

Fruit Quality Traits and Cultivation Practices in Chinese Bayberry (*Myrica rubra*): Current Status and Research Progress

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✉ Corresponding email: 1029281612@qq.comPlant Gene and Trait, 2026, Vol.17, No.3 doi: [10.5376/pgt.2026.17.0015](https://doi.org/10.5376/pgt.2026.17.0015)

Received: 16 May, 2026

Accepted: 20 Jun., 2026

Published: 30 Jun., 2026

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Preferred citation for this article:

Jin Y.Y., 2026, Fruit quality traits and cultivation practices in Chinese bayberry (*Myrica rubra*): current status and research progress, Plant Gene and Trait, 17(3): 216-234 (doi: [10.5376/pgt.2026.17.0015](https://doi.org/10.5376/pgt.2026.17.0015))

Abstract This study explored the current research status and progress of fruit quality traits and cultivation measures in Chinese bayberry (*Myrica rubra* Sieb. et Zucc), systematically analyzing advances in external quality, internal quality, and quality evaluation systems, and reviewing the major factors affecting fruit quality formation and their regulation technologies based on recent domestic and international studies. As an important subtropical fruit tree species in China, Chinese bayberry possesses high nutritional value, economic value, and potential for functional product development. Its fruits are rich in sugars, organic acids, vitamin C, anthocyanins, polyphenols, and volatile aroma compounds. Studies have shown that genetic background, ecological environment, and fruit growth and development are the major factors influencing fruit quality formation, among which light, temperature, water conditions, and maturity stage significantly affect sugar-acid metabolism, anthocyanin accumulation, and flavor formation. Appropriate water and fertilizer management, tree and flower-fruit regulation, protected cultivation, and green ecological cultivation techniques can effectively improve fruit size, coloration, sugar-acid ratio, and functional nutrient contents, thereby enhancing fruit commercial quality and stability. In recent years, the application of electronic nose, electronic tongue, Vis/NIR spectroscopy, hyperspectral imaging, and intelligent detection technologies based on machine learning and deep learning in Chinese bayberry quality evaluation has continuously expanded, providing new approaches for rapid, non-destructive, and accurate quality assessment. Although significant progress has been achieved in Chinese bayberry quality research, there are still limitations in understanding the mechanisms of quality formation, establishing standardized cultivation regulation systems, and developing unified quality evaluation standards. Overall, strengthening research on high-quality cultivar breeding, precision and intelligent cultivation, and green high-quality production systems will contribute to the high-quality and sustainable development of the Chinese bayberry industry.

Keywords Chinese bayberry; Fruit quality; Cultivation regulation; Quality evaluation; Intelligent detection

1 Introduction

Chinese bayberry (*Myrica rubra* Sieb. et Zucc) is one of the most important subtropical evergreen fruit trees native to China, originating from southern China and parts of East Asia, with a cultivation and domestication history of more than 2 000 years (Gao et al., 2024). At present, Chinese bayberry is mainly distributed in southern regions of China, including Zhejiang, Jiangsu, Fujian, Guangdong, Guangxi, and Yunnan provinces, among which Zhejiang and Jiangsu are the major commercial cultivation areas (Ren et al., 2021). As the country with the largest cultivation area and production of Chinese bayberry in the world, China's bayberry industry plays an important role in promoting mountainous economic development, increasing farmers' income, and advancing rural revitalization (Mo et al., 2024). In recent years, with the improvement of living standards and increasing awareness of healthy diets, market demand for high-quality specialty fruits and functional foods has continued to grow, further promoting the rapid development of the Chinese bayberry industry. However, Chinese bayberry fruits ripen rapidly, are highly perishable, and are extremely sensitive to temperature and storage conditions. Their shelf life at room temperature is usually only a few days, which greatly limits long-distance transportation and industrial utilization.

Chinese bayberry fruits are characterized by their bright color, unique flavor, and high nutritional and health-promoting value. Studies have shown that the fruits are rich in sugars, organic acids, vitamin C, phenolic compounds, flavonoids, and anthocyanins, among which cyanidin-3-O-glucoside not only contributes to the

attractive reddish-purple appearance but also exhibits strong antioxidant, anti-inflammatory, and anti-diabetic activities (Li et al., 2023). In addition, by-products such as leaves, kernels, and pomace also contain abundant bioactive compounds that can be used for the development of functional foods and natural antioxidant products (Mo et al., 2024). Fruit quality of Chinese bayberry includes both external quality traits, such as fruit size, color, and firmness, and internal quality traits, such as sugar-acid ratio, aroma volatiles, and functional nutritional components. Among them, sucrose is the major soluble sugar in ripe fruits, while citric acid is the predominant organic acid, and together they determine the characteristic sweet-sour flavor of Chinese bayberry.

At present, research on the formation and regulation mechanisms of Chinese bayberry fruit quality has been continuously advancing worldwide. Existing studies have demonstrated that genetic background, ecological environmental conditions, and cultivation management practices significantly affect fruit quality. Different cultivars exhibit obvious differences in fruit size, coloration, sugar-acid content, and accumulation of bioactive compounds, while sugars, organic acids, phenolics, and volatile substances change rapidly during fruit ripening. Ecological factors such as light, temperature, water availability, and soil conditions influence nutrient accumulation and flavor formation, whereas proper fertilization, water management, flower and fruit thinning, protected cultivation, and LED supplemental lighting can effectively improve both external and internal fruit quality (Tang et al., 2025). In addition, technologies such as preharvest melatonin treatment, ozonated water treatment, and low-temperature storage have shown favorable effects in delaying fruit senescence and extending shelf life (Chen et al., 2024).

This study aims to explore the current research status and progress of fruit quality traits and cultivation regulation measures in Chinese bayberry. With the development of molecular biology and omics technologies, important progress has been achieved in understanding the genetic and molecular mechanisms underlying fruit quality formation. Transcription factor families such as MYB and WRKY play important roles in regulating anthocyanin biosynthesis and flavonoid metabolism. Meanwhile, the construction of high-density genetic maps and multi-omics databases has provided new theoretical foundations and technical support for the analysis of fruit quality-related traits and molecular-assisted breeding. Although related studies have increased rapidly in recent years, comprehensive research integrating industrial development status, fruit quality formation mechanisms, cultivation management practices, and postharvest regulation technologies remains relatively limited. Therefore, this study further discusses external quality, internal quality, and quality evaluation systems of Chinese bayberry, and systematically analyzes the effects of cultivar, environment, and cultivation management on fruit quality formation, with the aim of providing theoretical references for high-quality cultivation, fruit quality improvement, and sustainable development of the Chinese bayberry industry.

2 Research on Fruit Quality Traits of Chinese Bayberry

2.1 External quality traits

The external quality of Chinese bayberry fruit is an important basis for consumers to evaluate commercial value and is also a key target affecting market competitiveness, fruit grading, and breeding selection. It mainly includes fruit size, fruit shape, peel color, fruit surface integrity, and ripening uniformity (Zhang et al., 2022; Xue et al., 2024). Among these traits, single-fruit weight, longitudinal and transverse diameters, and fruit shape index directly influence commercial grade and market price, and large-fruited bayberries are generally more favored by consumers. Significant differences in fruit size and shape exist among different cultivars and germplasm resources. For example, large-fruited cultivars such as ‘Dongkui’ possess high commercial value, whereas some local cultivars mainly produce medium- or small-sized fruits. Large-scale phenotypic analyses have shown that fruit size, fruit shape, and related appearance traits in Chinese bayberry generally exhibit continuous distributions with large coefficients of variation, suggesting that these traits may be quantitatively inherited and jointly influenced by genetic background, tree nutritional status, crop load, and cultivation environment (Zhang et al., 2024).

