

Integrated Orchard Management for High-Quality Bayberry Production

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Abstract This study focuses on the integrated management techniques for high-quality waxberry (*Myrica rubra*) orchards. Based on the biological characteristics, nutritional and medicinal value, and current status of the industry, the main problems in current production are analyzed. The study systematically summarizes key technical approaches to improving yield and fruit quality, including orchard site selection and establishment, cultivar selection and renewal, soil and fertilization management, water regulation, quality improvement, and green pest and disease control. By optimizing soil improvement and organic fertilizer application, implementing precise irrigation and drainage control, and reasonably regulating nutrient supply and orchard structure, fruit size, sugar content, and flavor quality can be significantly improved, while reducing environmental pressure. Combined with smart orchard technologies, ecological cultivation models, and the integration of agriculture and tourism, this research helps promote the transformation of the waxberry industry toward high quality, green development, and sustainability, and provides practical references for building a high-quality production system and upgrading the industry.

Keywords Waxberry (*Myrica rubra*); Orchard management; Quality improvement; Water and fertilizer regulation; Green control

1 Introduction

Chinese bayberry (*Myrica rubra* Sieb. et Zucc.), also known as red bayberry or waxberry, is one of the most representative subtropical fruit trees in East Asia. It is the only species with economic cultivation value in the family Myricaceae. It has been cultivated in southern China for at least 2 000~7 000 years, and the current planting area exceeds 330 000 hectares, with an annual production close to 1 million tons (Zhang et al., 2015). In addition to China, *Myrica* species are widely distributed in Asia, North America, South America, and parts of Europe, showing their global importance as both a specialty fruit and a medicinal resource. In major producing regions such as Zhejiang, Jiangsu, Fujian, and Guangdong, Chinese bayberry plays a key role in regional agricultural economies and farmers' livelihoods. This is mainly due to the development of specialized orchards, the promotion of superior cultivars (such as 'Dongkui' and 'Ding'ao'), and the continuous expansion of fresh fruit and processed product markets.

Chinese bayberry fruit is considered a "green and healthy food," rich in soluble sugars, organic acids, vitamins (especially vitamin C), minerals, and dietary fiber. Phytochemical studies have shown that it contains abundant bioactive compounds such as proanthocyanidins, anthocyanins, flavonols (e.g., myricetin and quercetin derivatives), and phenolic acids, which give it strong antioxidant capacity and diverse biological activities (Zhang et al., 2022). Extracts from its fruits, leaves, and bark have been reported to show antioxidant, anti-inflammatory, anti-allergic, anti-obesity, anti-diabetic, antibacterial, and anti-tumor effects, and may provide benefits for cardiovascular, cerebrovascular, and neuroprotective functions (Ren et al., 2019; Singh et al., 2025). These multifunctional properties support its wide industrial applications, ranging from fresh consumption and traditional processing (juice, wine, jam, preserved fruit, vinegar) to emerging uses such as extracting functional components, oils, and bioactive substances from seeds and processing residues (Mo et al., 2024).

The fruit ripening period of Chinese bayberry coincides with the rainy season in southern China. High humidity and insufficient sunlight often lead to yield reduction, sugar dilution, and shorter shelf life. The fruit has exposed skin and a soft texture, along with very high sugar and water content, making it highly prone to cracking, mechanical damage, rapid decay, and postharvest diseases. Under normal temperature conditions, its shelf life is

usually only a few days. In many production areas, traditional orchard management still relies on high input levels, including heavy use of chemical fertilizers and frequent application of pesticides or even antibiotics to maintain yield and control pests and diseases (Yi et al., 2024). Problems such as a high proportion of small fruits, uneven coloration, unstable sweetness and flavor, serious fruit cracking, and significant pre- and post-harvest disease pressure are still common, limiting the improvement of economic benefits.

This study systematically integrates the biological characteristics, nutritional and medicinal values, and recent progress in orchard management of Chinese bayberry, and explains the theoretical basis and practical significance of integrated orchard management for achieving high-quality fruit production. It clarifies the important role of Chinese bayberry in regional and global fruit production systems, summarizes its nutritional, economic, and therapeutic values, and analyzes the main problems and limitations in current orchard and postharvest management. Based on research on Chinese bayberry and other fruit trees, this study discusses the key components, mechanisms, and practical effects of integrated orchard management. By identifying development directions, application potential, and research needs, this study provides a theoretical framework and technical reference for transforming the Chinese bayberry industry from a traditional high-input model to a high-quality, sustainable, and eco-friendly production system.

2 Orchard Site Selection and Establishment Techniques

2.1 Selection of suitable planting areas (slope, elevation, drainage)

Waxberry is suitable for growth in warm and humid subtropical climates, requiring sufficient sunlight, moderate rainfall, and good air circulation. In major production areas, it is usually planted on hilly or low mountain slopes (Chen et al., 2025). In the Taizhou region of Zhejiang Province, the most suitable areas are mainly distributed in mid-hill zones, while high mountains above about 800 m and low-lying plains prone to waterlogging or with high groundwater levels are not suitable for planting (Shou et al., 2011). Studies in ecologically fragile orchard areas show that gentle slopes of about 3-10° can achieve a good balance between drainage, erosion risk, and operational convenience, making them the most suitable for new orchard establishment (Hu et al., 2023). Elevation, slope, and aspect together determine temperature conditions, cold air movement, and solar radiation, all of which significantly affect flowering, fruit set, and fruit coloration of waxberry.

