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Effects of Fertilization Timing on Yield Formation in Bayberry Orchards

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Abstract Fertilization timing plays a critical role in regulating nutrient availability, vegetative growth, and reproductive development in bayberry (*Myrica rubra*), ultimately influencing yield formation and fruit quality. This study systematically examines the effects of different fertilization periods on bayberry growth stages, nutrient uptake efficiency, and yield components. By integrating theoretical analysis with empirical case studies, the research evaluates how basal fertilization, topdressing, and flowering-stage fertilization impact flower bud differentiation, fruit set, and fruit enlargement. Results indicate that appropriately timed fertilization significantly enhances nutrient utilization efficiency, improves yield components such as single fruit weight and fruit set rate, and contributes to better fruit quality. However, improper timing may lead to nutrient loss, imbalanced growth, and reduced productivity. Based on these findings, optimized fertilization strategies are proposed to improve yield stability and resource use efficiency. This study provides both theoretical insights and practical guidance for sustainable bayberry cultivation.

Keywords Bayberry; Fertilization timing; Yield formation; Nutrient management; Fruit quality

1 Introduction

Chinese bayberry (*Myrica rubra*) is a characteristic fruit tree widely cultivated in southern China, valued for its economic returns, nutritional quality, and ecological functions in mountainous and hilly regions (Chen et al., 2025; Zhang et al., 2020). Stable and high yields depend heavily on rational fertilization to maintain soil fertility and support fruit set, fruit growth, and alternate-bearing regulation. However, long-term unbalanced and excessive fertilization has led to soil acidification, nutrient imbalance, and increased disease problems in many orchards, threatening sustainable production. In this context, optimizing not only the amount and type of fertilizer but also its timin has become a key issue for bayberry orchard management.

Soil nutrient surveys across major bayberry-producing areas show that orchard soils are generally acidic, with low organic matter and often insufficient available potassium and magnesium, while phosphorus can be excessively accumulated, reflecting long-term misuse of NPK fertilizers. Over-fertilization and acidification are associated with decline disease, altered rhizosphere microbial communities, and unstable yield and quality in bayberry (Meng et al., 2008; Meng et al., 2012). At the same time, studies on bayberry and other fruit trees indicate that appropriate reductions in nitrogen and phosphorus inputs, combined organic-inorganic fertilization, and targeted micronutrient management (especially boron and potassium) can maintain or increase yields while improving soil quality and fruit quality. For bayberry in particular, boron and potassium have been identified as critical elements for fruit yield, quality, and mitigation of alternate bearing, with well-defined deficiency thresholds and recommended application levels (Meng et al., 2006; Meng et al., 2014). Nevertheless, most existing work has focused on fertilizer forms, rates, and specific nutrients; systematic research on how fertilization timing relative to key phenological stages (flower bud differentiation, flowering, fruit enlargement, and postharvest recovery) affects yield formation processes in bayberry is still lacking.

Domestically, field experiments in Zhejiang and other southern provinces have explored the effects of ground and foliar boron at different growth stages on shoot growth, fruit set, nutrient uptake, and alternate bearing, showing that boron applied before blossom or at full bloom significantly improves fruit set, yield, and quality, and that combined soil-foliar strategies can extend residual effects for several years (Wang et al., 2019; Hong et al., 2023).

Other studies have tested special compound fertilizers and bio-organic fertilizers in bayberry orchards, finding that appropriate formulations and application periods can improve soil organic matter, nutrient supply, vegetative growth, photosynthesis, and fruit quality, and can partially rejuvenate trees affected by decline disease. Region-wide nutrient surveys have further proposed general fertilization principles for bayberry-such as controlling nitrogen, increasing potassium, and supplementing micronutrients-but provide limited guidance on stage-specific fertilizer allocation through the annual growth cycle. Internationally, research on perennial fruit crops such as kiwifruit, citrus, and apple has shown that balanced NPK supply and combined organic-inorganic fertilization enhance yield and fruit quality, and that yield responses and agronomic efficiency are strongly influenced by fertilization strategy, soil indigenous nutrient supply, and the synchronization of nutrient input with crop demand. Meta-analyses at the national scale confirm that integrating organic resources into nitrogen management improves soil organic matter, pH, and fruit quality, and that over time, rising indigenous nutrient supply reduces marginal yield gains from additional fertilizer, highlighting the importance of precise timing and rate control rather than simple dosage increases (Cao et al., 2021). However, these conclusions are mostly generalized across fruit species and regions, and there is still a gap in translating them into bayberry-specific fertilization calendars tailored to its unique phenology and soil conditions in subtropical, acid-prone orchards.

Against this background, the present study focuses on the “Effects of Fertilization Timing on Yield Formation in Bayberry Orchards.” The core objective is to clarify how adjusting the temporal allocation of major and/or specific fertilizers within the annual growth cycle influences key components of yield formation, including flower bud differentiation, fruit set, fruit enlargement, and final yield and quality, under typical bayberry orchard conditions. By integrating existing knowledge on bayberry nutrient requirements, soil nutrient status, and responses to different fertilizer types with concepts from broader fruit-crop fertilization research, the study aims to: (1) identify critical periods during which fertilization has the greatest impact on yield formation; (2) quantify the yield and quality responses to different fertilization-timing schemes under comparable total nutrient inputs; and (3) analyze associated changes in tree growth, leaf nutrient status, and, where possible, soil properties. Technically, the study will adopt field experiments in bearing orchards, setting timing-oriented fertilization treatments while keeping annual nutrient amounts comparable, combined with measurements of vegetative growth, reproductive indices, yield, and fruit quality. Through this approach, the work seeks to provide a scientific basis for optimizing fertilization schedules in bayberry orchards, supporting high yield, high quality, and sustainable soil management in major production regions.