Peel color is one of the most recognizable external quality traits of Chinese bayberry and is closely associated with fruit maturity and anthocyanin accumulation. Fruit color can gradually transition from white and pink to red, dark red, and nearly black, and this color gradient is mainly determined by differences in anthocyanin content and

composition (Xue et al., 2024). Dark-colored fruits usually contain higher anthocyanin concentrations and exhibit stronger antioxidant capacity, whereas white or yellow types contain low or undetectable levels of cyanidin-3-O-glucoside, resulting in lighter coloration. At the molecular level, MYB transcription factors and their gene clusters are considered important genetic regulators of fruit color variation in Chinese bayberry. MrMYB1 and related MYB/QTL regions are significantly associated with anthocyanin biosynthesis and fruit pigmentation (Cao et al., 2021; Zhang et al., 2024).

In addition to genetic factors, light, temperature, and water-fertilizer management also affect fruit coloration. Appropriate light conditions promote anthocyanin biosynthesis and deepen peel color, whereas prolonged rainy weather, dense canopies, or insufficient ventilation and light penetration may result in uneven coloration, dull appearance, and reduced commercial quality. Fruit surface integrity is also an important component of appearance evaluation. Fruit cracking, mechanical injury, and pest or disease damage not only reduce commercial value but also accelerate postharvest decay and impair storage and transportation performance. Therefore, research on Chinese bayberry external quality is gradually shifting from simple trait description to comprehensive quantitative evaluation systems based on color parameters, image recognition, fruit shape indices, and fruit uniformity (Zhang et al., 2024).

2.2 Internal quality traits

The internal quality of Chinese bayberry fruit mainly includes sugars, organic acids, vitamin C, phenolic compounds, flavonoids, anthocyanins, volatile aroma compounds, flesh texture, and antioxidant capacity, which are the core factors determining fruit flavor, nutritional value, and functional properties (Zhang et al., 2022). Among these, soluble solids content, titratable acidity, and sugar-acid ratio are important indicators for evaluating fresh-eating quality. Most studies have shown that sucrose is the predominant soluble sugar in ripe Chinese bayberry fruits, followed by fructose and glucose, while citric acid is the major organic acid. During fruit development and ripening, total soluble solids, sugars, and anthocyanin contents generally increase gradually, whereas titratable acidity decreases or stabilizes, resulting in the characteristic sweet-sour flavor balance of mature Chinese bayberry fruits.

Chinese bayberry is rich in various functional bioactive compounds, particularly anthocyanins, polyphenols, and flavonoids. Cyanidin-3-O-glucoside is the major anthocyanin component in Chinese bayberry and usually accounts for a high proportion of total anthocyanins, serving as an important material basis for the dark coloration and antioxidant capacity of the fruit. Significant differences in total phenolics, total flavonoids, total anthocyanins, and antioxidant capacity have been observed among cultivars, with black or dark-red fruits generally showing higher levels than pink or white types. Antioxidant evaluation methods such as DPPH, FRAP, ABTS, PSC, and CAA have demonstrated that the antioxidant capacity of Chinese bayberry is usually significantly positively correlated with total phenolic and flavonoid contents (Xia et al., 2021).

Flesh texture and aroma composition are also important aspects of internal quality evaluation. High-quality Chinese bayberry fruits are typically characterized by tender and juicy flesh, low fiber content, balanced sweetness and acidity, and rich aroma. The volatile aroma compounds of Chinese bayberry mainly include terpenoids such as α -pinene, β -caryophyllene, and D-limonene, as well as aldehydes and esters. Significant differences in volatile composition exist among cultivars and ripening stages, resulting in sensory characteristics such as pine-like, woody, grassy, and overripe aromas. During postharvest storage, temperature and ethylene treatments significantly affect sugar-acid balance, volatile release, firmness retention, and off-flavor formation. Moderate low-temperature storage helps delay quality deterioration, whereas higher temperatures may accelerate flavor degradation and fruit decay (Gao et al., 2024; Saeed et al., 2024).

2.3 Quality evaluation index system

With the continuous development of the Chinese bayberry industry, establishing a scientific, systematic, and quantifiable quality evaluation system has become increasingly important for improving fruit standardization, commercialization, and industrial competitiveness. At present, Chinese bayberry quality evaluation mainly includes sensory evaluation, physicochemical measurements, functional quality analysis, postharvest stability

evaluation, and molecular marker-assisted evaluation (Zhang et al., 2022; Zhang et al., 2024). Sensory evaluation mainly relies on comprehensive assessment of fruit size, color, aroma, sweetness and acidity, taste, and texture, which can directly reflect consumer experience. However, because sensory evaluation is easily influenced by subjective factors, it is usually combined with objective physicochemical indicators for comprehensive analysis. Physicochemical measurements are currently the most widely used methods and mainly include soluble solids, titratable acidity, sugar-acid ratio, vitamin C, total phenolics, total flavonoids, anthocyanins, fruit firmness, and color parameters. Among these, soluble solids and sugar-acid ratio are commonly used to evaluate fresh-eating quality, whereas anthocyanins, polyphenols, and antioxidant capacity are mainly used to evaluate functional quality.

In recent years, technologies such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), electronic nose, electronic tongue, near-infrared detection, and image recognition have gradually been applied to Chinese bayberry quality evaluation, improving the accuracy and efficiency of quality detection (Gao et al., 2024). In statistical analysis, multivariate methods such as principal component analysis, cluster analysis, and correlation analysis have been widely used for dimensionality reduction and cultivar classification of quality data. By integrating indices such as sugar-acid ratio, anthocyanin content, total phenolic level, color parameters, and aroma compounds, different Chinese bayberry cultivars can be classified into sweet type, balanced sweet-sour type, dark high-anthocyanin type, and highly aromatic type (Zhang et al., 2022). In addition, in postharvest storage and processing studies, indicators such as decay rate, fruit firmness, titratable acidity, phenolic compounds, antioxidant enzyme activity, and volatile markers have gradually been incorporated into quality evaluation systems to assess shelf-life stability and flavor changes (Saeed et al., 2024).

At the molecular level, studies based on telomere-to-telomere (T2T) reference genomes and genome-wide association analysis have linked multiple standardized quality traits with specific SNP loci and candidate genes, providing an important foundation for molecular marker-assisted selection of superior external and internal quality traits in Chinese bayberry (Zhang et al., 2024). Meanwhile, analyses of the MYB transcription factor family and its regulatory networks have provided candidate gene resources for improving fruit color, flavonoid biosynthesis, and functional quality (Cao et al., 2021; Xue et al., 2024). Although a unified industrial quality evaluation standard has not yet been established, integrating sensory evaluation, physicochemical detection, functional activity, postharvest stability, and molecular markers has become an important trend in constructing comprehensive quality evaluation systems and promoting targeted quality improvement in Chinese bayberry.

3 Major Factors Affecting Fruit Quality of Chinese Bayberry

3.1 Variety factors

Cultivar is the fundamental factor determining the formation of fruit quality in Chinese bayberry. Significant differences exist among cultivars in fruit size, coloration, sugar and acid contents, aroma characteristics, nutritional composition, and accumulation of functional compounds. A systematic evaluation of 173 Chinese bayberry germplasm accessions demonstrated extensive phenotypic variation in 29 quality traits, including fruit color, size, sugars, organic acids, and amino acids. Most traits exhibited continuous distributions, indicating that Chinese bayberry quality traits possess a complex quantitative genetic basis (Zhang et al., 2024). Common commercial cultivars currently include ‘Dongkui’, ‘Biqizhong’, ‘Dingao’, and ‘Wandao’. Among them, ‘Dongkui’ is favored by the market because of its large fruit size, bright color, and excellent commercial quality, whereas ‘Biqizhong’ is characterized by rich flavor, balanced sugar-acid ratio, and high anthocyanin content in dark-colored fruits (Zhang et al., 2024).