2.2 Soil improvement measures before orchard establishment

Surveys of waxberry orchards in Zhejiang Province show that local soils are generally acidic (pH 3.97~6.15), with low organic matter content. Phosphorus status is highly imbalanced, with low total phosphorus but very high available phosphorus. Available potassium is generally insufficient, and exchangeable magnesium deficiency is common, with some areas also showing calcium deficiency (Wang et al., 2019). These imbalances may lead to decline disease, weakened tree vigor, and reduced fruit quality.

The application of organic amendments such as farmyard manure, bio-organic fertilizers, and biochar has been proven to improve soil structure, increase organic matter content, raise pH, and enhance key nutrients (available N, P, K as well as Ca and Mg). At the same time, these practices can reshape the rhizosphere microbial community and metabolite composition (Ren et al., 2023). For compacted soils, deep plowing or subsoiling should be carried out, and organic amendments should be evenly incorporated into the planting zone. When soil pH or magnesium levels are too low, lime or magnesium fertilizers should be applied appropriately to create a deep and well-aerated root growth layer.

2.3 Orchard layout design (planting density, row spacing, roads, and drainage system)

Based on a 15-year study of waxberry orchards and decline disease trials in Zhejiang, a medium-density planting system with a spacing of about 4 m × 5 m (approximately 500 trees·hm⁻²) can meet canopy growth needs while also facilitating mechanized operations (Ren et al., 2023).

For high-yield dwarf and dense planting systems, spacing should be adjusted according to variety vigor, rootstock type, and soil conditions to ensure good ventilation and light penetration. Planting patterns directly affect cultivation methods, plant health, yield, and fruit quality by regulating plant population per unit area and light

interception patterns and intensity (Javaid et al., 2017; Haque and Sakimin, 2022). A row planting system (square or rectangular) is usually recommended, with rows oriented roughly north-south to optimize light distribution and facilitate mechanization. At the same time, a hierarchical road system (main roads and secondary paths) and drainage ditches designed along contour lines or slopes should be established to ensure rapid removal of excess surface water and prevent rill and gully erosion on slopes. Grass ditches or vegetative strips along drainage channels can further enhance soil stability and improve water quality (Simon et al., 2017).

2.4 Shelterbelt and ecological buffer zone design

Shelterbelts, as key structural components, can effectively reduce wind speed, prevent soil erosion, regulate the microclimate, and enhance habitat diversity, and have been widely recognized worldwide. Well-designed shelterbelts (considering height, width, orientation, and internal permeability) can not only increase crop yield, reduce evapotranspiration, and protect environmentally sensitive fruit crops, but also provide multiple ecosystem services, including biodiversity conservation, carbon sequestration, and air quality improvement (Weninger et al., 2021; Enescu et al., 2025).

In orchard ecosystems, artificially established shelterbelts and riparian buffer zones can also protect soil and water bodies. When tree species are well matched to site soil conditions, and combined with appropriate planting spacing and soil preparation measures, tree survival rates and growth performance can be significantly improved (Mathieu et al., 2024). For waxberry orchards located on open slopes, multi-row shelterbelts or hedgerows can be used, selecting local or well-adapted woody species and arranging them at suitable intervals based on shelterbelt height, with orientation perpendicular to the prevailing wind direction. At the same time, herbaceous ecological buffer zones should be established along field edges and around water bodies.

3 Variety Selection and Orchard Renewal

3.1 Recommendation of high-quality bayberry varieties

China has abundant bayberry germplasm resources. In recent years, genomic and phenotypic studies have clarified that different varieties show clear differences in fruit size, color, flavor, antioxidant capacity, and disease resistance (Zhang et al., 2024). At present, widely cultivated varieties such as ‘Biqi’, ‘Dongkui’, ‘Dingao’, ‘Zaojia’, as well as local elite lines like ‘SY-2’, are considered core high-quality resources due to their large fruit size, red to purple color, high soluble solids and anthocyanin content, and strong market acceptance.

‘Zaojia’ has been successfully bred as a multi-resistant variety and has been used as a reference material for high-quality genome assembly, showing its important value in both breeding and production. ‘SY-2’, a new bayberry variety selected from Dongting Mountain, shows strong tree vigor, large and round fruits (average 12.63 g), deep purple color, high soluble solids and anthocyanin content, and matures 5~7 days earlier than ‘Xiaoye Xidi’. It is considered a highly promising early-maturing high-quality variety (Dai et al., 2012). At present, multi-omics platforms such as the Bayberry Database have integrated genomic, transcriptomic, molecular marker, and germplasm resource information, which greatly promotes the precise selection and application of superior varieties in production (Jiao et al., 2012).

3.2 Matching varieties with ecological environment

In Zhejiang and Yunnan, ecological zoning based on temperature, extreme low temperature, rainfall during fruiting period, air humidity, altitude, and terrain can divide bayberry planting areas into most suitable, suitable, marginal, and unsuitable zones. Among them, regions with warm winters, humid spring and summer, and hilly or semi-mountainous terrain are the best for high-quality bayberry production. In contrast, high mountains and low-lying plains are not suitable due to higher risks of frost or waterlogging (Shou-Zhi, 2004).

