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# Study on Precision Fertilization and Regulation Technology for Improving Bayberry Fruit Quality

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**Abstract** Bayberry (*Myrica rubra*) is a commercially valuable fruit crop widely cultivated in subtropical regions, China is the main producer of Bayberry. But its fruit quality and yield are often inconsistent due to variable environmental and management factors. In this study, we investigated precision fertilization and regulation technologies to enhance bayberry fruit quality through integrated approaches that included soil and foliar nutrient diagnostics, controlled-release fertilization strategies, and the application of remote sensing and geospatial tools. We also explored regulatory techniques such as the use of plant growth regulators, optimized irrigation practices, and canopy management to improve nutrient distribution and fruit development. Smart agricultural technologies, including IoT sensors and machine learning-based nutrient scheduling models, were employed to refine fertilization timing and decision-making. A case study conducted in Southeast China demonstrated that these integrated technologies significantly improved fruit size, sugar-acid balance, and yield stability. Our results indicate that precision fertilization and regulation not only improve fruit quality and economic returns for farmers but also reduce environmental impacts, offering a sustainable framework for bayberry cultivation. Future research should focus on developing region-specific nutrient models and enhancing technology accessibility for smallholders.
**Keywords** Bayberry; Precision fertilization; Fruit quality; Smart agriculture; Sustainable horticulture

## 1 Introduction

Bayberry (*Myrica rubra*) is a fruit with great economic value. It is particularly important in many areas where people rely on fruit tree cultivation to sustain their lives and develop agriculture. In China, Bayberry is mainly distributed in the Yangtze River Basin and other southern regions, with a cultivation area of 75 000 $hm^2$ and a yield of 346 000 tons in Zhejiang Province. The ripening period of Bayberry fruit is between mid to late June and early July, which coincides with the off-season of fruits throughout the year. Bayberry fruit can effectively fill people's fruit gaps, and it has a bright color, unique flavor, and high nutritional value. It is a very popular fruit among people, which has also driven the development of planting industry in underdeveloped mountainous areas and semi mountainous areas, becoming an important part of the local economy and fruit tree industry.

However, there are still many difficulties in steadily improving the yield and quality of bayberry. Traditional fertilization and watering methods are often inefficient, easily causing nutritional imbalances and causing some environmental problems. These problems affect the size, taste and nutrition of the fruit. Bayberry's nutritional needs are complex in themselves, and the soil and plant conditions often change, making cultivation more difficult. It is not easy to achieve sustainable development while ensuring quality (Lu et al., 2022; Wang et al., 2023).

Now, precision fertilization and regulation technology is considered a good way to solve these problems. This technology uses some advanced sensors, data analysis tools and equipment that can change the amount of fertilizer to accurately replenish nutrients and water to plants according to the needs of fruit trees at different stages. Doing so can not only improve the quality and yield of the fruit, but also improve the efficiency of fertilizer and water use, reduce waste and environmental pollution (Singh et al., 2024; Xing and Wang, 2024). At the same time, real-time monitoring and decision support systems also help farmers to better manage and find a balance between economic benefits and environmental protection (Kumar et al., 2024).

The purpose of this study is to summarize the current research results on precision fertilization and regulation in bayberry cultivation, especially their impact on fruit quality and sustainable development. We will evaluate the effects of these nutrient and water management methods, identify key technical innovations, and propose directions for further research in the future. The promotion of these technologies will help to achieve stable bayberry yield and improved fruit quality, while promoting the long-term development of the entire industry.

## 2 Factors Affecting Bayberry Fruit Quality

### 2.1 Soil nutrient availability and heterogeneity

The different nutrient content and distribution in the soil will directly affect the quality of bayberry fruit. If the nutrients are unevenly distributed, the size, sweetness and nutritional content of the fruit will vary. For example, the sugar and amino acid content in different varieties of bayberry fruit is significantly different, and these differences may be related to soil nutrients and planting management methods (Zhang et al., 2011). In order for the fruit to grow well and have high quality, it is necessary to ensure that the nutrient supply is sufficient and balanced.

### 2.2 Climate variability and its impact on flowering and fruiting

Climate factors such as temperature and humidity directly affect the flowering, fruiting and ripening of bayberry. If the climate changes, it will affect when the fruit matures, the accumulation of sugar and acid, and the taste of the fruit. For example, studies have found that the temperature during storage will change some physiological indicators of bayberry and affect the retention of nutrients (Figure 1). Lower temperatures can better maintain the quality, color and nutrition of the fruit (Xun and Mei, 2013). Therefore, it is important to manage climate conditions well before and after harvesting so that the quality of the fruit can be more stable.


