total flavonoid content of 0.94 mg rutin·g^{-1} FW, total phenolic content of 1.44 mg gallic acid g^{-1} FW, proanthocyanidin content of 2.40 mg catechin·g^{-1} FW, and anthocyanin content of only 0.26 mg cyanidin-3-glucoside g^{-1} FW. Among all surveyed locations, blueberries from Caota Town showed relatively lower levels of anthocyanins and other bioactive compounds compared with high-altitude production areas in southwestern China.

Under the same cultivar background, blueberries from Caota Town also showed lower sweetness, total flavonoid content, and total phenolic content than those produced in high-altitude regions such as Yunnan and Guizhou. This suggests that low-altitude environments in eastern China may not naturally favor strong anthocyanin accumulation. However, this does not mean that Zhejiang is unsuitable for high-quality blueberry production. Instead, it indicates that ecological conditions strongly influence fruit quality, and more precise orchard management practices are needed to compensate for environmental limitations and improve fruit nutritional value.

5.2 Guizhou province

Guizhou Province is one of the most promising blueberry production regions in China. Its unique karst landscape, high altitude, large day–night temperature differences, and sufficient solar radiation provide favorable conditions for anthocyanin accumulation and the formation of other bioactive compounds. Zeng et al. (2020) compared blueberry quality from Xuanwei (750 m) and Xianchang (912 m) in Guizhou and found that fruit quality at both sites was significantly higher than that in Caota Town, Zhejiang Province. In Xuanwei, anthocyanin content reached 0.83 mg cyanidin-3-glucoside g^{-1} FW, while total flavonoids, total phenolics, and sweetness scores were also higher than those observed in low-altitude regions, indicating that Guizhou’s ecological conditions are more suitable for producing blueberries with high nutritional quality.

Recent studies further confirmed the advantages of Guizhou's blueberry production environment. Blueberries grown in the karst regions of Guizhou showed significantly higher anthocyanin content than fruits from other production areas, and Deng et al. (2026) identified the involvement of the VdMYB56-VdMYB69 regulatory module in anthocyanin accumulation. The combination of favorable ecological conditions and suitable genetic backgrounds promotes the expression of anthocyanin biosynthesis-related genes, contributing to the high functional nutritional value of Guizhou blueberries (Deng et al., 2026).

In addition to field production advantages, Guizhou has also developed effective postharvest preservation technologies. Wu et al. (2022) investigated the effects of ozone fumigation on postharvest quality of blueberries from Majiang County, Guizhou Province. During storage at 4 °C, ozone treatment significantly reduced fruit decay, delayed the decline of total phenolics and anthocyanins, and maintained higher antioxidant enzyme activity. After 80 days of storage, ozone-treated fruit retained higher soluble solids, total phenolic content, and anthocyanin levels than untreated fruit, demonstrating that appropriate postharvest technologies can effectively preserve blueberry nutritional quality.

5.3 Liaoning province

Liaoning Province is an important region for blueberry breeding and protected cultivation in northern China, with extensive experience in cultivar evaluation and high-quality fruit production. Akbari et al. (2026) systematically evaluated 21 highbush blueberry cultivars (*Vaccinium corymbosum* L.) under uniform greenhouse conditions at the Liaoning Institute of Pomology. Under the same environmental conditions, significant differences were observed among cultivars in total phenolics, anthocyanins, sugar content, and antioxidant capacity. Among the evaluated cultivars, 'Eureka', 'Twilight', and 'Rossini' showed particularly high anthocyanin accumulation, while some other cultivars exhibited higher total phenolic content or more favorable sugar-acid balance.

Because the experiment was conducted under controlled greenhouse conditions, environmental variation was largely minimized, making the results valuable for cultivar selection and production planning in northern protected cultivation systems. For commercial blueberry production in Liaoning, cultivars can be selected according to different market objectives, such as high anthocyanin content for functional food applications, high phenolic content for antioxidant products, or improved flavor characteristics for fresh markets. This provides a basis for differentiated production strategies in northern China.

5.4 South China production area

The South China blueberry production area mainly includes Guangdong, Guangxi, and Fujian provinces. These regions are characterized by high temperatures, abundant rainfall, and high humidity, and blueberry production commonly relies on substrate culture, container cultivation, and protected cultivation systems. Southern highbush blueberry and rabbiteye blueberry are the major cultivated types in these regions. Therefore, blueberry production in South China is mainly based on cultivation systems adapted to subtropical climatic conditions rather than a single regional model.

