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Yield Response and Cultivation Improvement of Woody Blueberries under Soil pH Regulation

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Abstract This study mainly discussed the physiological responses of woody blueberries under different pH soils, analyzed the changes in root development, yield, fruit nutrition and trace elements, sorted out some commonly used methods for regulating soil pH at present, such as applying sulfur and peat soil, explored the impact of these regulation methods on soil health and microbial environment, and also introduced some new technologies For instance, real-time pH measurement sensor devices in the fields, diagnosis of soil conditions through remote sensing technology, and some intelligent decision-making systems may all be applied to the precise management of blueberries. This study aims to offer some practical pH control suggestions to blueberry growers, helping them grow blueberries with higher yields and better quality, while also making cultivation more environmentally friendly and sustainable.
Keywords Woody blueberry; Soil pH; pH regulation; Fruit quality; Rhizosphere ecology

1 Introduction

The roots of woody blueberries are relatively shallow and are very sensitive to the pH level of the soil. Its favorite soil pH range is from 4.0 to 5.5. If the pH rises, blueberries won't grow well. The plant will grow shorter, the main stem will become thinner, the branches will be fewer, the dry weight of the leaves and roots will also decrease, and the overall growth will deteriorate. Meanwhile, the trace elements in the leaves will also be imbalanced, and the photosynthetic efficiency will also decrease (Yang et al., 2022a; Yang et al., 2022b; Bao et al., 2024). In addition, the microorganisms around the roots will also change due to pH changes, thereby affecting the nitrogen cycle and nutrient absorption (Li et al., 2024; Ma et al., 2024).

If the soil is slightly alkaline or the pH is not appropriate, blueberries will show a series of problems, such as slow growth, yellowing leaves, reduced yield, and decreased fruit quality (Jiang et al., 2019). In a high pH environment, the chlorophyll in blueberries decreases, photosynthesis weakens, and antioxidant capacity declines. Some varieties may even have physiological problems and die in severe cases (Yang et al., 2022a; Yang et al., 2022b). However, if the soil pH is not well regulated, it will also affect the distribution of the root system and the types of microorganisms, leading to a decrease in the activity of beneficial bacteria, which will further reduce the resistance and yield of blueberries (Wang et al., 2024).

This study tested several methods for regulating soil pH to examine their impact on the yield, quality and root environment of woody blueberries, analyzed the physiological response mechanisms of woody blueberries under different PHS, selected some varieties that can adapt to high PHS, and also proposed methods for improving soil and planting management. This study aims to help blueberries grow well and have high yields under different soil conditions, achieving more efficient and environmentally friendly cultivation.

2 Soil pH Requirements and Constraints in Blueberry Production

2.1 Optimal soil pH range for woody blueberries

Woody blueberries (such as highbush blueberries and rabbiteye blueberries) are crops that love acidic soil very much. Its favorite soil pH is mostly between 4.0 and 5.5. Some varieties have stricter requirements. For instance, Blomidon is most suitable for pH values ranging from 4.0 to 4.5, while Northcountry is suitable for pH values from 4.5 to 5.0 (Lee et al., 2021). In soil with a high content of organic matter, the pH value is best controlled between 4.0 and 5.0. In mineral soil, the ideal range is 5.0 to 5.5. If the pH exceeds 5.5, blueberries are prone to poor growth. For example, the leaves will turn yellow, the plants will not grow tall, and there will be fewer fruits (Figure 1) (Jiang et al., 2019; Zhou et al., 2022).