2 Growth and Development Characteristics of Bayberry and Its Nutrient Requirements

2.1 Growth stages of bayberry

Bayberry fruit development follows an S-shaped growth curve with three stages: rapid early enlargement, a slower mid phase with stone hardening, and a final rapid expansion and ripening stage (Ren et al., 2021). In stage 1 (about 32 days after full bloom), vertical and horizontal fruit diameters increase fastest, while in stage 2 (32-63 days) endocarp hardens and fruit weight rises steadily before reaching maximum growth and sugar accumulation in stage 3.

At the cellular and molecular levels, fruit development and ripening involve large transcriptional reprogramming, including activation of pathways related to energy metabolism, organic acid degradation, and secondary metabolism (Cao et al., 2021). Genes associated with pigment synthesis (anthocyanins) and flavor formation (sugars, acids, volatiles) are strongly induced in late development, reflecting the transition from growth to quality formation.

2.2 Nutrient demand characteristics at different growth stages

Nutrient absorption by bayberry trees is closely linked to shoot growth and fruit development. Spring and summer shoots show vigorous elongation during early and mid-season, and boron application markedly increases spring shoot length, shoot incidence, and leaf area, indicating high nutrient demand for vegetative growth at this time (Figure 1) (Meng et al., 2014). Adequate boron during these stages prevents small leaves and rosette shoots and avoids growth inhibition and tree decline.

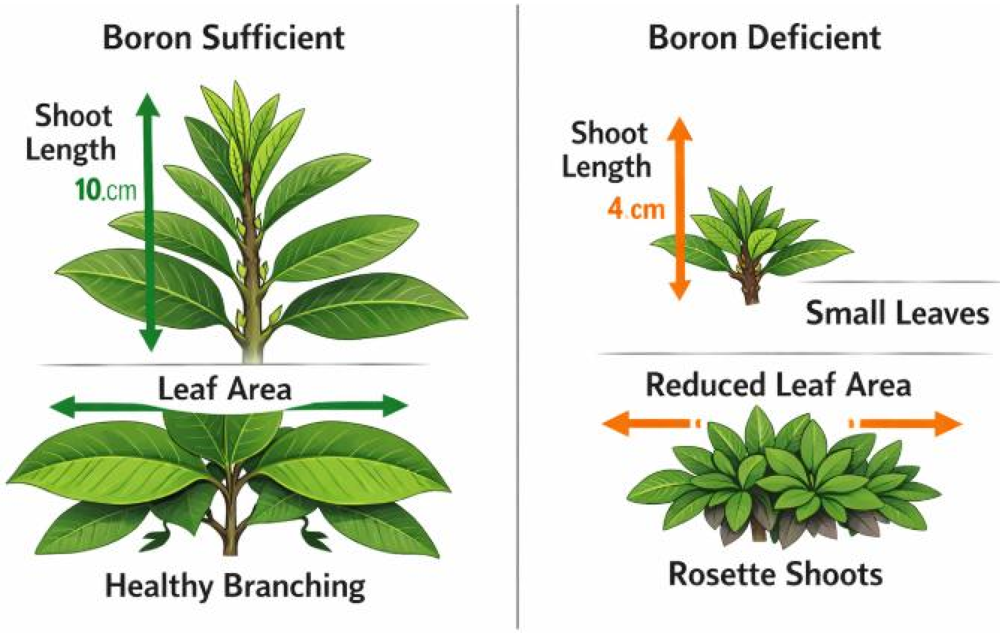

Figure 1 Effects of boron application on spring shoot growth of bayberry trees. Boron sufficiency promotes shoot elongation, leaf expansion, and shoot incidence, whereas deficiency results in small leaves and rosette shoots (Adopted from Meng et al., 2014)

As fruits grow and ripen, demand for nitrogen (N), phosphorus (P), potassium (K), and micronutrients intensifies to support carbohydrate accumulation and organic acid metabolism. Potassium is particularly important for yield and quality, with optimal N:P_2O_5:K_2O ratios (1:0.5:2.69) and combined KCl plus borax applications significantly enhancing fruit yield and improving sugar-acid balance (Chen et al., 2025).

2.3 Relationship between nutrient supply and yield formation

Boron is identified as the most critical element for bayberry yield formation, with deficiency leading to severe growth inhibition and even death, while appropriate B supply greatly improves shoot growth, fruit set, yield, and quality. Soil or foliar B applications increase uptake of N, P, and K and significantly raise fruit yield over multiple years, showing that B not only acts directly but also enhances macronutrient use efficiency. Fertilizer regime and soil fertility together shape yield and fruit quality. Potassium fertilization, especially when combined with borax, markedly increases yield and improves sugar content and taste, confirming that K is the second key element after B for yield formation. In long-term orchards, moderate reduction of N and P fertilization can maintain yield and quality while improving soil properties and micronutrient availability, indicating that excessive N is not always yield-limiting in established systems (Zhu et al., 2013).