Differences in genetic background among cultivars directly affect fruit color, ripening time, anthocyanin accumulation capacity, and antioxidant activity. Chinese bayberry germplasm resources include white, pink, red, and black-purple types, and these color types differ significantly in anthocyanin content, antioxidant capacity, and processing suitability (Xue et al., 2024). Dark-colored cultivars generally possess higher cyanidin-3-O-glucoside content and stronger antioxidant activity, making them more suitable for fresh consumption, high-anthocyanin products, and functional food development. In addition, different cultivars show distinct postharvest ethylene

release patterns, sugar-acid dynamic changes, and shelf-life performance, indicating that cultivar selection not only affects on-tree fruit quality formation but also determines postharvest quality retention capacity (Saeed et al., 2024).

At the molecular level, differences in Chinese bayberry fruit color are mainly controlled by anthocyanin biosynthesis-related genes and their allelic variations. Studies have shown that the MYB tandem gene cluster, especially MrMYB1.1-MrMYB1.3 and MrMYB2, is closely associated with the fruit color gradient ranging from white 'Shuijing' to dark-red 'Biqizhong'. Functional MrMYB1.1 and MrMYB1.3 alleles can activate anthocyanin biosynthesis-related genes, whereas a single-base deletion in MrMYB1.1 may result in gene inactivation and the formation of a white-fruit phenotype (Xue et al., 2024). Furthermore, telomere-to-telomere (T2T) reference genome and genome-wide association study (GWAS) analyses identified a significant SNP cluster related to fruit color on chromosome 6, containing MYB genes and candidate MLP-like protein genes, thereby providing important molecular marker resources for peel and flesh color improvement (Zhang et al., 2024).

3.2 Environmental factors

Ecological environmental conditions play important roles in the formation of Chinese bayberry fruit quality. Factors such as light, temperature, rainfall, humidity, and soil conditions all influence fruit development, coloration, sugar-acid metabolism, and the accumulation of functional compounds. Chinese bayberry is a typical subtropical fruit tree that grows best under warm, humid, well-drained, and slightly acidic environmental conditions. Appropriate temperatures are beneficial for fruit enlargement, sugar accumulation, and anthocyanin formation, whereas high- or low-temperature stress may lead to poor fruit development, uneven coloration, flesh softening, and flavor deterioration. Diurnal temperature differences during the fruit ripening stage usually favor the accumulation of sugars and aroma compounds and are therefore important microclimatic factors affecting fresh-eating quality.

Light is a key environmental factor affecting both external and internal quality of Chinese bayberry fruit. Studies using bagging materials with different light transmittance rates demonstrated that shading during early fruit development significantly reduced fruit coloration and multiple quality indices. Under non-light-transmitting bag treatments, sucrose, glucose, fructose, organic acids, total flavonoids, vitamin C, and total anthocyanin contents all decreased significantly, whereas titratable acidity increased. Combined transcriptomic and metabolomic analyses further showed that weak light conditions suppressed the expression of genes related to flavonoid and anthocyanin biosynthesis and reduced the accumulation of key anthocyanin metabolites. In contrast, bagging materials with better light transmittance promoted fruit coloration and improved overall fruit quality (Yang et al., 2025). In addition, MrMYB1 expression and anthocyanin biosynthesis are highly sensitive to light, and shading through bagging can inhibit fruit coloration and the expression of anthocyanin pathway genes.

Temperature and postharvest storage conditions also significantly affect the stability of Chinese bayberry fruit quality. Studies on different storage temperatures showed that low-temperature conditions of 0 °C-4 °C can slow down fruit firmness decline, sugar-acid degradation, and volatile compound changes, thereby better maintaining fruit flavor, texture, and shelf quality (Figure 1) (Saeed et al., 2024). Under higher temperatures, ethylene release and respiratory metabolism increase, accelerating fruit softening, color changes, and flavor deterioration, while off-flavor volatile compounds such as ethanol, benzaldehyde, and octanoic acid gradually accumulate (Gao et al., 2024). Room-temperature storage also causes rapid decreases in acidity and fluctuations in sugar-acid balance, significantly shortening the marketable shelf life of fresh fruits.

3.3 Growth and development factors

The growth and developmental status of Chinese bayberry trees directly affects fruit quality formation, among which tree age, tree vigor, crop load, and nutrient distribution are important influencing factors. Generally, Chinese bayberry trees in the full-bearing stage exhibit relatively stable fruiting ability, with better fruit size, sugar accumulation, and ripening uniformity, whereas young or aging trees are more likely to produce uneven fruit size and unstable quality. Excessive tree vigor may result in an imbalance between vegetative growth and reproductive growth, thereby affecting fruit coloration and sugar accumulation, while weak tree vigor reduces leaf

photosynthetic capacity and is unfavorable for fruit enlargement and metabolite accumulation. In addition, appropriate crop load helps maintain tree nutritional balance and improves fruit size, sugar-acid balance, and ripening consistency, whereas excessive fruit load intensifies nutrient competition among fruits, leading to smaller fruits, lower soluble solids, and uneven ripening. Therefore, practices such as flower and fruit thinning, proper pruning, and canopy regulation are commonly applied in production to adjust tree load and improve fruit commercial quality and quality stability.



Figure 1 Color development in five cultivars and cross-sections of Chinese bayberry fruits stored at different temperatures after harvest (Adopted from Saeed et al., 2024)

From the perspective of fruit development, the ripening stage is the key factor determining dynamic changes in Chinese bayberry fruit quality. During fruit ripening, chlorophyll and titratable acidity gradually decrease, whereas sugars, anthocyanins, and volatile compounds continuously accumulate, ultimately resulting in mature fruits characterized by softness, juiciness, balanced sweet-sour taste, and rich aroma. Comparisons among mature-green, pink, red-ripe, and fully ripe fruits have shown that total soluble solids, sugar composition, and total anthocyanin content usually reach relatively high levels at the fully ripe stage. In contrast, some antioxidant indices such as total phenolics and DPPH, FRAP, and ABTS activities may decline during ripening progression, and immature fruits sometimes exhibit stronger antioxidant capacity (Wu et al., 2018). Volatile compound composition also changes markedly during ripening. Immature fruits are usually dominated by citrus-like terpene aromas, whereas fully ripe fruits exhibit grassy, herbal, and cucumber-like aroma characteristics.

At the molecular and metabolic levels, Chinese bayberry fruit ripening is accompanied by extensive transcriptional reprogramming. RNA-Seq and EST studies have shown that genes related to anthocyanin biosynthesis are globally upregulated during ripening, while pathways associated with sugar-acid metabolism, energy metabolism, and cell wall modification undergo significant changes. Factors such as sucrose phosphate synthase and vacuolar ATPase subunits may participate in sugar accumulation and fruit quality formation. In addition, fruit maturity also affects postharvest quality trajectories. Immature and mature fruits usually exhibit obvious climacteric respiration and ethylene peaks, whereas fully ripe fruits may not display typical climacteric behavior. Under room-temperature conditions, soluble solids, titratable acidity, and organic acids decrease rapidly in fruits at all maturity stages (Wu et al., 2018). Therefore, fruit growth and development not only determine on-tree quality formation but also influence postharvest softening, aroma changes, and shelf life. Proper determination of harvest maturity is thus a crucial technical factor balancing fresh-eating quality, transportation performance, and processing suitability.