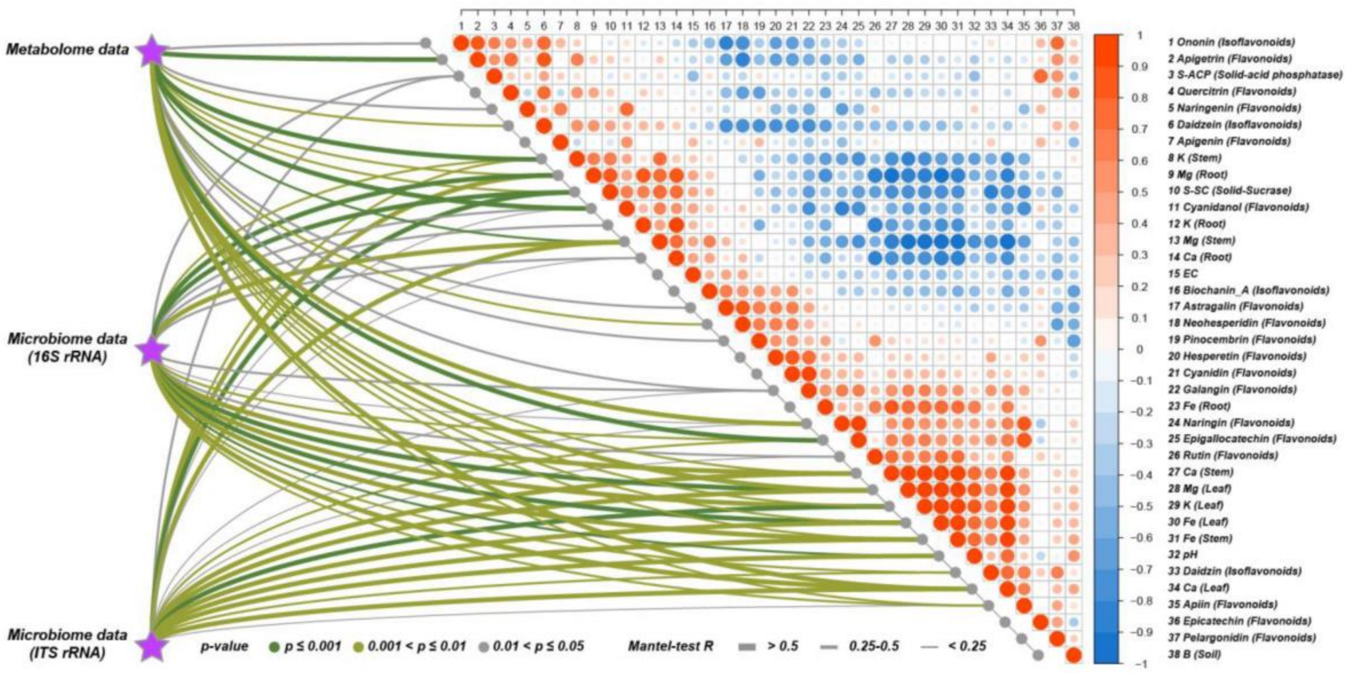

Figure 1 Correlation analysis of soil and plant chemical properties and root metabolome (Adopted from Zhou et al., 2022)
Image caption: The color gradient on the right represents Spearman's correlation coefficients. The chemical properties and metabolites used have passed the partial Mantel tests. The thickness of the curve in the figure is proportional to the Mantel r statistic of the corresponding distance correlation, and the color of the curve indicates the statistical significance based on 9999 permutations (the legend at the bottom corresponds to *p* values) (Adopted from Zhou et al., 2022)

2.2 Root physiology and pH-related nutrient uptake

The roots of blueberries are very sensitive to changes in pH. In an acidic environment, its roots activate a mechanism called H^+-ATPase to pump H^+ out, which is conducive to the absorption of trace elements such as Fe and Mn (Tamir et al., 2020; Tamir et al., 2021). However, if the pH is too high, this pump will not work well, the activity of the roots will decrease, the absorption of Fe and Mn will be poor, the leaves will be deficient in nutrients, and photosynthesis will also decline (Jiang et al., 2019; Yang et al., 2022b). One more important point is that blueberries prefer ammonium nitrogen (NH_4^+). If the content of NH_4^+ in the fertilizer is higher, it can help lower the pH near the roots and facilitate nutrient absorption

2.3 Common pH problems: alkalinity, acidification, and regional limitations

Alkaline soil (pH>5.5) is a big problem for growing blueberries. This situation is common in lime soil or areas with a lot of alkaline fertilizers, which can easily lead to iron and manganese deficiency and slow plant growth (Jiang et al., 2019). However, the soil should not be too acidic. If the pH is lower than 4.0, especially in mineral soil, aluminum or manganese poisoning may occur. Because the soil pH varies from place to place, in order to grow blueberries well, sulfur, peat or acidic organic matter is usually added to adjust the soil pH (Costello et al., 2019; Novak et al., 2023).