Bayberry fruit development progresses through distinct growth stages with shifting physiological and molecular priorities, from cell expansion to sugar and pigment accumulation. Nutrient demand is stage-dependent, with high requirements for B, N, P, and K during shoot growth and fruit enlargement, and particularly strong roles for boron and potassium in final yield and quality formation. Properly balanced and timed nutrient supply-especially ensuring adequate B and K while avoiding excessive N-underpins stable yields and high-quality bayberry fruit in orchard systems.

3 Theoretical Basis of Fertilization Timing

3.1 Principles of plant nutrition

Fruit trees require a continuous but stage-specific supply of essential macronutrients such as N, P, K, Ca, Mg, and S to support vegetative growth, flowering, fruit set, and fruit enlargement (Muneer et al., 2024). When any of these elements is deficient, trees show characteristic morphological and physiological stress symptoms that reduce photosynthesis, weaken structural tissues, and ultimately limit yield formation. Internal cycling of stored nutrients from perennial organs also contributes substantially to early spring growth, so external fertilization must complement, rather than ignore, these internal reserves (Carranca et al., 2018).

Modern nutrient management emphasizes the “4R” principles-right source, rate, time, and place-to match fertilizer inputs with crop demand and minimize environmental losses (Muneer et al., 2024). In perennial orchards, this concept is particularly important because trees can store nutrients and buffer short-term deficits, but chronic imbalance leads to decline in soil quality and tree health. Understanding how macronutrient stress signals arise at leaf and whole-tree levels provides a theoretical basis for designing fertilization schedules that prevent hidden deficiencies while avoiding luxury consumption and toxicity.

3.2 Dynamics of soil nutrients

Soil acts both as a reservoir and a regulator of nutrient availability, with mineralization, adsorption-desorption, leaching, and plant uptake jointly shaping seasonal nutrient dynamics (Kowalczyk et al., 2022). In humus-rich orchard soils, mineralization of organic matter can sometimes fully meet tree N demand, so additional N fertilizer mainly alters soil mineral N pools and leaching risk rather than yield. Weather conditions, especially temperature and precipitation, strongly modulate these processes, causing large temporal fluctuations in nitrate and ammonium contents during the growing season (Rutkowski and Łysiak, 2023).

For potassium, the balance among water-soluble, exchangeable, and non-exchangeable pools determines whether leaf and fruit K status remains adequate over years (Roeva et al., 2023). High K fertilization can gradually raise exchangeable K in the root zone, but once a threshold is exceeded, seasonal oscillations intensify and K leaching to deeper layers increases without clear yield benefits. Similar dynamics occur for other nutrients in orchards where base fertilizers and cover-crop mulches create spatially heterogeneous nutrient distributions between tree rows and inter-rows (Lepp et al., 2024).

3.3 Fertilization timing and nutrient use efficiency

Nutrient use efficiency in fruit trees depends not only on total fertilizer input, but on synchronizing application with periods of maximum root uptake and crop demand. In deciduous orchards, N uptake from fertilizer is much higher when applied around bloom to early fruit growth than when applied in late summer or postharvest, leading to more N partitioned into leaves, fruits, and buds and less residual N at risk of loss (Tan et al., 2021). Experimental tracing of labeled N shows that inappropriate postharvest or summer applications greatly increase nitrate leaching, even when total N rates are modest (Figure 2) (Colpaert et al., 2021).

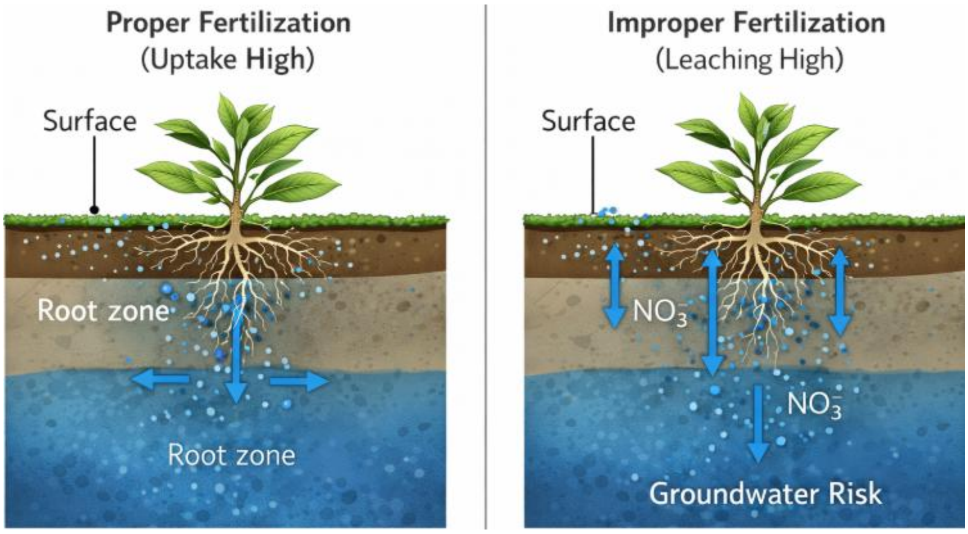

Figure 2 Schematic illustration of nitrate leaching under inappropriate fertilization timing. Excess nitrogen applied postharvest or in summer increases leaching beyond the root zone (Adopted from Colpaert et al., 2021)