4 Regulatory Effects of Cultivation Measures on Fruit Quality

4.1 Water and fertilizer management measures

Water and fertilizer management is an important cultivation practice affecting the formation of Chinese bayberry fruit quality and is directly related to fruit enlargement, sugar accumulation, sugar-acid balance, and yield stability. Rational fertilization provides the nutritional basis for tree growth and fruit development, among which nitrogen, phosphorus, and potassium have particularly significant effects on fruit quality. Appropriate nitrogen application promotes branch and leaf growth as well as photosynthesis; however, long-term excessive chemical fertilizer input, especially excessive nitrogen fertilization, can easily result in excessive tree vigor, decreased fruit sugar content, delayed ripening, intensified soil acidification, and organic carbon loss, which are unfavorable for the sustainable production of Chinese bayberry orchards (Hong et al., 2023). In contrast, moderately reducing nitrogen and phosphorus application can improve soil quality without significantly decreasing yield and fruit quality, indicating that balanced fertilization is more beneficial for stable production of high-quality Chinese bayberry than simply increasing fertilizer input (Chen et al., 2025).

Potassium fertilizer generally promotes sugar accumulation, peel coloration, and flavor formation, whereas phosphorus fertilizer is closely associated with root development and flower bud differentiation. Specialized compound fertilizers developed for Chinese bayberry can improve soil organic matter and nutrient content, increase leaf biomass and chlorophyll content, and enhance fruit total sugar, reducing sugar, and soluble solids contents. Among different application rates, approximately 8 kg per tree applied in two split applications showed favorable effects (Wu et al., 2021). Foliar nutrient regulation also has considerable application potential. Amino acid foliar fertilizer treatment on 'Dingao' Chinese bayberry significantly increased soluble solids, total sugars, sugar-acid ratio, and soluble solids/titratable acidity ratio, while reducing total acidity and improving postharvest water loss and decay rates, indicating its ability to simultaneously improve eating quality and storage tolerance.

Micronutrients and water management also influence Chinese bayberry fruit quality. Boron deficiency can cause small leaves, bud dieback, and reduced flowering and fruiting, whereas soil boron application or foliar boron spraying can improve fruit set, yield, single-fruit quality, and sugar-acid ratio. Combined application of boron fertilizer and paclobutrazol can also alleviate alternate bearing. In addition, intercropping ryegrass in Chinese bayberry orchards can improve rhizosphere soil properties and microbial environments, increase fruit sugar, vitamin C, and flavonoid contents, and reduce acidity, thereby providing a new technical approach for ecological water and fertilizer management (Li et al., 2023). Regarding water management, adequate water supply should be ensured during the fruit enlargement stage, whereas excessive rainfall or drastic soil moisture fluctuations during the ripening stage can easily lead to fruit cracking, sugar dilution, and increased decay. Therefore, precise irrigation and drainage management should be implemented according to different fruit developmental stages.

4.2 Tree, flower, and fruit management

Tree structure and flower-fruit management can influence Chinese bayberry fruit quality by regulating canopy microenvironment, source-sink relationships, and reproductive load. Proper training and pruning can improve canopy ventilation and light penetration, enhance leaf photosynthetic efficiency, and promote nutrient accumulation and uniform fruit coloration. Chinese bayberry trees generally have large canopies, and if not pruned for long periods, dense canopy closure can occur, resulting in insufficient inner-canopy light, increased pest and disease incidence, and uneven fruit coloration. Therefore, orchard management commonly includes thinning overly dense branches, vigorous shoots, and weak or diseased branches to optimize canopy structure and improve fruit commercial quality and ripening consistency.

Flower and fruit management is an important approach for regulating nutrient distribution and improving fruit quality. Excessive fruit load intensifies nutrient competition among fruits, leading to reduced single-fruit weight and insufficient sugar accumulation. Moderate flower and fruit thinning can reduce ineffective nutrient consumption and direct more assimilates toward retained fruits, thereby improving fruit size, coloration, soluble solids content, and sugar-acid ratio. The combined regulation of paclobutrazol and boron fertilizer has also been used to balance vegetative and reproductive growth. Spraying 100-200 mg·L⁻¹ paclobutrazol during the

full-bloom stage can increase fruit weight, soluble solids content, and sugar-acid ratio while reducing total acidity; however, excessively high concentrations may significantly reduce fruit set, and therefore the application rate must be carefully controlled.

Management practices directly affecting the local fruit environment can also improve fruit quality. Insect- and rain-proof nets not only reduce pest damage and fruit cracking risks but also increase fruit diameter, single-fruit weight, edible rate, and sugar-acid ratio, showing better overall effects than open-field cultivation or insecticide application alone. These nets can also alter the bacterial community structure on fruit surfaces, reducing microbial groups associated with sugar consumption and disease, thereby favoring fruit growth and sugar accumulation (Yu et al., 2021). In addition, fruit bagging treatments can affect fruit quality by regulating light conditions, temperature, humidity, and pest pressure around the fruit. Using opaque bags during the young fruit stage reduces sugars, total flavonoids, vitamin C, and total anthocyanin contents while increasing acidity, resulting in poorer coloration and reduced fruit quality (Figure 2) (Yang et al., 2025). Therefore, Chinese bayberry bagging should balance light transmittance, ventilation, and protective effects.