Chai et al. (2021) systematically analyzed 74 blueberry cultivars collected from southern China and identified 14 anthocyanin compounds. Malvidin, delphinidin, and petunidin were the major contributors to total anthocyanin content, while malvidin-3-O-galactoside was the most abundant individual anthocyanin compound. The study also showed that rabbiteye blueberry (*Vaccinium virgatum* Aiton) generally had higher total anthocyanin content than other blueberry groups, indicating strong genetic differences in anthocyanin accumulation capacity among blueberry types.

Nutrient management is also a key factor for southern blueberry production. Anwar et al. (2024) conducted a substrate culture experiment at South China Agricultural University to evaluate the effects of different ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) ratios on blueberry growth and fruiting (Figure 3). The results showed that nitrogen form significantly affected plant growth, nutrient uptake, physiological characteristics, flowering, and fruit set. A 50:50 NH_4^+-N:NO_3^--N ratio produced the best overall vegetative growth and fruit-setting performance, whereas a 25:75 ratio was more favorable for soluble sugar accumulation and fruit flavor improvement. These findings indicate that precise fertigation management is essential for improving blueberry quality under subtropical production conditions.

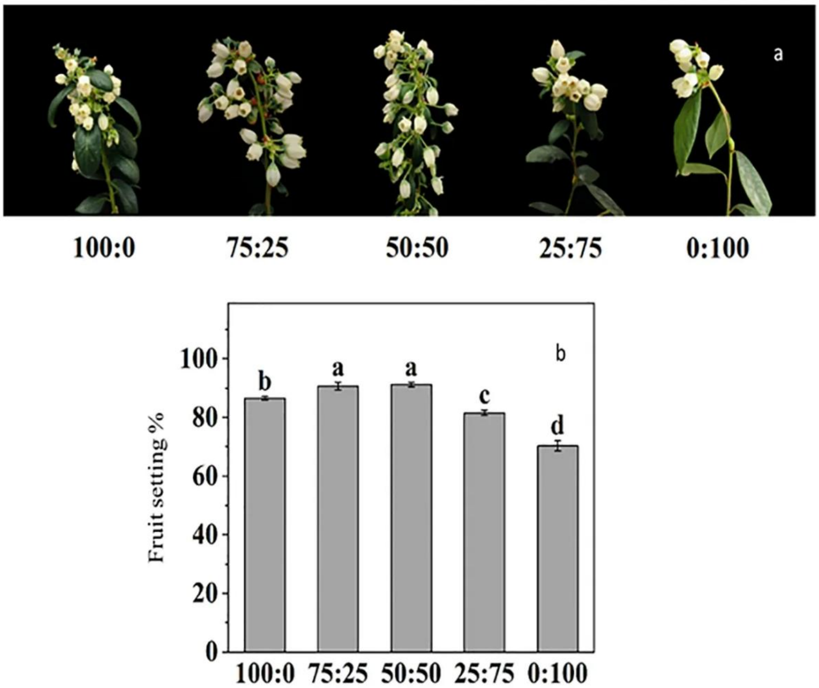

Figure 3 The effect of NH_4^+-N: NO_3^--N levels on flower induction (A) and fruit setting percentage (B) in blueberry. Results are presented as the mean (n=4) and the bars above columns represent the standard deviation (SD). Different letters above the bars indicate significant differences ($p< 0.05$) (Adopted from Anwar et al., 2024)

5.5 Southwest China production area

Yunnan Province has become one of the fastest-growing and highest-quality blueberry production areas in southwestern China in recent years. The region combines low latitude, high altitude, large day-night temperature differences, and strong solar radiation, creating favorable conditions for sugar accumulation and anthocyanin formation. As a result, Yunnan has become an important production base for premium blueberries in China.

Zeng et al. (2020) compared blueberry quality from several Yunnan production areas, including Shigu, Yinqiao, Yousuo, Haikou, and Longpeng. Blueberries from Yunnan consistently showed higher sweetness and greater accumulation of bioactive compounds than those from low-altitude eastern regions. Among these sites, Longpeng showed the highest anthocyanin content, reaching 1.34 mg cyanidin-3-glucoside g^{-1} FW, while several Yunnan production areas also ranked highly in total flavonoid and total phenolic contents. These results demonstrate the advantages of southwestern high-altitude environments for improving blueberry nutritional quality.