Soil factors such as pH, nutrient imbalance, and salinity also significantly affect variety performance. In the southeastern coastal areas, saline-alkali soils seriously limit the growth of traditional red bayberry rootstocks. However, using wax myrtle (*Morella cerifera*) as a rootstock allows ‘Biqi’ to maintain good growth under high Na, Mg, and Ca conditions. It shows dark green leaves and good fruit quality, with larger fruits, higher sucrose and citric acid content, and earlier flowering and fruiting (Huang et al., 2025). Studies on dwarf and high-density

cultivation indicate that salt-tolerant wax myrtle rootstocks can promote early fruiting, improve fruit size and flavor, and adapt to saline-alkali soil conditions.

3.3 Grafting and variety renewal techniques

Grafting is a key technique for rapid renewal of bayberry varieties. It allows the combination of high-quality scions with rootstocks that have better adaptability or stress resistance, and also helps renew old orchards. From physiological and molecular perspectives, grafting can shorten the juvenile phase, regulate tree vigor and canopy structure, increase yield, and enhance resistance to soil stress and pathogens (Williams et al., 2021; Habibi et al., 2022; Loupit et al., 2023). Successful grafting depends on coordinated hormone regulation (such as auxin, cytokinin, ethylene, gibberellin, abscisic acid, and jasmonic acid), wound healing, vascular reconnection, and compatibility between rootstock and scion at physiological and molecular levels.

In practice, techniques such as cleft grafting, bark grafting, and top grafting are commonly used to replace inferior or mixed varieties with uniform high-quality ones, thus shortening the fruiting period and improving orchard uniformity.

Grafting 'Biqi' onto wax myrtle rootstock in saline-alkali soil shows good graft compatibility, normal growth, and excellent fruit quality, indicating that proper rootstock-scion combinations can effectively utilize marginal land (Huang et al., 2025). With the development of SSR markers, high-density SNP genotyping, and telomere-to-telomere (T2T) genome technologies, it is now possible to systematically screen rootstock-scion compatibility and rootstock effects, thereby shortening the breeding and evaluation cycle of new combinations.

4 Soil and Fertilization Management Measures

4.1 Annual fertilization regime (basal fertilizer, topdressing, and post-harvest fertilization)

Long-term investigations in red soil orchards have shown that imbalanced fertilization and declining soil organic matter are closely related to problems such as weakened tree vigor, smaller fruit size, and unstable yield (Zhuang et al., 2024). The annual fertilization regime for waxberry should align nutrient supply with phenological stages, while combining quick-acting mineral nutrients with slow-release organic nutrient sources.

In field trials on weakened waxberry trees, during key growth stages—flower bud differentiation and new shoot emergence—compound fertilizer (NPK 15-15-15) and bio-organic fertilizer (based on sheep manure) were applied in trenches near the canopy drip line and then covered with soil (Ren et al., 2021). Compared with the unfertilized control, this fertilization timing significantly improved vegetative growth, fruit traits, and the physicochemical properties of rhizosphere soil.

4.2 Combined application of organic fertilizers and green manure

Livestock and poultry manure, compost, cover crops, and other organic amendments can improve soil structure, increase organic carbon content, and enhance microbial and enzyme activities. They also often improve fruit quality traits such as sugar content and antioxidant capacity (Chatzistathis et al., 2021; Dhaliwal et al., 2023).

In waxberry studies, bio-organic fertilizer based on sheep manure significantly increased exchangeable calcium and magnesium, as well as available phosphorus and potassium in the soil. At the same time, it reshaped the rhizosphere microbial community and metabolite composition, which were closely associated with the alleviation of decline disease and improvement of tree health (Ren et al., 2021).

Returning green manure to the field, combined with balanced chemical fertilization, can significantly increase soil organic carbon and its active fractions, total nitrogen content, and enzyme activities. It can also increase the yield of the following crop by 34%-53%, while reducing soil bulk density and slightly lowering soil pH (Xu et al., 2023).

4.3 Soil testing and precision fertilization

Precision fertilization for waxberry should begin with diagnosing soil limiting factors, such as strong acidity, low organic matter content, and imbalances in nutrients like phosphorus, potassium, calcium, and magnesium. Based

on this, targeted fertilizer types, application rates, and methods should be developed to improve fruit quality and tree health.

In waxberry orchards affected by decline disease, exchangeable calcium, magnesium, and available phosphorus are key factors influencing the structure of rhizosphere microbial communities. Regulating these nutrients through compound fertilizers and bio-organic fertilizers can significantly alter microbial communities and soil metabolite composition.

Specialized waxberry fertilizers and foliar nutrient products, when applied at appropriate rates and frequencies, can increase soil organic matter, leaf chlorophyll content, and fruit sugar and soluble solids content (Guo et al., 2009).

From a broader perspective, soil testing should be used as the basis to guide the partial replacement of mineral NPK fertilizers with organic and bio-fertilizers. This helps maintain soil nutrient balance, enhance carbon sequestration capacity, and achieve long-term sustainability of crop production (Selim, 2020; Urmi et al., 2022).