2.4 Influence of soil type, texture, and buffering capacity

Different soil types can also affect the effect of pH regulation. Soils like peat soil or sandy loam, where pH adjustment is relatively easy, changes rapidly and over a wide range, are more suitable for growing blueberries (Lee et al., 2021; Novak et al., 2023). However, loam silty soil, which has strong buffering capacity and changes pH very slowly, is not very suitable for blueberries (Ochmian et al., 2020). If the soil organic matter content is high, it is easier to maintain a low pH, which is also conducive to root growth (Costello et al., 2019; Zhou et al., 2022). In addition, the amount and duration of effect of acid-adjusting agents (such as sulfur, peat, sulfur-oxidizing bacteria, etc.) also depend on the buffering capacity of the soil.

3 Effects of Soil pH on Growth, Yield, and Fruit Quality

3.1 pH effects on vegetative growth and root development

If the pH of the soil rises, blueberries are likely to grow poorly. For instance, the plant becomes shorter, the main trunk becomes thinner, the number of branches decreases, and the dry weight of leaves, stems and roots all drops. The greenness of leaves (SPAD value), chlorophyll content and photosynthetic efficiency will also decrease (Jiang et al., 2019). In alkaline soil, the roots grow poorly, the types of surrounding microorganisms decrease, and the enzyme activity in the soil also declines. All these will affect the nutrient absorption and normal growth of blueberries (Zhou et al., 2022; Egorova et al., 2024). In addition, the roots of blueberries have no root hairs. They absorb nutrients through the mycorrhizal system formed together with fungi, and this system works best in acidic soil.

3.2 Yield response under various pH conditions

The yield of blueberries is highly influenced by soil pH. Research has found that if the pH is raised from 4.5 to 6.5, the yield of blueberries will drop by more than 60%. The fruit ripens later and the number of flower buds and flowers will also decrease (Egorova et al., 2024). The adaptability of different blueberry varieties to alkalinity varies, but generally speaking, the yield is the best when the pH is below 5.5 (Yang et al., 2022a). Adjusting soil pH with organic materials such as corn stalks and pine needles can also significantly increase the yield per blueberry plant and the weight of individual fruits (Kim et al., 2017).

3.3 Impacts on fruit set, berry size, anthocyanin content, and flavor profile

In an environment with a high pH value, blueberries bear less fruit, the fruit becomes smaller, the sweetness decreases, the sourness intensifies, and the overall taste deteriorates (Egorova et al., 2024). When the soil pH is appropriate, the contents of anthocyanins, soluble solids and vitamin C in the fruits will be higher and the quality will be better. Under high pH conditions, the taste of the fruit will become milder, the sugar-acid ratio will decrease, affecting the appearance and commercial value (Jiang et al., 2019; Yu et al., 2020).

3.4 Role of pH in nutrient availability and physiological disorders

If the soil pH is too high, it will also make it difficult for trace elements such as iron, manganese and zinc to be absorbed by plants, and it is easy to have nutrient deficiency problems, such as yellowing of leaves and withering of edges (Jiang et al., 2019). When the pH is high, most of the nitrogen in the soil turns into nitrate nitrogen. However, blueberries are not very fond of this form of nitrogen and it may also lead to iron precipitation, making the iron deficiency problem more severe (Smith and Harris, 2017). However, it should not be too sour either. If the pH is too low, it will cause excessive ions such as aluminium and manganese, generating toxicity, which is not good for the roots and fruits of blueberries (González-Villagra et al., 2021; Ngoc et al., 2022).

4 Soil pH Regulation Strategies in Blueberry Cultivation

4.1 Use of acidifying amendments

Common acid-adjusting materials include sulfur powder, sulfuric acid, phosphogypsum and urea phosphate. Studies have shown that sulfur powder can rapidly lower the pH of the soil, while urea phosphate not only makes the soil acidic but also enhances the activity of soil enzymes (Ochmian et al., 2020). In addition, by adjusting the types of nitrogen fertilizers, such as increasing the proportion of ammonium nitrogen, the soil can also become more suitable for blueberry growth (Tamir et al., 2021; Tamir et al., 2022).