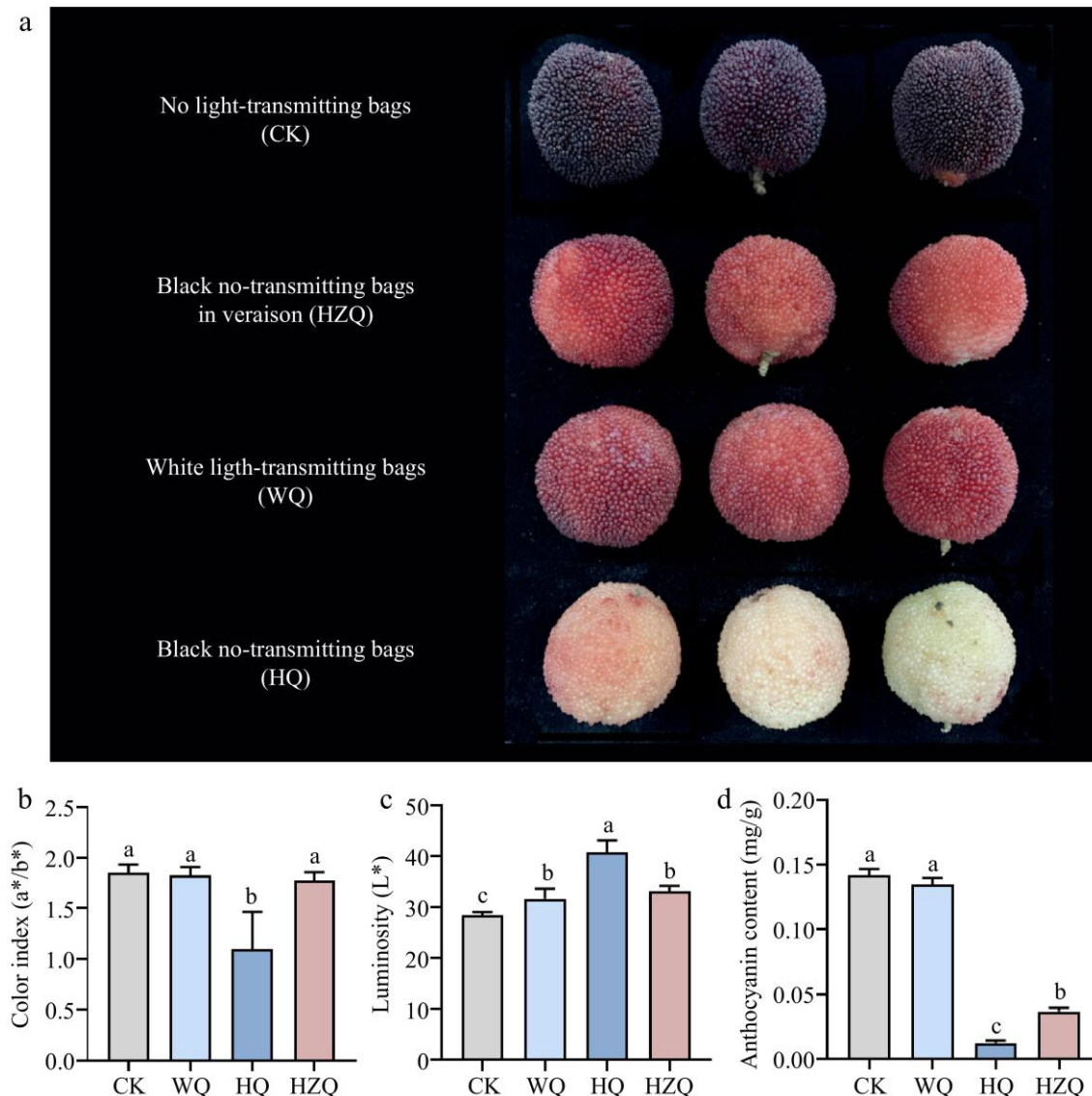


Figure 2 (a), (b) Effect of fruit color, (c) luminosity, and (d) anthocyanin in mature Chinese bayberry after treatment with different light-transmitting bags (Adopted from Yang et al., 2025)

Image caption: Bars represent the mean and standard error of three independently transformed biological replicates (n = 3). Different letters indicate statistically significant difference in one-way ANOVA analysis ($p < 0.05$); HQ: Blank-no-transmitting bag treatment; WQ: white-light treatment (Adopted from Yang et al., 2025)

4.3 Facility cultivation and green cultivation techniques

Facility cultivation and protected cultivation provide effective approaches for regulating temperature, light, and rainfall during critical periods of Chinese bayberry fruit development. Rain-shelter cultivation, greenhouse cultivation, insect- and rain-proof netting, and mulching cultivation can improve orchard microclimate and reduce the negative effects of continuous rainfall during the ripening period. Particularly during the fruit ripening stage, rainy weather often causes fruit cracking, decay, and disease occurrence, whereas rain-shelter facilities can reduce water accumulation on fruit surfaces and disease pressure, thereby improving fruit integrity, marketability, and postharvest storability.

Greenhouse cultivation can avoid the adverse effects of rainfall during harvest and improve single-fruit weight, fruit size, soluble solids content, and sugar-acid ratio, showing superior fruit quality compared with open-field cultivation. The physiological basis for these improvements may be associated with enhanced sucrose phosphate synthase activity and reduced acid invertase activity under greenhouse conditions, thereby promoting sucrose accumulation and improving sugar-acid quality (Wu et al., 2021). In controlled facility environments, LED supplemental lighting technology can further precisely regulate light intensity and spectral composition. For example, optimized LED supplemental lighting significantly increased fruit weight, soluble solids, and vitamin C content while reducing organic acid content in ‘Heitan’ Chinese bayberry. ‘Dongkui’ showed relatively weaker responses but still exhibited certain quality improvements, indicating cultivar-specific differences in light environment regulation requirements (Tang et al., 2025).

Green ecological cultivation technologies are important directions for the high-quality development of the Chinese bayberry industry. Their core objective is to maintain and improve fruit quality while reducing chemical inputs and improving orchard ecological environments. Intercropping ryegrass in Chinese bayberry orchards can improve soil physicochemical properties, rhizosphere microbial communities, and metabolic environments, thereby increasing fruit sugar, vitamin C, and flavonoid contents while reducing acidity (Li et al., 2023). Insect- and rain-proof nets, as green facility technologies, can simultaneously achieve pest control, rainfall exclusion, and microclimate regulation, thereby improving fruit size, edible rate, and economic benefits while reducing pesticide dependence (Yu et al., 2021). In addition, grafting ‘Biqizhong’ onto North American bayberry (*Morella cerifera*) rootstocks enables plants to maintain healthy growth under saline-alkaline soil conditions and increases fruit sucrose and citric acid contents, providing new possibilities for high-quality Chinese bayberry production in saline-alkaline areas (Saeed et al., 2023).

5 Research Progress in Detection and Evaluation Technologies for Chinese Bayberry Quality

5.1 Traditional detection methods

Traditional quality detection methods are an important foundation for evaluating Chinese bayberry fruit quality and are still widely used in scientific research, cultivar comparison, postharvest quality analysis, and commercial grading. Sensory evaluation is one of the most common traditional methods and mainly assesses overall fruit quality based on fruit color, size, shape, aroma, sweetness and acidity, flesh texture, juiciness, and overall acceptability. This method is highly intuitive and can directly reflect consumer perception of fresh fruit quality, thus playing an important role in fruit grading, market evaluation, and flavor description. Descriptive sensory analysis combined with physicochemical indices has been used to classify sweetness, acidity, and aroma characteristics among different Chinese bayberry cultivars, thereby providing a basis for selecting superior fresh-eating cultivars.

Physicochemical measurement is the core component of the traditional quality evaluation system and mainly includes soluble solids, titratable acidity, sugar-acid ratio, vitamin C, total phenolics, anthocyanins, fruit firmness, sugars, organic acids, and color difference parameters (Xuan et al., 2022). Among these, soluble solids are commonly used to reflect sugar content, whereas titratable acidity is used to evaluate acidity; together, they determine flavor balance in Chinese bayberry fruit. Vitamin C, polyphenols, and anthocyanins are often analyzed to evaluate nutritional and functional quality. Conventional analytical methods, such as refractometry for Brix determination, acid-base titration for titratable acidity, spectrophotometry for total phenolics and anthocyanins,

and high-performance liquid chromatography (HPLC) for sugars and organic acids, have provided important data for studies on fruit quality formation.

Traditional sensory evaluation systems and standardized analytical methods remain important references in Chinese bayberry quality research. In studies on Chinese bayberry juice, evaluators trained according to Chinese GB/T and ISO standards used quantitative descriptive analysis to establish flavor descriptors such as sourness, sweetness, bitterness, and astringency. Combined with analyses of nine organic acids, three sugars, and total polyphenol content, partial least squares analysis was used to establish relationships between sensory flavor characteristics and key chemical compounds. In addition, manual sensory evaluation can also be used to determine thresholds for “off-flavor” formation during storage, such as identifying the transition point from normal flavor to deteriorated flavor under different storage temperatures (Gao et al., 2024). However, traditional methods generally suffer from limitations including sample destructiveness, time-consuming procedures, high labor intensity, and strong subjective variability, making them insufficient for the modern Chinese bayberry industry’s demand for high-throughput, online, and rapid grading technologies.

5.2 Modern detection technologies

With the development of sensing technologies, spectral analysis, and chemometrics, modern detection technologies have been increasingly applied in Chinese bayberry quality research. In particular, non-destructive optical detection, electronic sensing, and volatile fingerprint analysis have provided faster, more objective, and data-driven approaches for quality evaluation. Color difference analysis objectively evaluates fruit color changes through comprehensive color parameters such as L, a, and b values. Digital image analysis, combined with image acquisition and computer processing, can rapidly analyze fruit size, shape, coloration, and surface defects, thereby improving the standardization of external quality evaluation.

Visible/near-infrared (Vis/NIR) spectroscopy is one of the earliest and most mature non-destructive technologies used in Chinese bayberry detection. Reflectance spectra within the 325-1075 nm range have been used to establish partial least squares models for rapid prediction of acidity and pH in intact Chinese bayberry fruit, showing high model correlations. Near-infrared transmittance spectroscopy has also been applied to predict titratable acidity, malic acid, and citric acid contents in different cultivars, demonstrating good application potential under temperature-controlled conditions. In recent years, hyperspectral imaging has further integrated spectral and spatial image information, allowing simultaneous prediction of single-fruit weight and soluble solids content, even for packaged fruit. After feature selection, PLS modeling, and model transfer correction, prediction stability across batches can be significantly improved (Yuan et al., 2025).