5 Water Management and Drainage Control

5.1 Critical water demand periods (flowering stage and fruit expansion stage)

Effective water management in waxberry orchards needs to balance avoiding drought, maintaining root aeration, and improving fruit quality. Water shortage and improper irrigation are among the main limiting factors in global fruit production, especially when water stress coincides with key phenological stages, which can significantly reduce tree growth, yield, and fruit size (Devin et al., 2023; Ru et al., 2025). The flowering-fruit set stage and the fruit expansion stage are critical water-demand periods. Water deficit during flowering usually reduces fruit number, while water shortage during fruit expansion has the most significant impact on final fruit size and marketable yield (Berríos et al., 2023).

5.2 Irrigation methods under orchard conditions

The choice of irrigation method should consider local water resource conditions, orchard terrain, and soil type, with a focus on covering the active root zone. Drip irrigation, widely used in orchards in China, can deliver water directly to the root system, reduce evaporation loss, decrease leaf wetness and disease occurrence, and maintain a good soil water-air balance throughout the growing season. Compared with surface irrigation and sprinkler irrigation, drip irrigation can significantly improve yield and water use efficiency, especially under water-limited conditions, and can also reduce fertilizer leaching and soil salinization (Yang et al., 2023; Fareed et al., 2024; Long et al., 2025).

Micro-sprinkler irrigation systems also perform well in orchards. When irrigation timing is optimized, they can improve the uniformity of soil moisture distribution and water storage efficiency. Reducing irrigation time from 24 hours to 19 hours can significantly increase water storage efficiency (from 72% to 89%) and reduce deep percolation losses (Ortega-Farías et al., 2022).

In hilly or semi-arid orchards, constructing rainwater collection systems and infiltration-enhancing measures to guide runoff into the main root zone can increase soil moisture in the 0-60 cm layer by 24%-44%, while also increasing fine root density and yield. This shows good potential under water-scarce conditions (Guo et al., 2021).

5.3 Drainage in rainy seasons and root protection

In regions with concentrated rainfall and high humidity, rapid drainage and root protection are as important as supplemental irrigation. Excess rainfall can raise the groundwater level and cause excessive soil saturation in the root zone, leading to root hypoxia, diseases, and tree decline. Subsurface drainage systems such as buried pipes or blind ditches can significantly reduce soil moisture and groundwater levels, shorten the duration of waterlogging, and increase yield by 6%-8% compared with surface drainage alone (Qi et al., 2025).

Optimizing subsurface drainage spacing can also increase crop yield by promoting root biomass and adjusting aboveground growth allocation, indicating that proper drainage can effectively reduce the negative physiological

effects of excess water. In medicinal plants that are prone to root diseases, rain-shelter facilities can effectively reduce the direct impact of rainfall on soil, lower soil moisture and root rot incidence, and increase soil enzyme activity and beneficial microbial populations, sometimes performing even better than fertilization measures (Abd El-Hafez et al., 2020).

5.4 Technical measures to prevent fruit cracking

Preventing fruit cracking requires careful control of fruit water relations, especially during the rapid fruit expansion and ripening stages. In many fleshy fruits, heavy rainfall or excessive irrigation before harvest can cause a sudden increase in soil or fruit water content, leading to a large water gradient between the peel and the flesh. Applying mild deficit irrigation (80%-100% of full irrigation) at appropriate stages can maintain or slightly increase yield while improving water productivity. This approach works well around the flowering period but is not suitable during the late fruit expansion stage (Wen et al., 2023).

6 Fruit Quality Improvement Techniques

6.1 Measures to improve fruit size, color, and sugar content

Compared with open-field cultivation, greenhouse cultivation significantly increases single fruit weight, fruit diameter, soluble solids content, and the sugar–acid ratio of bayberry. This is mainly due to enhanced sucrose accumulation and increased activity of related enzymes, indicating that optimizing the microclimate and carbohydrate metabolism is a key way to improve fruit size and sweetness (Wu et al., 2021). In Chinese bayberry, the use of insect-proof and rain-proof nets can increase fruit diameter and weight by 22.6% and 82.4%, respectively, with the proportion of high-grade fruit exceeding 91%. At the same time, soluble solids and sucrose content are increased while titratable acidity is reduced. This shows that isolating fruit from rainwater and pests not only protects the fruit but also promotes sugar accumulation and flavor balance (Yu et al., 2021) (Figure 1). Under controlled light conditions, supplementing with LED light can significantly increase fruit weight, fruit diameter, soluble solids, and vitamin C content in the ‘Black Charcoal’ bayberry cultivar, while reducing organic acid content. This again highlights the key role of light quality and intensity in determining fruit size and sweetness (Tang et al., 2025).

6.2 Nutrient management during fruit expansion stage

Nutrient management during the fruit expansion stage should meet the high demand for carbohydrates, nitrogen, and mineral elements, while avoiding excessive promotion of vegetative growth. The soluble solids content and sugar–acid ratio of greenhouse-grown bayberry are higher than those in open-field cultivation, which is closely related to the increased activities of sucrose phosphate synthase and acid invertase. This suggests that maintaining leaf photosynthesis and the activity of sugar metabolism enzymes during the fruit expansion stage can directly improve fruit sweetness and flavor (Wu et al., 2021). Insect-proof and rain-proof nets not only protect bayberry fruits from pests and cracking, but also alter the microbial community structure on the fruit surface, which is beneficial for carbon and nitrogen metabolism and mineral transport. In other fruit trees, a balanced supply of nitrogen and potassium (often combined with biofertilizers) can promote fruit enlargement and increase soluble solids and vitamin content. However, excessive nitrogen in the later growth stage may delay coloration, dilute sugar content, and increase the risk of diseases (Kumar et al., 2022; Zahid et al., 2022).