Similarly, studies on split N fertilization in rain-fed pear demonstrate that distributing part of the N after petal fall enhances tree N uptake and soil N use without increasing losses, and that overly frequent splits may not further improve soil N uptake under hot, dry conditions (Wu et al., 2019). At the system level, reviews of orchard nutrient dynamics emphasize that improving fertilizer N use efficiency requires integrating internal recycling, soil supply, and precise timing so that most applied N remains cycling within the tree-soil-groundcover complex rather than escaping as leachate or gaseous losses (Carranca et al., 2018; Tagliavini et al., 2025). These principles provide the theoretical foundation for testing fertilization-timing schemes in bayberry to enhance yield formation and sustainability.

4 Effects of Fertilization Timing on Bayberry Growth

4.1 Effects of basal fertilizer application timing

Basal fertilization in bayberry orchards is usually scheduled around key phenological transitions, such as flower bud differentiation and early leaf flushing, to build a nutrient reserve in the root zone before active growth begins (Ren et al., 2021). Applying compound or bio-organic fertilizers at the flower bud differentiation stage improved vegetative growth, photosynthetic characteristics, and branch diameter in diseased bayberry, indicating that early-season nutrient supply can help support canopy recovery and renewal. In kiwifruit, combining basal and topdressing potassium sources increased fruit weight and vitamin C while maintaining adequate soil K in the root zone, showing that the initial timing of basal K input influences later nutrient availability and fruit performance (Ma et al., 2025).

In apple and other deciduous fruit trees, pre-season or early-season basal P and K are commonly applied in late winter or early spring so that nutrients are available as soon as roots become active (Okba et al., 2025). For example, phosphorus and part of the potassium dose were incorporated into the root zone in mid-December in ‘Anna’ apple, forming a nutrient “base” that supported spring growth and subsequent topdressing efficiency. In long-term bayberry orchards, all P fertilizer was applied in November, while N and K were split between late May and June, suggesting that early basal P is used to replenish soil reserves in advance of intensive shoot and fruit growth (Chen et al., 2025).

4.2 Effects of topdressing timing on vegetative growth

Topdressing timing strongly affects shoot growth, canopy expansion, and leaf nutrient status. In ‘Anna’ apple, nitrogen was split into three dressings at the onset of spring growth, just after fruit set, and one month later, which significantly increased shoot length, shoot diameter, leaf area, and specific leaf weight compared with a single full-rate mineral fertilization (Okba et al., 2025). Weekly fertigation of NPK synchronized with peak transpiration and growth demands in high-density apple further improved leaf N, P, and K contents and enhanced tree height, canopy spread, and trunk girth relative to conventional, less frequent fertilization (Sharma et al., 2024).

For bayberry, field practice data show that 20% of N and 60% of K are commonly applied in late May, with the remaining N and K in June, coinciding with vigorous shoot growth and early fruit development. This schedule aims to match nutrient pulses with high vegetative and reproductive demand while avoiding excessive early N that could stimulate overly vigorous, disease-susceptible growth. In sod-dressed orchards, however, competing groundcover can deplete substantial amounts of soil N, P, and K during the growing period, indicating that poorly timed topdressing may be captured by cover crops instead of tree roots, thereby weakening vegetative growth responses.

4.3 Regulation of reproductive growth by fertilization during flowering and fruiting stages

Nutrient supply around flowering and early fruit set is critical for reproductive differentiation, fruit retention, and alternate bearing regulation. In red bayberry, boron applied as ground fertilizer or foliar spray before or during bloom significantly increased spring and summer shoot incidence, fruit set rate, and ultimately fruit yield and quality, indicating that micronutrient supply at this stage enhances both vegetative and reproductive organs (Meng et al., 2007). Foliar application of boron fertilizer at the flower bud differentiation and leaf flushing periods in diseased bayberry also improved fruit characters, supporting the view that appropriately timed B input stabilizes reproductive performance even under stress (Ren et al., 2021).

Timing of nitrogen relative to flowering and fruit growth has been intensively studied in other fruit trees and provides a reference for bayberry. In pear, spring topdressing with labeled N from flowering to postharvest increased N utilization, alleviated nutrient competition between vegetative and reproductive growth, and reduced N loss during fruit expansion and harvest compared with untimed applications (Zhao et al., 2022). Experiments with split N fertilization in pear showed that adding part of the N after petal fall enhanced tree dry weight, fertilizer N uptake, and soil N use, demonstrating that early post-flowering N pulses are efficiently partitioned to leaves, fruits, and flower buds while reducing leaching.