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)

### 2.3 Physiological and genetic characteristics influencing fruit development

Different varieties of bayberry have different genes, so the quality of the fruit will also be different, such as sugar content, amino acids, fruit size, color and ripening time (Dai et al., 2012). In addition, wax synthesis on the peel and some key metabolic activities will also affect the fruit's water retention capacity, disease resistance and storage time, which will affect the overall quality of the fruit (Wu et al., 2023). Therefore, selecting varieties with good physiological properties and excellent genetic characteristics is the key to improving fruit quality and consistency.

## 3 Advances in Precision Fertilization Technology

### 3.1 Site-specific nutrient diagnosis using soil and foliar analysis

Today's precision fertilization technology increasingly emphasizes soil and leaf analysis. Through these analyses, it is possible to more accurately determine how to fertilize. Modern sensing technologies such as ion-selective electrodes, colorimetry, and spectroscopy can measure the amount of major nutrients such as nitrogen, phosphorus, and potassium even in relatively complex fields. These tools can help us understand the nutritional status of plants in real time and facilitate the formulation of more appropriate fertilization plans. This not only solves the problem

of different nutrients in different parts of the field, but also allows plants to better absorb nutrients, thereby improving the quality of fruits (Silva et al., 2024; Singh et al., 2024). If the results of soil and plant analysis are used in conjunction with a decision support system, the accuracy of fertilization recommendations and the best time to fertilize can be further improved (Chen et al., 2014; Lu et al., 2022).Taizhou Huangyan Pingtian Fengling Bayberry Professional Cooperative, based on more than ten years of Bayberry planting practice, has concluded that fertilization to the roots should be stopped 25 to 30 days before the fruit matures. However, when the leaf color turns white, foliar fertilizer should be applied to fully utilize leaf photosynthesis to supply nutrients to the fruit. This type of Bayberry has better quality and taste.

### 3.2 Controlled-release fertilizers and timing optimization

Controlled-release fertilizers and the timing of fertilization are very important to ensure that crops can absorb enough nutrients as needed. For example, nanofertilizers, coated fertilizers, and some fertilizer technologies that can be released slowly can make nutrient supply more stable, reduce fertilizer loss, and improve utilization efficiency (Munir et al., 2024). If these technologies are used in conjunction with variable fertilization and integrated water-fertilizer systems, fertilizers can be delivered to the roots on time when crops need nutrients, which can not only help the fruit continue to grow, but also reduce the impact on the environment (Dilshika et al., 2024). In addition, predictive models and time analysis tools can also help us arrange fertilization plans more scientifically to adapt to changes in different weather and crops (Xing and Wang, 2024).

### 3.3 Integration of remote sensing and geospatial tools in fertilization planning

Remote sensing and geospatial technologies are now also being applied to fertilization planning, changing the past single management approach. High-resolution images taken by satellites and drones, such as multispectral images, thermal imaging, and radar images, combined with machine learning algorithms, can clearly show changes in soil properties, crop health, and nutrient distribution (Avola et al., 2024; Gheorghe et al., 2025). These technologies allow us to use variable rate fertilization technology (VRT) to accurately place fertilizers where and when they are needed according to the actual conditions of different locations. Remote sensing technology can also be combined with different interpolation methods to improve prediction accuracy while preserving the differences in fertilization management in different places (Radočaj et al., 2022; Nie et al., 2024). The use of these digital tools not only improves resource utilization, but also increases yields and reduces environmental impact (Fue et al., 2025).

## 4 Regulatory Strategies for Enhancing Fruit Quality

### 4.1 Use of Plant growth regulators (e.g., GA, ABA) in fruit development phases

Plant growth regulators (PGRs), such as gibberellins (GA) and abscisic acid (ABA), are critical for regulating fruit quality. Substances such as ABA, jasmonic acid, and brassinolide can promote the increase of anthocyanins after external spraying, making the fruit better in color and higher in nutritional value. Regulators such as ethylene, auxin, cytokinin, and GA not only affect the synthesis of anthocyanins, but also affect other aspects of fruit quality such as size, firmness, and sweetness. Different application times, concentrations, and methods will affect the final effect, and improper use may cause problems, such as causing plant physiological disorders (Hajam et al., 2018; Wang et al., 2022). Therefore, understanding the mechanism of action of these regulators in regulating gene expression and metabolism will help us use them more scientifically and efficiently in fruit tree cultivation (Chen et al., 2020; Rafiq et al., 2025).