7 Integrated Pest and Disease Management Measures

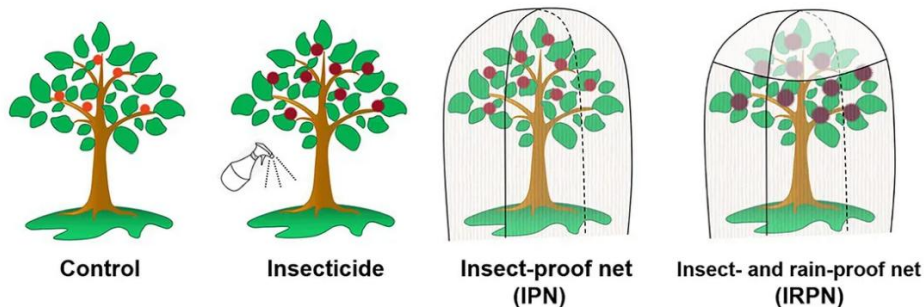
7.1 Identification of major pests and diseases in waxberry orchards

Waxberry is seriously threatened by twig blight, mainly caused by *Pestalotiopsis versicolor* and *P. microspora*. These pathogens have been confirmed as the key agents responsible for large-scale branch dieback in major production areas. In recent years, several other fungi have also been identified as important causal agents of twig blight (Ren et al., 2013; Li et al., 2020; Chen et al., 2021). Meanwhile, new leaf diseases continue to emerge. For example, leaf spot caused by *Nigrospora aurantiaca* shows a relatively high incidence and damage level in commercial orchards, especially on young leaves. This indicates that the disease spectrum of waxberry is expanding, and accurate diagnosis of newly emerging pathogens is critical for timely control (Fu et al., 2025).

A Chinese bayberry trees protected by insect- and rain-proof nets



B Different treatments of Chinese bayberry trees



C *Drosophila* grown on fruits of Chinese bayberry

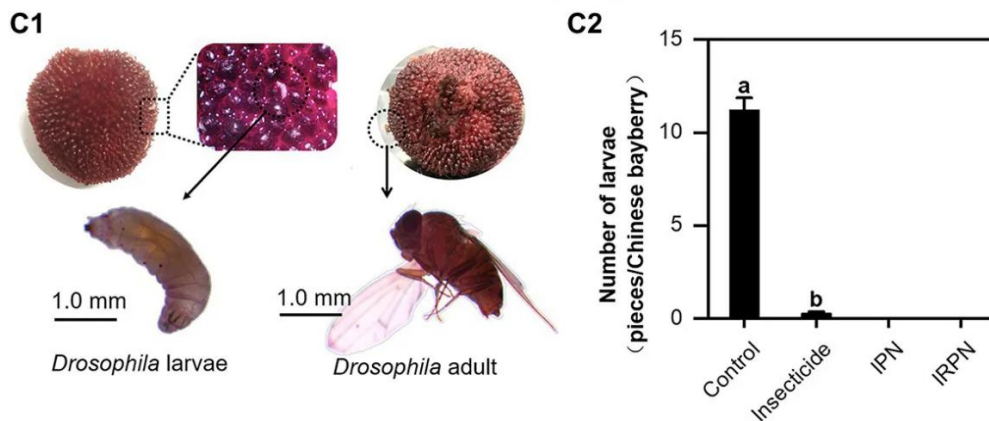


Figure 1 *Drosophila* growth on Chinese bayberry fruits collected from trees grown in different environments. (A) Field image of Chinese bayberry trees protected by insect-proof nets (IPNs) and rain-proof films during the fruit maturation period. (B) The trees were grown under natural conditions (controls) or treated separately with insecticides, IPNs or insect- and rain-proof nets (IRPNs). (C) *Drosophila* (C1) and number of *Drosophila* (C2) on Chinese bayberry fruits collected from untreated and treated trees (Adopted from Yu et al., 2021)

Excessive use of pesticides and antibiotics in waxberry orchards has led to increased residues in soil and along the “soil–fruit–fruit fly” chain. This promotes the accumulation of antibiotic resistance genes and virulence factors in soil and fruit-associated microbial communities, highlighting the need for more restrained and scientifically guided use of chemical inputs (Yi et al., 2024).

7.2 Field monitoring and early intervention

Efficient field monitoring and early intervention are central to IPM systems. Pest and disease management should begin with accurate species identification, followed by a clear understanding of their biology and behavior. Population dynamics and risk levels should be systematically monitored before economic thresholds are exceeded (González-Núñez et al., 2022).

Remote sensing and advanced detection technologies—such as multispectral imaging, UAV platforms, and rapid field diagnostic tools—can detect pest and disease stress before visible symptoms appear. This is achieved through canopy reflectance changes or rapid molecular detection, allowing earlier and more precise spatial interventions while reducing the need for large-scale pesticide applications (Abd El-Ghany et al., 2020; Iost Filho et al., 2020; Buja et al., 2021; John et al., 2023).