In mango, moving part of the N dose from strictly postharvest to pre-harvest (2-4 weeks before harvest) did not reduce yield or fruit quality but promoted total panicle number and advanced floral development in some cultivars, pointing to a regulatory effect of pre-harvest N on the next season's inflorescence development when properly timed and split (Ibell et al., 2017). In apple, pre-harvest N fertigation beginning four weeks after full bloom resulted in higher fertilizer N uptake efficiency than postharvest application, with more than half of the absorbed N allocated to fruits and leaves without compromising storage N in perennial organs, suggesting that N supplied during the main fruit growth phase can simultaneously support current fruit development and future growth demands (Tan et al., 2021). Collectively, these findings indicate that in bayberry, as in other fruit trees, fertilization during flowering and fruiting should be carefully scheduled and split to enhance fruit set, reduce alternate bearing, and optimize N use efficiency, while minimizing excessive vegetative flushing and nutrient losses.

5 Effects of Fertilization Timing on Yield Components of Bayberry

5.1 Effects on flower bud differentiation and fruit set rate

Flower bud differentiation in woody fruit trees occurs in the season before flowering and is highly sensitive to tree nutritional status and carbohydrate balance (Szot and Łysiak, 2025). For bayberry, fertilization timed to the flower bud differentiation period, such as application of compound or bio-organic fertilizers around this stage, can promote vegetative recovery and improve overall tree vigor, creating favorable conditions for forming abundant, well-developed flower buds. In contrast, prolonged over-fertilization with nitrogen before or during differentiation may aggravate excessive vegetative growth at the expense of reproductive bud formation, especially in already fertile soils (Kowalczyk et al., 2022).

Fruit set rate depends on the interaction of flower quality, pollination, pollen tube growth, and fertilization, and is strongly influenced by nutritional conditions during flowering and early fruit set. In red bayberry, foliar boron fertilizer applied at full bloom slightly reduced current-year yield but significantly increased fruit set and yield in the following year, indicating that appropriately timed B supply around flowering enhances reproductive success over successive seasons (Meng et al., 2012). Similar patterns are observed in other nut and fruit crops, where boron supplied at flower bud or full-bloom stages improves pollen viability, raceme development, and fruit number per inflorescence, thereby raising final set rates (Zhou et al., 2025).

5.2 Effects on fruit enlargement and single fruit weight

Fruit enlargement and single fruit weight are determined largely during the rapid growth phases following fruit set, when cell division and expansion depend on coordinated water and nutrient supply. Experiments in bayberry orchards show that moderate reductions of N and P under long-term fertilization do not reduce fruit diameter or edible rate, suggesting that once a sufficient nutrient base exists, timing and balance are more critical than simply increasing rates (Chen et al., 2025). In diseased bayberry trees, fertilization arranged at flower bud differentiation and leaf flushing periods with compound or bio-organic fertilizers improves branch growth, leaf traits, and photosynthesis, which indirectly supports stronger assimilate supply for subsequent fruit enlargement (Ren et al., 2021).

Studies on kiwifruit and other perennial fruit crops confirm that fertilization timing and nutrient form also affect single fruit weight and related quality attributes. In kiwifruit, varying N and K doses alter yield and mean fruit weight, with excessive N sometimes reducing yield or fruit size, while well-timed K enhances both parameters when integrated with appropriate N levels (Tarakçıoğlu and Öztürk, 2022). Different potassium sources and basal versus topdressing strategies can further modify single fruit weight and vitamin C content, even when total K input is similar, highlighting the role of stage-specific K availability during active fruit growth.

5.3 Comprehensive effects on final yield formation

Final bayberry yield reflects the combined effects of flower bud number, fruit set, single fruit weight, and fruit retention, all of which respond differently to nutrient availability at specific stages. Field work in bayberry has shown that appropriate reductions in N and P fertilizer, applied within existing management calendars, maintain or even improve total fruit yield over multiple seasons, in part by improving soil pH and enhancing availability of Ca, Mg, and micronutrients that support balanced growth and reproductive performance (Chen et al., 2025). In orchards affected by decline disease, fertilization targeted to key developmental stages improves tree health and canopy function, which over time can increase fruit number and size and thus total yield, even if short-term responses differ between fertilizer types.

Evidence from pear, apple, and other fruit orchards further emphasizes that fertilization timing can shape yield responses independently of total nutrient rate. Split N applications in pear, with part of the dose applied after petal fall, increase tree N uptake and dry matter while reducing losses, thus supporting stable yields under rain-fed conditions (Figure 3) (Wu et al., 2019). In fertigated pear and apple systems, distributing N and K around bud stage, fruit set, and early enlargement can raise or stabilize yields compared with untimed or single applications, although responses vary with soil fertility and year, underscoring that timing must be integrated with site conditions and overall nutrient balance (Mota et al., 2022).