### 4.2 Water management techniques coupled with nutrient regulation

Water regulation is also important, especially regulated deficit irrigation (RDI), which is a good way to find a balance between yield and quality. Studies have shown that moderate RDI can increase fruit weight, firmness, and sugar, soluble solids, and pigment content, thereby improving the nutrition and taste of the fruit. If water management and precise nutrient regulation are combined, resources can be used more efficiently, helping the fruit to develop better while maintaining the sustainability of production. These measures can be used together to save water without reducing quality, and can even improve fruit quality, which is especially useful in water-scarce areas (Xu et al., 2024).

### 4.3 Pruning and canopy control to optimize nutrient partitioning

Pruning and controlling the structure of the crown are important practices to help fruit trees better distribute nutrients. Proper pruning allows fruit trees to better absorb sunlight and helps ventilation, so that the fruit can get more nutrients. By cutting off some excess branches, the tree can transfer more nutrients to the growing fruits and reduce nutrient competition between branches. In this way, the size, color and uniformity of the fruit will be more ideal. Crown management can also reduce the adverse effects of weather changes and is conducive to precise fertilization and irrigation operations. These methods, combined with modern agricultural technology, can help us continue to grow high-quality fruits and increase the yield of the entire orchard (Yadav et al., 2023; Bacelar et al., 2024). The Dongkui, which has a relatively high and large canopy, is best pruned with three-dimensional concave convex wavy and large branch pruning. This can transform the surface shape of the Bayberry tree from a round head shape to a three-dimensional concave convex shape, increase the number of fruiting branches in the inner and lower parts of the crown, and improve the yield and quality of Yangmei (Figure 2) (Huang and Liang, 2020).

Figure 2 The bayberry (Dongkui) concave convex pruning technique (Photo by Jindao Huang)
Image caption: A Concave convex pruning; B Mature Performance

## 5 Role of Smart Agricultural Technologies

### 5.1 Decision support systems for nutrient scheduling

Decision support systems (DSS) are helping farmers make better fertilization decisions. These systems combine data from soil conditions, crop status, and weather to optimize fertilization methods. The system uses data analysis and predictive models to give accurate fertilization recommendations, which can improve efficiency and reduce environmental impact. For example, some DSS platforms can process real-time field data and then tell farmers where and how to apply fertilizer, which can increase yields and use resources more rationally (Bacenetti et al., 2020; Cesco et al., 2023). DSS can also be connected to farm management tools and open data platforms to enable farmers and agricultural technicians to make more informed decisions (Cambra-Baseca et al., 2019).

### 5.2 IoT-based sensors for real-time monitoring of soil and crop status

Internet of Things (IoT) technology has been widely used in agriculture. Tools such as wireless sensors and automatic monitoring devices can monitor various data in the field online, such as soil moisture, nutrient concentration, pH and temperature. The information collected by these sensors is uploaded to the cloud platform, which can then be viewed remotely and fertilized automatically according to the needs of the crops (Rehman et al., 2022; Jani and Chaubey, 2024; Rajagopalakrishnan et al., 2025). This system can greatly reduce manual operations and avoid fertilizer waste. Once problems are found, they can be dealt with in time, thus ensuring efficient and environmentally friendly growth of crops (Shaikh et al., 2022; Pathmudi et al., 2023; Rajak et al., 2023).

### 5.3 Machine learning and modeling tools for predictive fertilization

Now, more and more people are using machine learning and modeling tools to predict the most appropriate fertilization. These tools can process large amounts of data from sensors, remote sensing, and past records, and then analyze what nutrients crops need and when, and make personalized fertilization arrangements (Agrahari et al., 2021). For example, by combining hyperspectral imagery and machine learning technology, it is possible to accurately determine whether crops are lacking fertilizer, especially nitrogen fertilizer, and then manage them in a

targeted manner (Hassan et al., 2021). Predictive models can also be used in the "digital twin" system of agriculture, which can help farmers make arrangements in advance by simulating different situations and improve the sustainable development of agriculture (Maraveas, 2022).