7.3 Biological and physical control methods

Biological and physical control methods should be prioritized to reduce reliance on synthetic chemical pesticides. In the control of waxberry twig blight, *Bacillus siamensis* S3 and *B. tequilensis* S5, isolated from the rhizosphere, show strong antagonistic activity against *P. versicolor* (Figure 2). Their culture broth and extracellular filtrates can inhibit mycelial growth by more than 75%-80% and significantly reduce lesion size on detached leaves. Microscopic observations suggest that this inhibition is closely related to the production of chitinase, protease, and lipopeptides such as surfactin, iturin, and mycosubtilin. These strains have potential for development as spray agents or soil treatments and may serve as alternatives or supplements to fungicides (Ali et al., 2020).

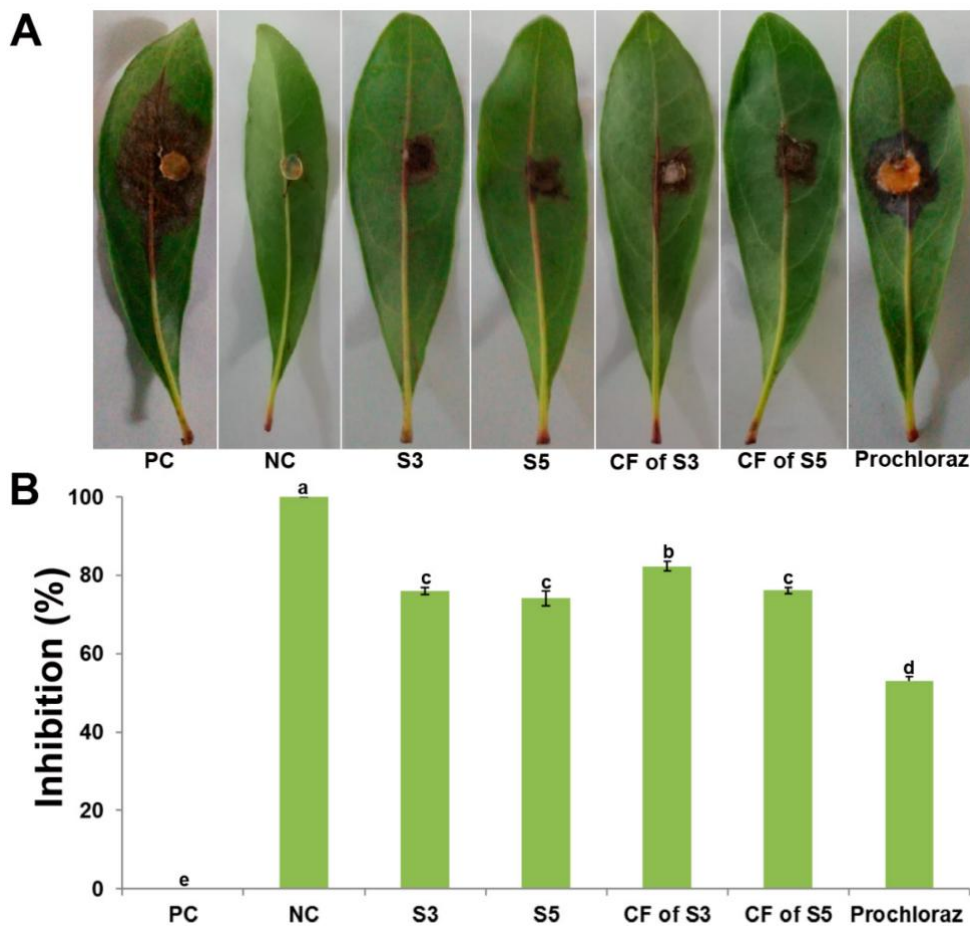


Figure 2 Detached leaf assay for antifungal activity. (A) Effects of antagonistic bacteria and their extracellular culture filtrate on bayberry leaves against *P. versicolor* XJ27. (B) Disease inhibition (%) relative to positive control. Data are mean \pm SE of three replications for each treatment. Same letters are not significantly different at $p \leq 0.05$. For positive control (PC), only the fungal mycelial plug was inoculated. For negative control (NC), a sterile PDA plug without mycelia was used. CF, extracellular culture filtrate. Prochloraz denotes fungicide (Adopted from Ali et al., 2020)

More broadly, biological control strategies—such as the use of antagonistic microorganisms, bacteriophages, microbiome regulation, and engineered biocontrol agents—are becoming key components of sustainable disease management. These approaches should be integrated with resistant varieties, agronomic practices, and limited chemical control (Pandit et al., 2022).

In terms of physical control, insect-proof and rain-proof nets have proven effective in waxberry production. They not only reduce pest damage but also improve fruit size and quality, while lowering infection risks caused by rain splash and mechanical injury (Furmańczyk et al., 2022). Other measures commonly used in organic orchards and IPM systems can also be applied, such as mass trapping, pheromone-based mating disruption, and mechanical removal and pruning of diseased branches.

7.4 Rational reduction of chemical pesticide use

Laboratory screening studies on waxberry twig blight show that prochloraz performs best, followed by pyraclostrobin, difenoconazole-prochloraz mixtures, difenoconazole alone, and myclobutanil (Li et al., 2020). However, excessive use of antibiotics and pesticides in waxberry systems can select for resistant pathogens and pest populations, while also increasing the abundance of resistance genes, mobile genetic elements, and virulence factors in soil, fruit, and associated fruit flies.