Electronic sensing technologies rapidly identify flavor quality by simulating human olfactory and gustatory systems. Electronic noses use multi-gas sensor arrays to monitor volatile flavor changes during storage. Combined with sensory evaluation and GC-MS analysis, they can identify stages of off-flavor formation and key volatile markers. Studies have shown that electronic nose response patterns change regularly with prolonged storage time and increasing temperature, allowing identification of off-flavor fruit stored for more than 2 days at 20 °C or more than 7 days at 10 °C, which is associated with the accumulation of ethanol, benzaldehyde, octanoic acid, and other volatiles (Gao et al., 2024). By combining electronic noses with stochastic resonance signal processing and regression models, indicators such as firmness, color, pH, total soluble solids, and reducing sugars can also be predicted, demonstrating potential for low-cost and rapid overall quality evaluation.

Electronic tongues are mainly used to analyze taste characteristics such as sweetness, sourness, bitterness, and astringency. In Chinese bayberry juice analysis, electronic tongues combined with sensor arrays and discriminant analysis effectively differentiated juices from different origins and cultivars, while correlating electronic tongue signals with organic acids, sugars, total polyphenols, and sensory scores. In addition, HS-GC-IMS technology can establish volatile fingerprint profiles during storage of Chinese bayberry juice and NFC products, identifying off-flavor markers such as ethanol and ethyl acetate, thereby providing a new approach for monitoring processing quality and early warning of flavor deterioration (Xuan et al., 2022). Low-cost portable Vis/NIR devices have also

been applied for non-destructive detection of sugar and acidity in Chinese bayberry fruit, and their portability makes them more suitable for small-scale growers and field grading applications (Wang et al., 2023).

5.3 Intelligent evaluation technologies

In recent years, the rapid development of artificial intelligence, big data, machine vision, and the Internet of Things (IoT) has promoted the transformation of Chinese bayberry quality evaluation from traditional single-point detection to intelligent, real-time, and systematic approaches. Intelligent recognition technologies based on machine vision can automatically collect fruit images and use machine learning or deep learning algorithms to identify fruit size, color, defects, and maturity, thereby enabling rapid grading. Compared with traditional manual sorting, intelligent recognition technologies have advantages including fast detection speed, unified standards, traceability, and suitability for online deployment. In orchard production, machine vision can also be used to monitor fruit ripening processes and canopy growth status, thereby supporting timely harvesting and precision management (Knott et al., 2022).

In sensor data modeling, machine learning has become an important tool for constructing Chinese bayberry quality detection models. Electronic nose data combined with stochastic resonance signal processing and multivariate regression models can be used to predict firmness, pH, color, soluble solids, and reducing sugars with high prediction accuracy. In postharvest flavor evaluation, artificial neural network models can verify the classification performance of electronic noses in distinguishing normal-flavor and off-flavor fruits under different storage temperatures (Gao et al., 2024). In spectral detection, algorithms such as partial least squares analysis, principal component analysis, and artificial neural networks are often combined with Vis/NIR or hyperspectral data for acidity prediction, cultivar identification, and cross-batch model transfer (Yuan et al., 2025). These technologies improve detection efficiency and data processing capability, providing technical support for rapid and non-destructive quality evaluation of Chinese bayberry fruit.

Image-based deep learning technologies have also begun to be applied to maturity and quality detection in Chinese bayberry. Zheng et al. (2025) proposed a cascaded framework combining the lightweight instance segmentation model SOLOv2-Light and multi-feature regression for field maturity detection of Chinese bayberry fruit (Figure 3). After segmenting individual fruits, the system integrated deep semantic features, LAB color information, and multi-scale texture features, while using a/b values obtained by colorimeters as maturity labels, achieving high segmentation performance and low maturity prediction error. When maturity was divided into three levels, classification accuracy reached 95.5%. From the perspective of industrial applications, future intelligent quality evaluation of Chinese bayberry is expected to develop toward multi-source data fusion and online detection. In orchards, machine vision and IoT technologies can be combined to monitor fruit maturity, temperature, humidity, and soil moisture; in sorting facilities, hyperspectral imaging and Vis/NIR technologies can be used for automatic grading; and in processing plants, electronic noses, electronic tongues, and HS-GC-IMS can be used to monitor flavor stability (Dhiman et al., 2022; Apostolopoulos et al., 2023). With the development of lightweight models, portable sensors, and cloud platforms, Chinese bayberry quality detection is expected to achieve real-time application from laboratories to orchards, storage systems, and processing lines (Hassan et al., 2025; Júnior et al., 2025).

6 Current Problems in Existing Research

6.1 Insufficient research on the mechanisms of quality formation

In recent years, increasing attention has been paid to the mechanisms underlying Chinese bayberry fruit quality formation, and technologies such as genomics, transcriptomics, and metabolomics have gradually been applied to the analysis of quality traits. However, overall, the mechanisms governing fruit quality formation still lack systematic, in-depth, and experimentally validated theoretical explanations. At present, a high-quality telomere-to-telomere (T2T) reference genome and genome-wide association studies (GWAS) have linked 29 quality traits with 1 937 SNP loci and 1 039 candidate genes, and identified an important MYB/MLP regulatory locus associated with fruit color on chromosome 6 (Zhang et al., 2024). Nevertheless, for complex quality traits

such as fruit texture, flavor balance, aroma compound accumulation, storability, and postharvest softening, studies on key allelic variations, regulatory networks, and functional validation remain insufficient.

Simple Scene



Multi-objective Stacking Scene



Figure 3 Prediction performance of the regression model (Adopted from Zheng et al., 2025)

Image caption: A simple scenario and a complex scenario with multiple stacked fruits. The predicted maturity percentage is shown above each fruit. Each color represents a distinct instance mask (Adopted from Zheng et al., 2025)

Existing studies mainly focus on a limited number of quality indicators, including sugars, acidity, anthocyanins, and flavonoids, whereas research on terpene metabolism, cell wall metabolism, antioxidant systems, hormone signaling, and volatile aroma formation is still inadequate (Yang et al., 2025). Transcriptomic studies during fruit ripening have shown that anthocyanin biosynthesis-related genes are generally upregulated during fruit maturation, and significant changes also occur in sugar-acid metabolism and energy metabolism pathways. However, many candidate genes remain at the stage of correlation analysis, lacking further validation through gene editing, transient expression, genetic transformation, or population genetics approaches (Sun et al., 2024).

In addition, Chinese bayberry fruit quality formation is the result of interactions among genetic factors, environmental conditions, developmental stages, and cultivation practices, yet most current studies still focus on single factors or a few cultivars. For example, studies on light exposure and fruit bagging have demonstrated that weak light conditions reduce the accumulation of sugars, organic acids, vitamin C, flavonoids, and anthocyanins, and identified HY5 and LDOX as possible regulators involved in light-induced coloration (Yang et al., 2025). However, the interactions among light signaling, hormone signaling, transcription factor networks, and metabolic pathways remain unclear. Furthermore, most studies are concentrated on a few major cultivars such as ‘Biqi’ and ‘Dongkui’, while investigations involving large germplasm populations, multiple ecological regions, and different cultivation systems are still relatively limited (Zhang et al., 2024). Therefore, current quality regulation in Chinese bayberry production still relies heavily on empirical cultivation practices rather than precise regulation based on mechanistic understanding.