## 6 Case Study of Bayberry in Southeast China

### 6.1 Background and context: region profile and challenges before intervention

Southeast China, especially Zhejiang and Fujian, is an important region for growing bayberry (Ren et al., 2013). Before the introduction of precision fertilization and regulation technology, orchards in these areas encountered many problems. For example, bayberry has a long young fruit period and matures late. Sometimes the fruit setting rate is very low or even no fruit is produced. Traditional management methods cannot solve these problems, but make the situation worse. The fruit quality is unstable, the size varies greatly, and the sugar-acid ratio is not good. These problems limit the yield and affect the market value.

### 6.2 Implementation of integrated precision fertilization and regulation approach

To improve these conditions, the local government began to use a comprehensive approach to manage bayberry orchards. This approach includes many practices, such as spraying plant growth regulators, scientific pruning, thinning out excess fruits, retaining low branches, introducing pollinators, scientific fertilization, soil cultivation, and good pest and disease control. The use of plant growth regulators and improved fertilization plans aims to make nutrient supply more in line with the needs of bayberry at different growth stages (Figure 3). Pruning and canopy management help to make sunlight more even and distribute nutrients more reasonably. Arranging pollinators and good pest and disease management help improve the overall health of the tree and promote normal fruit growth (Lei, 2014).

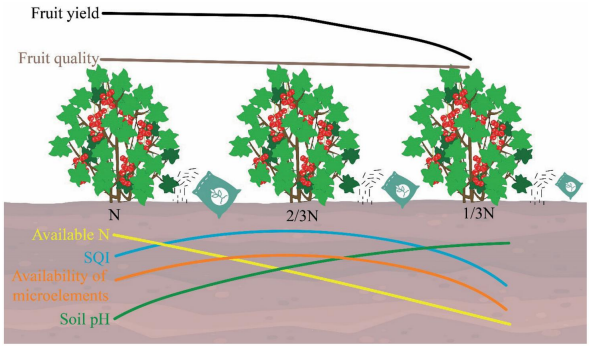


Figure 3 Conceptual graph to elucidate effects of chemical N fertilizer reduction on soil properties, soil quality index (SQI), and fruit yield and quality (Adopted from Chen et al., 2025)

### 6.3 Results: improvements in fruit size, sugar-acid ratio, and yield consistency

After adopting precision fertilization and regulation methods, the yield of bayberry has increased significantly. The fruiting condition in the orchard is better, the fruit is larger, and the yield each season is more stable. The optimization of plant growth regulators and nutritional management has improved the quality of the fruit and the ratio of sugar and acid is more appropriate. At the same time, scientific pruning and crown management have improved the uniformity of the fruit and strengthened the production capacity of the entire orchard, solving the problem of low fruit yield and large differences (Zeng et al., 2017).

## 7 Environmental and Economic Impacts

### 7.1 Reduction in fertilizer waste and nitrate leaching

Precision fertilization, especially variable rate fertilization, can greatly reduce fertilizer waste and nitrate loss. This method arranges fertilizer application according to the actual situation of different areas in the field, rather than spreading it evenly. This not only reduces the amount of fertilizer applied, but also allows fertilizer to be absorbed by plants more effectively, while reducing the risk of nitrogen fertilizer entering the environment. Studies have found that compared with traditional fertilization methods, the use of precision fertilization technology can reduce nitrogen fertilizer use by up to 19%, greenhouse gas emissions are also reduced by about 13.6%, and energy

efficiency is improved (Bacenetti et al., 2020; Jovarauskas et al., 2021). These effects are mainly due to the more precise application of fertilizers, which is no longer randomly spread, thus reducing the problem of overapplication and fertilizer loss with water (Núñez-Cárdenas et al., 2022; Medel-Jiménez et al., 2023).

### 7.2 Economic benefits for farmers from quality premium pricing

Precision fertilization not only helps farmers save money on fertilizer, but also improves crop quality and makes it easier for farmers to enter the high-end market. Economic data show that even if fertilizer use does not increase or even decreases, precision fertilization can increase yields by about 14% and profit margins by 6% or more (Kjærsgaard et al., 2022; Romano et al., 2024). Changes such as more uniform fruit size and a more ideal sugar-acid ratio will make the product sell better and the unit price higher, and the farmer's total income will naturally increase (Saikinov et al., 2024). In addition, because inputs are reduced and efficiency is improved, farmers' overall income is more stable and sustainable (Loures et al., 2020; Bahmutsky et al., 2024).