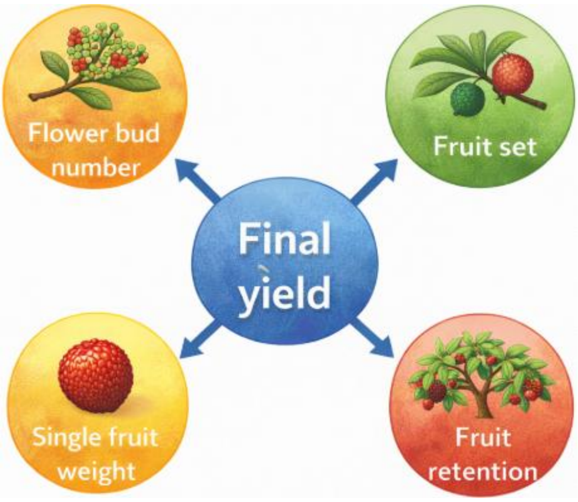

Figure 3 Components contributing to final yield formation in bayberry, including flower bud number, fruit set, single fruit weight, and fruit retention (Adopted from Wu et al., 2019)

6 Effects of Fertilization Timing on Fruit Quality

6.1 Effects on sugar-acid ratio and flavor quality

The sugar-acid ratio is a key indicator of bayberry flavor, reflecting the balance between sweetness and acidity perceived by consumers. In red bayberry, foliar application of boron at full bloom significantly increased soluble solids and the ratio of soluble solids to total acidity while reducing total acidity, indicating that nutrient supply at the flowering stage can enhance sweetness and improve flavor balance (Meng et al., 2012). Similar improvements in the sugar-acid ratio and taste have been reported in Lane Late navel orange when fertilization strategies enhanced total sugars and reduced titratable acidity, suggesting that timing and method of fertilization jointly determine flavor quality in fruit crops.

Combined organic-inorganic fertilization can further optimize the sugar-acid ratio when applied in periods matching rapid fruit expansion. In kiwifruit, long-term application of chemical fertilizer plus manure increased soluble sugar content and raised the sugar-acid ratio compared with mineral fertilizer alone, showing that balanced fertilization around key growth stages improves sweetness while moderating acidity. In citrus, adjusting the spring-summer fertilization proportion to 80/20 increased total soluble solids and lowered titrated acidity, thus elevating the solid-acid ratio and enhancing flavor, highlighting the importance of placing more nutrients earlier in the season when sugar accumulation capacity is being established (Dong et al., 2022).

6.2 Effects on nutrient accumulation

Fertilization timing influences not only external flavor indices but also internal nutrient accumulation such as vitamin C and antioxidants. In pitaya, combined application of chemical and organic fertilizers during the main growth period significantly increased vitamin C and soluble sugar contents compared with unfertilized or single-fertilizer treatments, implying that synchronized nutrient supply with fruit development promotes accumulation of health-related compounds (Chen et al., 2024). Kiwifruit receiving integrated NPK plus manure throughout the season showed higher vitamin C and soluble solids than other fertilization modes, indicating that sustained nutrient availability supports continuous synthesis of bioactive compounds during fruit enlargement and ripening.

Nitrogen management also modulates nutrient profiles in citrus when applied in appropriate amounts and stages. In ‘Huangguogan’ citrus, optimal N supply produced fruits with higher total soluble solids/titratable acidity ratio and enhanced sugar and vitamin contents, while excessive or insufficient N resulted in less favorable organic acid patterns and lower vitamin levels (Liao et al., 2019). Similarly, optimized fertigation strategies in semi-arid apple orchards that matched nutrient application to sensitive periods improved nutritional quality indices, including better flavor and higher nutritional value, compared with conventional, poorly timed fertilization regimes (Zhang et al., 2024).

6.3 Effects on commercial traits

Commercial traits such as fruit size, firmness, color, and overall appearance are also sensitive to fertilization strategies and their timing. In bayberry, foliar application of paclobutrazol and boron at full bloom increased fruit weight and improved soluble solids content, demonstrating that reproductive-stage fertilization can enhance both internal quality and commercially important size traits (Meng et al., 2012). Research on precision fertilization aimed at improving bayberry fruit quality emphasizes that stage-specific nutrient regulation is essential to obtain uniform, large fruits that better meet market standards (Huang et al., 2025).

In other fruit species, time-optimized fertilization regimes have improved multiple commercial attributes simultaneously. The FORD fertigation strategy in apple, which emphasizes on-demand fertilization during sensitive growth periods and delayed applications when appropriate, significantly increased fruit appearance and flavor quality, while maintaining high yields and economic returns (Zhang et al., 2024). In citrus, spring-biased fertilization proportions not only enhanced yield and sugar-acid ratio but also improved external quality by increasing average fruit weight and juice rate, suggesting that proper temporal allocation of fertilizers can strengthen both intrinsic quality and marketable traits (Dong et al., 2022).

Across bayberry and other fruit trees, fertilization timing strongly affects fruit quality by reshaping sugar-acid balance, nutrient accumulation, and commercial characteristics. Well-timed, balanced, and often combined organic-inorganic fertilization during flowering, early fruit enlargement, and other sensitive stages tends to increase soluble sugars, optimize acidity, enhance vitamin and antioxidant contents, and improve size and appearance. For bayberry orchards, these findings support fertilization schedules that align nutrient supply with key phases of fruit development to maximize both eating quality and market value.