6.2 Incomplete cultivation regulation technology system

Although cultivation and management technologies for Chinese bayberry have continuously developed, there is still a lack of standardized, systematic, and region-specific regulation systems aimed at fruit quality improvement. Most existing studies focus on individual production stages or single technologies, such as water and fertilizer management, canopy regulation, bagging, insect- and rain-proof nets, LED supplemental lighting, and postharvest preservation, whereas studies on the synergistic effects, application boundaries, and long-term ecological impacts of these measures remain limited. For example, insect- and rain-proof nets can effectively control fruit flies, improve fruit size, edible rate, and sugar-acid ratio, and optimize fruit-surface microbial communities, but related studies are still mainly restricted to single cultivars and regions, and continuous evaluation of their long-term effects on tree vigor, soil microorganisms, and orchard ecosystems is lacking (Yu et al., 2021).

Facility cultivation and precision light environment regulation also exhibit strong cultivar dependence and insufficient standardization. LED supplemental lighting can significantly improve fruit size, soluble solids, and vitamin C content in the cultivar ‘Black Charcoal’, but its effects are relatively limited in cultivars such as ‘Dongkui’, indicating that different cultivars respond differently to light intensity, spectral composition, and lighting periods. Therefore, cultivar-, region-, and developmental stage-specific light regulation systems still need to be established (Tang et al., 2025). Similarly, technologies such as water and fertilizer regulation, flower and fruit thinning, canopy pruning, and harvest maturity management may produce different effects under different ecological regions and cultivars, but systematic comparisons and standardized technical protocols are currently lacking.

The postharvest preservation technology system also requires further improvement. Technologies such as ultrasonic treatment combined with slightly acidic electrolyzed water, ozone water treatment, low-temperature storage, and optimized temperature management can reduce microbial populations, delay fruit softening, and maintain sugar-acid balance and phenolic contents. However, most studies are still limited to experimental conditions or small-scale validation and have not yet formed integrated systems linked with harvest maturity, transportation damage control, packaging materials, cold-chain logistics, and market circulation periods (Suo et al., 2023; Gao et al., 2024). Moreover, current research mainly focuses on short-term quality or shelf-life indicators, while comprehensive evaluations regarding economic cost, carbon footprint, low-residue production, farmer operability, and industrial promotion models remain insufficient. Therefore, future cultivation regulation of Chinese bayberry should shift from optimization of individual technologies toward integrated “cultivar-environment-tree-facility-postharvest” management systems.

6.3 Lack of unified quality evaluation standards

At present, Chinese bayberry quality evaluation has not yet formed unified and widely applicable industrial standards, which to some extent restricts the standardization, branding, and commercialization of the industry. Current quality evaluation systems have gradually expanded from traditional sugar-acid indices to multidimensional indicators including external appearance, phenolic compounds, flavonoids, anthocyanins, antioxidant activity, texture, volatile compounds, sensory evaluation, and postharvest storability (Gao et al., 2024; Saeed et al., 2025; Yang et al., 2025). However, different studies, production regions, and enterprises often adopt different detection methods, indicator combinations, and evaluation thresholds, resulting in poor comparability among research results.

For example, studies on Chinese bayberry juice processing indicate that sugar-acid ratio, total sugar, and titratable acidity are key factors influencing sensory preference and can be used to screen suitable processing cultivars. However, these evaluation criteria have not yet been effectively linked with fresh fruit commercial grades, processing grades, or national and industry standards. Flavor studies can classify cultivars according to aroma-active compounds and sensory characteristics, but corresponding grading systems applicable to market circulation, brand construction, and trade evaluation have not yet been established. In postharvest quality research, methods such as electronic nose off-flavor classification, artificial neural network models, volatile markers, and

texture analysis possess important scientific value, but they have not yet been transformed into practical industrial evaluation procedures and standard thresholds (Suo et al., 2023; Gao et al., 2024).

Furthermore, unified relationships among genetic markers, laboratory detection indices, and market grades for fresh and processed products are still lacking. Although GWAS studies have identified 29 quantifiable quality traits and related loci, these molecular indicators have not yet been systematically translated into breeding selection standards, cultivar certification indices, or commercial grading criteria (Zhang et al., 2024). Meanwhile, different consumer groups exhibit varying preferences for Chinese bayberry quality; some focus more on sweetness and taste, whereas others emphasize nutritional functionality, safety, or processing suitability. Therefore, future studies should establish multidimensional comprehensive evaluation systems covering appearance quality, flavor quality, nutritional and functional quality, safety quality, postharvest quality, and processing quality, while promoting the integration of non-destructive detection, intelligent evaluation, and molecular marker data with industrial standards.

7 Future Development Directions

7.1 Breeding of high-quality new varieties

With increasing consumer demands for Chinese bayberry fruit quality, the breeding of high-quality new cultivars will become a core direction for the future development of the industry. Current market demands have gradually shifted from focusing solely on fruit size and yield to comprehensive traits such as flavor quality, nutritional value, functional components, storability, transportation tolerance, and green safety. Therefore, breeding objectives for Chinese bayberry should shift from traditional high-yield orientation toward coordinated improvement of high quality, efficiency, multifunctionality, and adaptability. By developing new cultivars with balanced sugar-acid ratios, attractive coloration, tender flesh, and high contents of anthocyanins and flavonoids, the market competitiveness and industrial value of Chinese bayberry can be further enhanced (Zhang et al., 2024; Saeed et al., 2025).

In recent years, genomics and multi-omics technologies have provided an important foundation for molecular design breeding in Chinese bayberry. Telomere-to-telomere reference genomes and GWAS analyses of 173 germplasm accessions have identified 1,937 SNP loci and 1,039 candidate genes associated with 28 fruit quality traits, among which MYB and MLP-like gene regions on chromosome 6 are closely related to fruit coloration and anthocyanin accumulation (Zhang et al., 2024). The Chinese bayberry database integrates multi-omics information including genomes, transcriptomes, molecular markers, phenotypes, and fruit images, thereby providing a platform for quality trait marker development, candidate gene screening, and computer-assisted breeding (Ren et al., 2021). In addition, high-density SNP genetic maps and QTL mapping studies have laid the foundation for marker-assisted selection of traits related to tree growth, leaf characteristics, and yield performance (Zhang et al., 2021).

These molecular research achievements have gradually begun to integrate with breeding practice. For example, the new hybrid line ‘BD-107’, developed from a cross between ‘Biqi’ and ‘Dongkui’, showed superior fruit firmness, sugar content, and vitamin C content compared with both parents, and also contained richer terpene and flavonoid compounds, demonstrating the potential of hybrid breeding for improving flavor, texture, and functional quality (Saeed et al., 2025). In addition, studies on developmental regulatory genes such as MrSPL4 suggest that these genes may influence vegetative growth and flowering time, thereby providing new strategies for breeding early-maturing, highly adaptable, and facility-suitable cultivars (Zhang et al., 2022). In the future, breeding of Chinese bayberry cultivars should further focus on the coordinated improvement of flavor quality, nutritional functionality, storability, pest and disease resistance, stress tolerance, maturity regulation, and processing suitability.

7.2 Precision and intelligent cultivation

Precision and intelligent cultivation represent important trends in the development of modern fruit industries and are also key approaches for improving fruit quality stability and production efficiency in Chinese bayberry. Traditional Chinese bayberry cultivation mainly relies on empirical management, which often results in

uncertainties in water and fertilizer supply, pest control, canopy regulation, and harvest judgment, thereby causing resource waste and quality fluctuations. In the future, technologies such as sensor monitoring, automated control, machine vision, and artificial intelligence models should be used to monitor soil moisture, nutrient status, canopy light conditions, tree vigor, and fruit maturity in real time, enabling the transition from experience-based management to data-driven management (Sharma and Shivandu, 2024; Soussi et al., 2024).