### 7.3 Contribution to sustainable orchard management practices

Precision fertilization is an important method for orchards to achieve sustainable development. It can help maintain soil health, reduce environmental pollution, and save resources through efficient monitoring tools, data analysis systems, and localized measures (Finger et al., 2019). This practice is also consistent with the sustainable development goals advocated by everyone now. It can not only reduce greenhouse gas emissions, save water and fertilizer, but also ensure that the yield does not decrease, and even improve the quality of crops (Bhakta et al., 2019). In addition, combining digital technology and data management can also make orchards more adaptable to climate change or extreme weather (Xing and Wang, 2024).

## 8 Challenges and Future Directions

### 8.1 Limitations in current adoption of precision technologies among smallholders

Many smallholder farmers are still unable to use precision fertilization technology, mainly because of many practical difficulties. These difficulties include not being able to use digital tools, not being able to afford new equipment, not knowing how to operate the system, and problems such as inaccurate data or lack of supporting infrastructure. Smallholder farmers have few resources and insufficient technical support, so they find it difficult to truly use advanced methods such as sensors, variable fertilization, and data management (Xing and Wang, 2024; Fue et al., 2025). In order for this technology to be truly popularized, these economic, technical, and basic conditions must be resolved so that more people can afford and use it.

### 8.2 Need for region-specific fertilization models and calibration datasets

Because the soil environment varies from place to place, and the needs of crops in different regions are also different, it is necessary to establish fertilization models and data standards that are more in line with local conditions. Some current precision fertilization systems often find it difficult to cope with the complex changes in the agricultural environment. Without local adjustments, the fertilization recommendations given by the system may not be very accurate. For these technologies to really work, more accurate local data must be available, and local soil, weather, and crop characteristics must be taken into account. To improve the accuracy and reliability of the technology, the key is to combine advanced sensing technology with local data on the basis of formulating unified indicators (Radočaj et al., 2022; Silva et al., 2024).

### 8.3 Future research priorities in nutrient signaling and quality trait expression

Future research directions can focus more on studying how crops receive and process nutrient signals, and how these signals affect fruit quality. Current smart sensors, machine learning, and new materials have provided some tools that allow us to more accurately monitor and control nutrient supply, but further research is needed to link these nutrient changes with quality changes in crops such as bayberry. If changes in soil microorganisms, biochemical indicators, and real-time monitoring technology can be combined, yields and fruit quality can be better improved. To promote the in-depth development of this type of technology, it is not enough to rely on one field. It requires cooperation among multiple disciplines to make new breakthroughs in scientific research and practical applications of precision fertilization, and truly achieve high-quality and sustainable fruit production (Yao and Ye, 2025).

## 9 Concluding Remarks

Precision fertilization is changing the way bayberry is grown. It can deliver the nutrients that plants need precisely at the right time and in the right place. This method solves some old problems of traditional fertilization, such as over-fertilization, uneven nutrient distribution, and environmental pollution. Through tools such as remote sensing technology, variable fertilization, and data analysis, precision fertilization can make the fruit size more ideal, the sugar-acid ratio more reasonable, and the yield more stable. At the same time, it can also improve resource utilization efficiency, reduce fertilizer waste and environmental impact. These changes not only improve the quality of the fruit, but also allow growers to earn more.

Now, the precision fertilization technology used in bayberry is also increasingly used in the cultivation of other fruit trees. Nutrient management methods that combine organic fertilizers, inorganic fertilizers, and microbial agents have been proven to improve soil health, increase fruit tree yields, and enhance the adaptability of crops to climate change. Precision agricultural tools such as geographic information systems (GIS), global positioning systems (GPS), and sensor-controlled water and fertilizer systems also help growers achieve more sophisticated field management and reduce resource waste. These practices can make orchards and other perennial crops more efficient and environmentally friendly, which is important for achieving the goal of high-yield and sustainable horticultural production.

The combination of scientific and technological development and digital technology is critical to the future of the horticultural industry. Precision fertilization is a good example. It uses data to guide field management, which not only increases yields, but also reduces environmental pressure and makes farmers more profitable. However, to make better use of this technology, further research is needed, such as establishing accurate models suitable for various regions, increasing the possibility of use by small farmers, and deepening the relationship between nutritional signals and fruit quality. Finally, the integrated development of science and technology will promote fruit tree cultivation towards higher quality, stronger adaptability, and more environmentally friendly directions.

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

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