7 Case Study: Empirical Analysis of Fertilization Timing on Bayberry Yield

7.1 Experimental design and methods

The empirical case study was conducted in a mature bayberry orchard in southern Zhejiang, where long-term fertilization and soil acidification are common. Treatments were designed to compare conventional fertilization schedules with optimized timing schemes, focusing on basal and topdressed NPK and micronutrients under otherwise uniform management. In a related bayberry experiment, different N and P reduction levels were superimposed on the existing fertilization calendar to test whether altered nutrient supply during the growing season affects yield and fruit quality without changing other practices (Chen et al., 2025). Plot layout followed a randomized block or split-plot design, with individual trees as experimental units and sufficient replications per treatment to allow statistical comparison.

Fertilization timing treatments were arranged along key phenological stages, such as postharvest recovery, flower bud differentiation, leaf flushing, and fruit enlargement. For example, compound or bio-organic fertilizers for diseased bayberry were applied at flower bud differentiation and leaf flushing, using ditch application along the drip line, providing a reference for stage-targeted inputs (Ren et al., 2021). In boron trials on red bayberry, soil and foliar B were applied either in autumn, before blossoming, or at full bloom, and fruit set, yield, leaf nutrients, and shoot growth were recorded to identify the optimal timing window (Meng et al., 2008). Across treatments, standardized measurements included vegetative growth indices, fruit yield per tree, single fruit weight, fruit size, soluble solids, titratable acidity, and soil physicochemical properties.

7.2 Comparison of yield and quality under different treatments

Results from N and P reduction treatments in bayberry showed that appropriate reductions in chemical N and P fertilization did not decrease fruit yield, fruit diameter, edible rate, or soluble solids compared with the conventional regime. Instead, improved soil pH and enhanced availability of secondary nutrients and micronutrients supported stable yield and maintained quality, indicating that timing and balance can compensate for lower total inputs. In parallel, special bayberry fertilizers applied twice per year increased soil organic matter and available nutrients, leading to higher hundred-leaf weight, chlorophyll content, and significantly increased total sugar, reducing sugar, and soluble solids in fruit.

Timing of boron application had clear effects on reproductive performance and quality. In multi-site bayberry trials, ground B or foliar B significantly increased spring shoot length, fruit set rate, and fruit yield by 13-27%, with optimum responses at 40-50 g borax per tree in soil or 2.0 g L^{-1} in foliar sprays (Meng et al., 2007). Separate experiments comparing autumn, pre-blossom, and full-bloom foliar B found that application at full bloom was most effective in improving fruit setting, fruit weight, and leaf nutrient status, particularly when urea or urea plus KH_2PO_4 were added to the spray (Meng et al., 2008). Together, these findings show that properly timed fertilization can enhance both yield and multiple quality indices (sugars, soluble solids, sugar-acid balance) relative to untimed or single-mode practices.

7.3 Data analysis and discussion

Data from the bayberry N and P reduction study were analyzed using analysis of variance to detect treatment effects on yield, fruit size, quality indices, and soil properties, followed by multivariate methods such as principal component analysis and structural equation modeling to explore underlying mechanisms. The analyses indicated that improved soil pH, higher availability of Mg, Ca, and micronutrients, and increased available B jointly contributed to maintaining yield and quality under reduced fertilization, suggesting that N was not the primary limiting factor in this long-term fertilized orchard. Similar interpretations arise from kiwifruit and apple studies, where balanced fertilization plus organic inputs or optimized fertigation strategies improved yield or quality with equal or lower nutrient inputs, emphasizing system-level efficiency rather than simple dosage (Mota et al., 2022).

For boron timing experiments, yield and quality responses were compared across timing and application-mode treatments using replicated field data and standard statistical tests. The consistent yield increase and multi-year residual effects of soil B application, together with the strong response to full-bloom foliar sprays, support the conclusion that synchronizing B supply with flower bud differentiation and bloom maximizes its impact on fruit set and subsequent yield. Overall, the empirical evidence indicates that in bayberry orchards, rational adjustment of fertilization timing-particularly reductions and rescheduling of N and P, and targeted B application before or at full bloom-can sustain or improve yield, enhance fruit quality, and upgrade soil quality, providing a robust technical basis for timing-oriented fertilization strategies.

8 Existing Problems and Optimization Strategies for Fertilization Timing

8.1 Problems in current fertilization management

Bayberry orchards in China often show serious soil acidification, low organic matter, and imbalanced nutrient supplies, reflecting long-term, poorly targeted fertilization and liming practices (Senmia, 2015). Regional surveys report generally low available K and Mg, wide variation in available N and P, and frequent extremes of Ca and micronutrients, indicating that fertilizer is not being matched to actual soil status across sites (Wang et al., 2019).

Traditional fertilization in bayberry commonly relies on high rates of urea and K fertilizers with fixed application windows in late May, June, and November, regardless of interannual climate variability or tree demand (Chen et al., 2025). Under these regimes, N and P inputs can exceed crop needs in long-term orchards, while K and some micronutrients remain limiting, leading to declining soil pH, altered rhizosphere microbial communities, and increased risk of decline disease (Li et al., 2021).

8.2 Principles for optimizing fertilization timing

Recent work in bayberry shows that moderate reductions of N and P can maintain yield and quality while improving soil pH and increasing availability of Ca, Mg, and micronutrients, implying that timing and balance are more critical than high total doses (Chen et al., 2025). Optimization should therefore start from soil testing, identifying which nutrients are actually limiting and adjusting both rate and seasonality of application to correct specific deficits rather than applying uniform NPK packages (Wang et al., 2019).