Waxberry production should follow these principles: make decisions based on thresholds, rotate modes of action, avoid calendar-based preventive spraying, strictly observe pre-harvest intervals, and prohibit unnecessary antibiotic use. This aligns with the IPM concept, where chemical control is used only as a last line of defense after preventive, biological, agronomic, and physical measures (Bai et al., 2023; Golan et al., 2023).

7.5 Green control technologies

Non-chemical management strategies for berry crops emphasize the central role of biological control, the use of resistant or tolerant varieties, agronomic practices that enhance plant immunity, and improved diagnostic techniques. At the same time, an increasing number of validated commercial biocontrol products are available for effective control of fungal diseases (Taoussi et al., 2024).

Mycoviruses isolated from Pestalotiopsis-infecting fungi in waxberry branches show high diversity and may reduce pathogen virulence (hypovirulence effect), providing a potential resource for a new type of biological control based on “internal regulation” of pathogens (Chen et al., 2021).

The theory and policy of biological control suggest that long-term success depends on balancing production efficiency, ecological function, social acceptance, and economic feasibility. This requires the development of integrated, adaptive, and multi-stakeholder-supported “green” control systems (He et al., 2021).

In practice, green management in waxberry orchards should include: the use of resistant varieties and disease-free seedlings, creation of habitats that support biodiversity, precise application of microbial agents (such as *Bacillus* spp.), use of low-risk inputs and physical barriers, and integration with advanced monitoring and early warning systems.

8 Harvesting and Postharvest Handling Techniques of Bayberry

8.1 Determination of appropriate harvest maturity

Bayberry is a typical climacteric fruit. After harvest, it shows a peak in ethylene release and softens rapidly, especially under room temperature conditions. When fruits are harvested at an “immature” stage or judged as “mature” only by color, they can still exhibit a clear climacteric respiration rise and ethylene peak within 48 hours at 20 °C. At the same time, the contents of sugars and organic acids change significantly. In contrast, fully “mature” fruits do not show a climacteric peak, but they deteriorate and decay quickly. During storage, total soluble solids (TSS) increase, while titratable acidity (TA) decreases. However, if fruits are overripe on the tree, shelf life is shortened and the risk of decay increases (Zhang et al., 2005).

With the development of machine vision and hyperspectral technologies, objective and non-destructive maturity evaluation in the field has become possible. By combining multiple features such as color and texture, maturity prediction accuracy can reach about 91%. The chromatic parameter a^*/b^* ratio is highly correlated with anthocyanin accumulation and visual maturity (Kai et al., 2021; Zheng et al., 2025). Image-based intelligent maturity detection helps determine optimal harvest timing for different varieties and orchard zones, reducing variability within batches and improving allocation between fresh consumption and processing markets.

8.2 Standardized harvesting methods to reduce damage

Due to the characteristics of bayberry fruit, including high respiration intensity, susceptibility to mechanical damage, and rapid softening, its harvesting method should be similar to that used for berry crops such as strawberries and raspberries, adopting gentle and standardized manual picking practices. Fruits intended for the fresh market should be hand-harvested at the target maturity stage. During harvesting, fruits should be handled carefully to avoid finger pressure damage, and a short fruit stalk should be retained by cutting or gently twisting the fruit during picking. After harvest, fruits should be graded directly in the field and packed into the final packaging containers to reduce repeated handling (Horvitz, 2017; Jain et al., 2023).

Harvesting should be carried out in the early morning or evening when temperatures are lower. Wet fruits should be avoided, because surface moisture increases friction damage and decay (Shah et al., 2023). Increasing harvest frequency (for example, harvesting blueberries every 2-3 days) can effectively reduce the proportion of overripe fruits, minimize cumulative mechanical damage, and significantly improve storage performance (Godara et al., 2025).

8.3 Sorting, packaging, and short-term storage

After harvest, bayberries should be sorted immediately. Fruits with mechanical damage, disease, or those that are immature or overripe should be removed, because mixed batches accelerate decay and act as sources of pathogen spread. Standard postharvest handling includes cleaning, grading, pre-cooling, proper packaging, and refrigerated storage. These steps are key to reducing losses.

For bayberry, shallow and rigid packaging containers should be used to limit stacking height and distribute weight evenly. This helps avoid compression and juice leakage, both of which accelerate microbial spoilage (Kunwar et al., 2024).

Temperature and relative humidity management are especially important. Rapid pre-cooling to the proper storage temperature after harvest is considered the most critical factor in delaying senescence and decay (Palumbo et al., 2022). In areas without a cold chain, low-cost cooling technologies such as zero-energy cooling chambers or “pot-in-pot” systems can be used to provide short-term preservation (Hassan et al., 2025).

8.4 Transportation and preservation technologies

Transportation is the stage where bayberry is most vulnerable. Vibration, collision, and poor temperature control can quickly offset the benefits of earlier careful handling. In many fruits, poor transport conditions and long distances are the main causes of mechanical damage and postharvest losses (Bisht and Singh, 2024).

For bayberry, maintaining a continuous cold chain, using vibration-resistant packaging, and delivering fruits quickly to the market are essential. During loading, transport, and distribution, temperature should be kept at 0 °C-4 °C with high relative humidity to suppress ethylene-induced ripening, softening, and decay (Saeed et al., 2024).