In recent years, the blueberry industry in Yunnan has rapidly developed toward large-scale facility production and standardized management. Major production areas such as Honghe, Lijiang, and Shilin have widely adopted substrate cultivation, smart fertigation systems, and standardized production technologies. These production systems have contributed to fruit characteristics including high sugar content, good firmness, and rich anthocyanin accumulation, while gradually improving the competitiveness of Yunnan blueberries in domestic and export markets.

6 Future Perspectives

6.1 Development of high-quality blueberry production

The future development of the blueberry industry will gradually shift from yield-oriented production toward quality-oriented production, with fruit quality becoming a key indicator of industry competitiveness. As consumers increasingly focus on flavor, nutrition, and health benefits, blueberry production should not only aim to increase yield but also consistently produce high-quality fruit with elevated levels of anthocyanins, phenolics, flavonoids, and vitamin C. Future breeding programs, cultivation practices, and postharvest technologies will place greater emphasis on improving quality throughout the production chain, allowing blueberries to better meet the demands of fresh consumption, functional food processing, and premium markets.

High-quality production will increasingly rely on a whole-chain quality management strategy, covering cultivar selection, orchard establishment, water and nutrient management, harvest decisions, and postharvest preservation. Future blueberry evaluation standards will gradually move beyond yield per unit area and incorporate multiple indicators, including fruit appearance, flavor, bioactive compound content, storage performance, and commercial value. This transition will promote the transformation of the blueberry industry from “high-yield production” toward “high-quality and high-efficiency production”.

6.2 Sustainable orchard management

Future blueberry orchard management will place greater emphasis on efficient resource utilization and ecological protection, aiming to improve production efficiency while maintaining stable fruit quality. Considering the shallow-rooted and acid-loving characteristics of blueberry, continuous improvement of soil or substrate conditions will be essential. Practices such as appropriate mulching, organic matter supplementation, precise irrigation, and balanced fertilization can improve nutrient use efficiency, maintain root activity and plant health, and reduce unnecessary resource inputs while ensuring stable fruit quality.

With the development of sustainable agriculture, the concept of sustainable blueberry production will expand beyond simply reducing fertilizer and pesticide use. It will also include carbon emission reduction, improved water-use efficiency, and reduced postharvest losses. Future production systems should further integrate environmentally friendly inputs, biostimulants, smart irrigation, and digital management technologies to establish a green production system covering cultivation, harvesting, storage, transportation, and marketing. Such approaches will improve resource efficiency and enhance the overall economic value of the blueberry industry.

6.3 Digital and intelligent quality management

Traditional blueberry production largely relies on growers’ experience to determine fruit maturity, irrigation timing, and fertilization schedules, which is difficult to meet the requirements for stable quality in large-scale commercial production. In the future, non-destructive technologies such as near-infrared spectroscopy (NIR) and hyperspectral imaging will play increasingly important roles in fruit quality monitoring. These technologies can rapidly obtain information related to soluble solids content, maturity, internal fruit quality, and some bioactive compounds, providing support for harvest prediction and quality grading. Meanwhile, machine vision and artificial intelligence algorithms can identify changes in fruit color, maturity stage, and disease symptoms. Combined with drone-based remote sensing, these technologies can monitor canopy structure, plant nutritional status, and water stress, helping growers optimize irrigation, fertilization, and harvesting strategies to improve management efficiency and fruit quality consistency.

Digital twin orchards may become an important direction for future intelligent blueberry production. By integrating weather data, soil sensors, smart irrigation systems, plant growth information, and fruit quality data, dynamic orchard models can be developed to predict and optimize blueberry growth processes, enabling a transition from experience-based management to data-driven decision-making. Future efforts should strengthen the integration of horticulture, artificial intelligence, and agricultural engineering, transforming digital tools into practical solutions that can be adopted by growers and promoting blueberry production toward greater precision, efficiency, and quality (Figure 4).

6.4 Strengthening field-based production research

Although significant progress has been made in understanding the mechanisms underlying blueberry quality formation, many current studies are still based on laboratory experiments, short-term treatments, or single production regions. The long-term stability and commercial applicability of these findings require further validation under real orchard conditions. Future research should focus on multi-year, multi-location, and multi-cultivar field trials, establish standardized fruit quality evaluation systems, and systematically investigate the interactions among genetic background, environmental conditions, and cultivation practices in regulating bioactive compound accumulation.