4.2 Organic acid applications and pH-buffering mulches

Adding some organic materials, such as pine bark, humus or vinegar residue, can not only improve soil structure, but also slowly release organic acids to help maintain soil acidity, while increasing organic matter. Some pine needles or acidic humus can also be spread on the ground. These mulch can act as a buffer and slow down the change of pH, which is very helpful for the blueberry root system and the microorganisms in the soil (He et al., 2022; Li et al., 2024). Studies have found that vinegar residue can improve soil nutrients and microbial diversity more effectively than pine bark.

4.3 Selection of acid-tolerant rootstocks and cultivars

The adaptability of different blueberry varieties to pH varies. Some varieties, such as ‘Chaoyue No.1’ and ‘Briteblue’, can grow well even in soil with a relatively high pH, indicating that they have a certain alkali tolerance (Jiang et al., 2019; Yang et al., 2022a; Yang et al., 2022b). By breeding such varieties with high pH tolerance or choosing appropriate rootstocks, blueberries can adapt to more soil types and be cultivated more flexibly.

4.4 Precision liming and monitoring to correct over-acidification

If the soil pH is too low (below 4.0), it will also affect the growth of blueberries. At this point, a small amount of lime (such as calcium carbonate) can be used to increase the pH to 5.0~5.5, while also supplementing nutrients such as calcium and magnesium. Research shows that as long as the amount is well controlled, lime will not raise the pH too high; instead, it can help blueberries grow better (Schreiber and Nunez, 2021). In addition, the pH of the soil should be checked regularly, and the application of fertilizers and conditioners should be adjusted according to the situation. Only in this way can excessive acidity or nutrient imbalance of the soil be avoided (Douillard et al., 2025).

5 Integrated Soil and Water Management under pH Control

5.1 Irrigation water pH and its role in long-term soil acid-base balance

Blueberries are very sensitive to the pH level of the soil. If the pH of the irrigation water is appropriate, it helps maintain an acidic environment around the roots, which can assist it in better absorbing nutrients and promoting growth. The use of pulse drip irrigation (that is, watering in small amounts multiple times) can not only make the soil moisture distribution more uniform, but also control the soil pH more stably, allowing blueberries to grow better, with higher yield and higher utilization rate of water and fertilizer. However, if the pH of the water is too high or the frequency of irrigation and the amount of fertilizer application are unreasonable, it is easy to cause nitrate nitrogen loss and also disrupt the soil acid-base balance (Messiga et al., 2020; Messiga et al., 2021; Guo et al., 2022).

5.2 Interaction between pH and soil microbiota

The pH of the soil can also affect the types and activities of microorganisms within it. An appropriate pH makes it easier for beneficial bacteria to grow and is also conducive to the decomposition of organic matter and the nitrogen cycle. The application of organic fertilizer can not only increase the types of microorganisms, but also raise the levels of metabolites such as amino acids, helping the soil provide nutrients better (Tan et al., 2022). Some improvement methods, such as mixing peat with acidified rice husks, can also increase the number of nitrogen-fixing microorganisms and make the nitrogen cycle smoother (Li et al., 2024). In addition, in the intercropping system of blueberries and soybeans, by adjusting soil pH and organic matter content, microbial activity can also be improved and problems caused by continuous cropping can be reduced (Ma et al., 2024).

5.3 Fertilizer formulation and compatibility with pH-sensitive systems

Blueberries prefer to absorb ammonium nitrogen. However, if too many acidic fertilizers like ammonium sulfate are applied, the soil pH will drop too low, making it difficult for elements such as calcium and magnesium to be absorbed, and may also cause nutrient deficiency problems (Messiga et al., 2020; Messiga et al., 2021). The use of organic fertilizers or some special compound fertilizers (such as those containing potassium sulfate) can adjust pH while increasing the content of soil organic matter and trace elements, which is beneficial to the growth of blueberries (Douillard et al., 2025). In addition, the application method of fertilizers is also very important. For example, the effects of drip irrigation and broadcasting are different. The choice should be based on the actual conditions of the soil and blueberries (Figure 2) (Jayasinghege et al., 2024).