Facility cultivation and controlled-environment technologies will become important directions for precision cultivation of Chinese bayberry. In protected cultivation systems, LED supplemental lighting can improve fruit quality through precise regulation of light intensity and spectral composition. Studies have shown that optimized LED lighting can increase fruit weight, soluble solids, and vitamin C content while reducing organic acid content, especially in the cultivar ‘Black Charcoal’, indicating that genotype-specific “light recipe” management has considerable application potential (Tang et al., 2025). Insect- and rain-proof nets can reduce pest damage and fruit cracking, improve fruit size, sugar-acid ratio, and economic returns, and simultaneously reduce the risks associated with sugar-consuming and pathogenic microorganisms by regulating fruit-surface microbial communities, thereby achieving coordinated regulation of microenvironment, microbial populations, and fruit quality (Yu et al., 2021). Intercropping with ryegrass can improve rhizosphere nutrient conditions, microbial structure, and metabolite composition, while increasing fruit sugars, vitamin C, and flavonoid contents and reducing acidity, thus providing an ecological model for region-specific precision water and fertilizer management (Li et al., 2023).

Intelligent sensing and robotic technologies will also play increasingly important roles in Chinese bayberry orchard management. A Chinese bayberry fruit recognition model based on an improved YOLOv7-tiny network and attention mechanisms achieved a fruit detection recall rate of 97.6% under natural conditions, while maintaining a lightweight architecture suitable for deployment on mobile harvesting robots (Zheng et al., 2025). In addition, lightweight instance segmentation models combined with multi-feature regression can be used for field fruit maturity recognition, thereby providing real-time decision support for timely harvesting and selective picking. In the future, considering the complex canopy structure of Chinese bayberry trees, severe fruit occlusion, concentrated harvesting periods, and the susceptibility of fruits to mechanical damage, research should focus on the development of maturity recognition, intelligent harvesting, non-destructive sorting, and integrated postharvest cold-chain systems.

7.3 Construction of green and high-quality production systems

The construction of green and high-quality production systems is an important direction for achieving sustainable development in the Chinese bayberry industry. Although traditional high-input cultivation systems have improved yield to some extent, excessive application of chemical fertilizers and pesticides may lead to soil degradation, increased ecological pressure, and declines in fruit quality. Future Chinese bayberry production should place greater emphasis on resource-use efficiency, ecological environmental protection, fruit safety, and farmer profitability, thereby promoting the transformation of the industry from a purely high-yield orientation toward green, high-quality, efficient, and sustainable development (Liu et al., 2020; Sharma and Shivandu, 2024).

The establishment of green production systems requires greater adoption of organic fertilizer substitution, biological control, ecological regulation, and orchard biodiversity management. Ryegrass intercropping can improve soil structure and rhizosphere microecological environments while increasing fruit sugars, vitamin C, and flavonoid contents and reducing acidity, thereby achieving both ecological benefits and quality improvement simultaneously (Li et al., 2023). Insect- and rain-proof net technologies not only improve yield and quality but also reduce pesticide use and pest contamination, making them more compatible with green and low-residue production systems (Yu et al., 2021). Therefore, future green production of Chinese bayberry should focus on developing integrated technical systems combining “organic fertilizer substitution-orchard grass cover-biological control-rain shelter cultivation-precision water and fertilizer management-intelligent monitoring”.

Future green and high-quality production systems should also be integrated with postharvest preservation, cold-chain logistics, deep processing, and brand development. Chinese bayberry possesses high nutritional and

health-promoting value and shows considerable potential in functional foods, juices, wines, vinegars, dried fruit, and bioactive compound extraction (Zhang et al., 2022). Therefore, further studies on harvesting, preservation, storage, transportation, and processing technologies are needed to extend the industrial chain and increase product added value. Meanwhile, the establishment of unified green production standards, quality evaluation systems, and regional branding systems could enhance consumer trust and promote the transformation of the Chinese bayberry industry from a fresh-fruit-oriented market toward a diversified model integrating “fresh consumption + processing + functional products + ecological branding.”

8 Concluding Remarks

In recent years, research on Chinese bayberry fruit quality has gradually evolved from the early basic description of ripening changes to multi-omics analyses of the genetic and biochemical regulatory mechanisms underlying fruit quality formation. Early EST and RNA-Seq studies identified a large number of differentially expressed genes during fruit ripening, revealing coordinated upregulation of anthocyanin biosynthesis-related genes and significant alterations in sugar and organic acid metabolism, which together determine fruit color and flavor quality. With the development of high-quality genome assembly technologies, including the recent telomere-to-telomere (T2T) reference genome and earlier draft genomes, researchers have further elucidated antioxidant, flavonoid, and terpenoid metabolic pathways and identified key expanded gene families and candidate regulatory factors associated with antioxidant capacity and flavor traits. Genome-wide association studies (GWAS) based on large germplasm populations linked 29 measurable fruit quality traits to more than 1,000 genes and identified important MYB/MLP loci closely associated with fruit color formation. At the same time, studies of the MYB family revealed key transcription factors regulating metabolic flux between anthocyanins and flavonols. In addition, the development of molecular marker technologies such as SSR, EST-SSR, SNP, and InDel markers, together with the establishment of multi-omics databases, has further promoted germplasm identification, genetic diversity analysis, and molecular breeding research in Chinese bayberry, thereby providing a more robust platform for fruit quality improvement.

In addition to genetic research, cultivation management and postharvest handling practices have gradually been recognized as important approaches for regulating Chinese bayberry fruit quality. Field studies have shown that insect- and rain-proof nets can not only effectively control major pests but also improve fruit size, edible rate, and sugar-acid ratio while optimizing fruit-surface microbial community structure, thereby significantly enhancing commercial fruit quality and yield. Protected cultivation and LED supplemental lighting technologies can precisely regulate orchard microenvironments and fruit coloration parameters, significantly increasing fruit weight, soluble solids, and vitamin C content while reducing acidity in some sensitive cultivars, although responses differ considerably among cultivars. Postharvest studies have demonstrated that ethylene regulation and low-temperature storage conditions play crucial roles in maintaining fruit quality. Cold storage at approximately 4°C can slow firmness decline, stabilize sugar-acid changes, and extend shelf life, indicating that storage environment is an important factor influencing consumer acceptance. In addition, studies on flesh compartment development and hormonal regulation suggest that cultivation practices affecting hormonal balance, canopy structure, and source-sink relationships interact with intrinsic fruit developmental programs and jointly determine final fruit texture and juiciness. Overall, optimized cultivation and postharvest management technologies tailored to different cultivars are equally important as genetic background for achieving stable production of high-quality Chinese bayberry fruit.

Looking forward, the integration of genomics, physiology, and modern agricultural technologies will provide broad prospects for upgrading the Chinese bayberry industry. Applications of high-resolution genomes, GWAS signals, and high-density molecular markers make marker-assisted breeding and even genomic selection possible, helping overcome the long juvenile period of Chinese bayberry and accelerating the breeding of superior cultivars with improved flavor, coloration, antioxidant capacity, and environmental adaptability. At the same time, abundant local germplasm resources and regional genetic diversity provide important foundations for exploiting heterosis and selecting superior hybrid combinations. In the production sector, integrating insect- and rain-proof nets, precise light management, and low-input green cultivation systems with optimized postharvest handling

technologies can further improve fruit safety and added value while reducing postharvest losses. Moreover, studies on Chinese bayberry fruits, kernels, and processing by-products have demonstrated broad application potential in functional foods and nutraceutical products, particularly due to their strong antioxidant and antidiabetic activities, which may significantly extend the industrial value chain of Chinese bayberry. In the future, further efforts are still needed to clarify the mechanisms underlying fruit quality formation, establish region- and cultivar-specific cultivation systems, and develop unified quality evaluation and grading standards linking genetic markers, laboratory detection indices, and market grades, thereby promoting the high-quality and sustainable development of the Chinese bayberry industry.

Acknowledgments

The author acknowledges GenBreed Publisher for providing editorial assistance.

Conflict of Interest Disclosure

The author affirms 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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