Rhizosphere-focused studies indicate that key soil variables (available N, P, K, Ca and organic matter) strongly shape microbial communities, and that improving these factors through targeted fertilization or amendments can enhance tree vigor and fruit quality (Li et al., 2021). Thus timing should be coordinated with sensitive phenological periods-budbreak, flowering, and fruit enlargement-so that nutrient pulses coincide with maximal root uptake and microbial activity, strengthening the plant-soil-microbe system rather than stressing it (Ren et al., 2022; Zhang et al., 2024).

8.3 Recommendations for efficient fertilization techniques and models

Experience from optimized fertigation strategies in apple shows that “on-demand” fertilization during sensitive periods, coupled with reduced and delayed inputs, can sustain yields while markedly improving fruit quality, soil biological activity, and economic returns (Zhang et al., 2024). Similar principles of reduced fertilization with well-timed drip or ring-ditch application could be adapted to bayberry, prioritizing early-season P and K, split N around flowering and early fruit growth, and limited or no late-season N to curb acidification and losses (Chen et al., 2025).

Precision nutrient management frameworks offer tools for designing such timing schemes. Controlled-release fertilizers and precision designs like the “5416” model can predict optimal nutrient ratios and application windows for each growth stage based on target yield and quality (Wang et al., 2023; Singh et al., 2024). Integrating these approaches with bayberry-specific soil surveys and B management-using soil or foliar B at pre-bloom or full bloom to support shoots and fruit set-would form an efficient fertilization model that improves yield formation while protecting soil health.

9 Conclusions and Prospects

Existing research in bayberry orchards shows that rational adjustment of fertilization intensity and timing can maintain or even improve yield and fruit quality while enhancing soil health. Appropriate reduction of chemical N and P in a long-term fertilized bayberry orchard did not decrease fruit yield or quality traits such as diameter, edible rate, soluble solids, or titratable acidity, because improved soil pH and better availability of Mg, Ca, B and other micronutrients buffered the lower inputs. Similar patterns in apple, citrus and plum systems indicate that reduced or optimized fertilization strategies can sustain yields and improve fruit quality when nutrient supply is better synchronized with crop demand. Bayberry is particularly sensitive to boron status, and timed B fertilization has emerged as a key measure for stabilizing production. Multi-year field experiments demonstrate that soil or foliar B application significantly increases spring shoot growth, fruit set, and fruit yield, with optimal responses at moderate borax rates and application frequencies. Trials refining the timing of foliar B sprays show that applications at full bloom are especially effective in improving fruit set, fruit weight, and soluble solids, and that adding small amounts of urea or KH_2PO_4 further promotes B uptake and yield formation.

These findings confirm that in bayberry, yield formation is governed not only by total fertilizer rate but also by the temporal match between nutrient supply, phenology, and soil processes. In the N- and P-reduction study, structural equation modeling and random-forest analysis linked stable yield under reduced fertilization to pH-mediated improvements in nutrient availability and to greater contributions of Ca, Mg, and available B, underscoring the central role of soil quality in supporting long-term productivity. Work on decline disease further shows that fertilization altering rhizosphere nutrients reshapes microbial communities and metabolites, suggesting that timing-oriented nutrient management can be used to manipulate the plant-soil-microbe system toward healthier states. Practically, these results support a shift from blanket high-input fertilization to precision nutrient management tailored to bayberry's phenology. Reviews of precision nutrient management in fruit crops emphasize "right time" and "on-demand" supply using fertigation, slow-release fertilizers, and decision tools to raise nutrient use efficiency and economic returns while lowering pollution risks. The FORD fertigation strategy in semiarid apple orchards, combining formula fertilization with on-demand and delayed applications, achieved similar yields but higher fruit quality and net profit at reduced fertilizer rates, illustrating a transferable framework for designing stage-specific nutrient schedules in bayberry systems.

Future work should first refine quantitative fertilization-timing models for bayberry that couple tree nutrient demand, soil nutrient dynamics, and climatic variability. The bayberry N and P reduction study highlighted the importance of legacy nutrients and soil buffering capacity, but did not explicitly distinguish the effects of shifting application dates within the season. Integrating multi-year field trials with process-based models and high-resolution monitoring of soil moisture, pH, and mineral N would enable the design of site-specific timing schemes that minimize leaching and gaseous losses while safeguarding yield. Precision nutrient management reviews point to substantial gaps in deploying sensors, remote sensing, and variable-rate technologies in fruit orchards, which should be addressed for bayberry in particular. Second, more attention is needed to micronutrient timing, interactions with growth regulators, and long-term ecological effects. Boron nutrition in bayberry has been relatively well documented, but optimal synchronization of soil and foliar B with other nutrients, and with compounds such as paclobutrazol that modulate vegetative-reproductive balance, requires further experimentation across cultivars and sites. Long-term studies should also track how different fertilization schedules influence rhizosphere microbial networks, soil acidification, and the incidence of decline symptoms, building on evidence that soil pH shifts and altered microbial communities are closely associated with bayberry health status. Together, these research directions can underpin fertilization-timing strategies that are both high-yielding and environmentally sustainable.

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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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