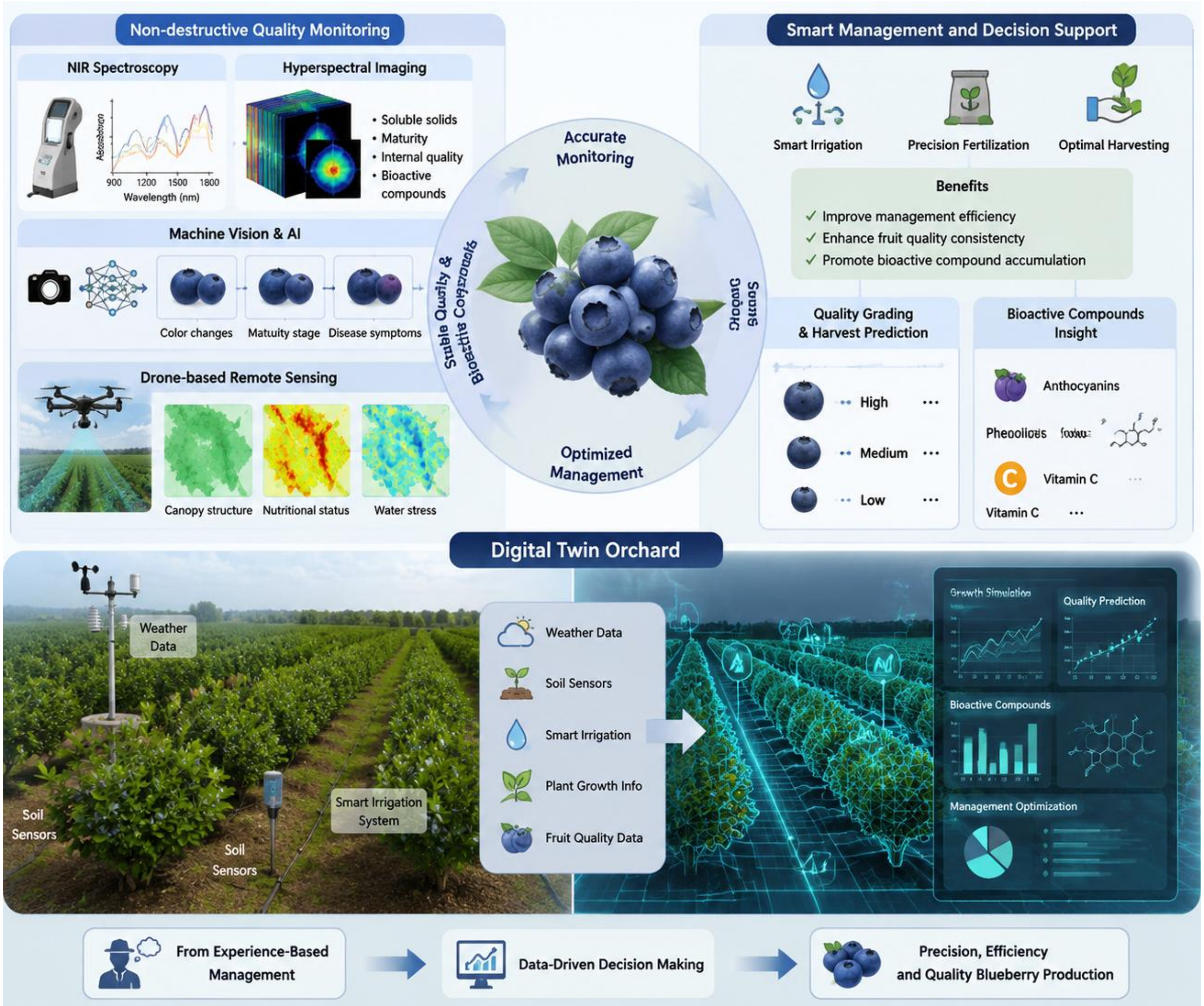

Figure 4 Digital and intelligent dynamic management of blueberry orchards

China has a wide range of blueberry production areas with substantial differences in climate, soil properties, and cultivation systems. Future studies should establish long-term field monitoring platforms in major production regions such as Zhejiang, Shandong, Liaoning, Guizhou, and Yunnan, and conduct continuous evaluations using standardized cultivars, management practices, and quality indicators. Key parameters should include fruit quality, bioactive compounds, postharvest storage performance, and market adaptability. Such research will provide a scientific basis for developing region-specific blueberry production models. In addition, closer integration among commercial production, breeding programs, nutritional regulation, and postharvest technologies will accelerate the transfer of research findings into practical applications and support the high-quality development of the blueberry industry in China.

Author Contributions

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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