Advanced postharvest technologies provide more options to extend freshness during transportation. Slightly acidic electrolyzed water combined with ultrasound treatment (US + SAEW) can significantly reduce pesticide residues, dirt, larvae, and microorganisms on the fruit surface. It can delay the onset of decay by about 6 days, reduce weight loss and color changes, maintain fruit firmness, improve the sugar-acid ratio, and preserve phenolics, anthocyanins, and antioxidant capacity (Suo et al., 2023). In addition, applying hot air treatment at 48 °C for 3 hours before cold storage can significantly reduce decay by regulating fungal community structure (increasing beneficial endophytes and reducing pathogenic fungi), while maintaining fruit quality (Dai et al., 2021).

9 Practical Development Trends and Optimization Directions

9.1 Application of simple smart orchard tools (monitoring and irrigation control)

Multi-parameter IoT-based orchard monitoring platforms can track real-time data such as air temperature, soil moisture, light intensity, rainfall, and wind speed, and upload them to mobile terminal interfaces. Through more precise environmental regulation, these systems can reduce labor input, stabilize yields, and improve fruit quality (Hu et al., 2025).

In terms of irrigation, integrating soil, plant, and meteorological data into closed-loop or model-based control systems can significantly improve water use efficiency compared with traditional open-loop scheduling methods (Bwambale et al., 2022; Gamal et al., 2025). Smart irrigation platforms based on cloud computing and IoT show that connecting multiple small-scale farms to a centralized data analysis system helps optimize water allocation and supports climate-adaptive agricultural production in water-scarce regions (Et-Taibi et al., 2024). For the waxberry industry, priority should be given to promoting cost-effective tools such as soil moisture sensors, simple weather stations, and mobile data platforms to support fertilization and irrigation decisions, rather than relying on high-end automated systems that are difficult for small farmers to maintain.

9.2 Expansion of eco-friendly orchard models

Moderately reducing nitrogen and phosphorus inputs in waxberry orchards can improve soil quality (e.g., slowing acidification and increasing organic carbon levels) without affecting yield or fruit quality, indicating that optimized fertilization can achieve both production and ecological goals.

Introducing ryegrass as a cover crop under the waxberry canopy can significantly increase fruit sugar, vitamin C, and flavonoid content, while also improving soil physicochemical properties, rhizosphere microbial community structure, and secondary metabolism, which overall benefits orchard ecosystem optimization (Li et al., 2023).

More broadly, plant growth-promoting microorganisms and biofertilizers are important components of sustainable orchard systems. When combined with organic amendments, conservation agriculture, and agroforestry practices, they can effectively promote nutrient cycling, improve soil health, and enhance system resilience (Freitas and Silva, 2022). Agroforestry systems based on fruit trees, which combine fruit production with crops or livestock and optimize resource use throughout the life cycle, are considered an effective approach to improving orchard sustainability. Model tools are already available to design such systems under different soil and climate conditions (Barbault et al., 2024). In major waxberry-producing regions, eco-friendly orchard models that integrate cover crops, reduced and precise fertilization, biofertilizer use, and structural diversification should be promoted to achieve both high-quality fruit production and low environmental impact.

9.3 Integration with agritourism and brand building

Agritourism centered on orchards has been shown to bring clear socio-economic benefits. It not only provides additional income for farmers and creates jobs, but also promotes environmental and cultural sustainability through visitor education and nature-based experiences. Participatory activities such as fruit picking, science popularization displays, and direct farm sales can significantly increase tourists' willingness to purchase local agricultural products (Brune et al., 2021). From a destination perspective, value co-creation in agritourism—through visitor participation, interaction, and “citizen behavior”—can significantly enhance the brand equity of rural tourism destinations via enjoyable experiences, meaningful experiences, and perceived value (Zhou and Chen, 2023).

Successful agritourism regions often rely on producer cooperation networks, shared marketing platforms, and recommendation mechanisms. Digital marketing tools such as social media, visual storytelling, and online reviews further strengthen the attractiveness of agritourism destinations and support personalized experiences (Kulikova et al., 2024). For the waxberry industry, combining orchard production with seasonal picking festivals, ecological orchard education activities, processed product tasting, and unified regional branding can simultaneously increase farmers' income and enhance the brand value of “high-quality waxberry.”

9.4 Directions for orchard standardization improvement

Sustainable orchard systems based on clear principles of nutrient management and soil biodiversity have already provided a technical basis for developing standards in fertilization, cover crop use, biofertilizer application, and soil protection. With the rapid development of smart agriculture and IoT technologies, it is necessary to establish unified monitoring indicators, threshold settings, data formats, and decision rules, so that even simple systems can be connected to regional decision support and benchmarking frameworks (Ali et al., 2023).

Eco-farms that successfully integrate with rural tourism usually rely on clear market demand orientation, endogenous development motivation, resource endowment, technical support, and resource integration. This suggests that establishing clear standards for product quality, service design, and environmental performance can promote the integration of agriculture and tourism and drive farm upgrading (Xiao et al., 2025).

Future optimization of the waxberry industry should focus on establishing standardized systems for varieties and rootstocks; regulating ecological fertilization, cover crop planting, and biological control practices; defining basic monitoring and irrigation control requirements; and aligning production standards with agritourism service standards and branding systems. At the same time, coordinated support from policies, technology extension, and producer organizations is needed, along with dynamic updates, to ensure the continuous development of waxberry orchards toward an integrated system that is smart, eco-efficient, and market-oriented.

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