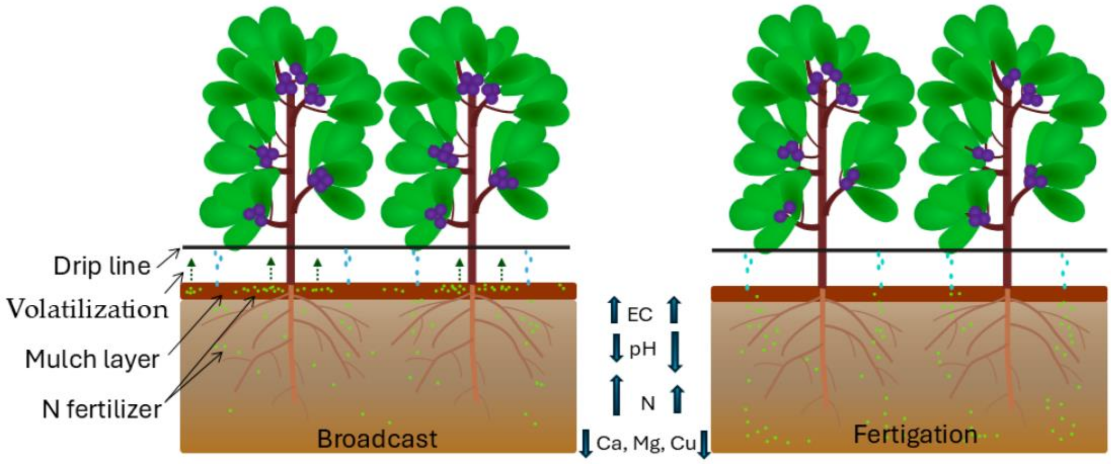

Figure 2 Impact of long-term nitrogen (N) fertilization and application methods (Adopted from Jayasinghege et al., 2024)

Image caption: N fertilizer applied as broadcast (BROAD) treatments initially remains in the sawdust after application, gradually becoming available in the root zone as it dissolves with irrigation water. Fertilizer not directly under drip irrigation tends to dissolve more slowly, with some loss due to volatilization. In contrast, fertigation (FERT)-applied N passes through the mulch layer more readily and becomes immediately available to plants, though a higher portion may be lost through leaching compared to BROAD treatments. All N treatments increase electrical conductivity (EC) and reduce pH, but the pH decline occurs more rapidly with FERT treatments (illustrated by arrows, with arrow heights indicating the extent of change). These soil changes also reduce the availability of calcium (Ca), magnesium (Mg), and copper (Cu) to plants, while N availability appears slightly higher in BROAD treatments due to differences in the rate and pattern of fertilizer distribution (Adopted from Jayasinghege et al., 2024)

5.4 Long-term effects of repeated amendment use on soil structure and health

Although long-term use of mineral fertilizers can enhance soil fertility, it can also easily lead to a decrease in soil pH, a reduction in organic matter, and a significant loss of nitrate nitrogen, affecting soil health and sustainable planting (Messiga et al., 2020; Jayasinghege et al., 2024). In contrast, conditioners such as organic fertilizers and peat, if used for a long time, can increase organic matter in the soil, improve soil structure and microbial diversity, and also enhance soil buffering capacity and nutrient supply (Tan et al., 2022). However, it should also be noted that long-term use may cause excessive phosphorus accumulation in the soil. Therefore, regular checks and scientific crop rotation are still necessary (Li et al., 2024; Douillard et al., 2025).

6 Technological Tools and Monitoring Systems

6.1 In-field pH sensors and precision soil mapping

Installing pH sensors in the fields enables real-time observation of changes in soil acidity and alkalinity, making timely adjustments convenient. Farmers can also regularly measure the soil pH using the potentiometric method and then manage it according to the zoning of the plots, keeping the soil pH stable between 4.0 and 5.5, which are favored by blueberries. In this way, blueberries will grow better and have a higher yield. With precise mapping technology, it is also possible to draw which plots of land have a pH level that is too high or too low, facilitating targeted treatment.

6.2 Remote sensing and spectral tools for pH-associated stress detection

Remote sensing and spectroscopy techniques are also quite useful. For example, they can be used to observe the color and greenness (SPAD value, CCI index, etc.) of blueberry leaves over a wide range, because these are closely related to soil pH (Jiang et al., 2019; Yang et al., 2022). Sometimes, with the help of drones or satellites, along with the assistance of ground instruments, it is possible to identify early on whether blueberries are growing poorly or their leaves are discolored due to incorrect soil pH, facilitating prompt intervention.

6.3 Decision support tools and real-time pH adjustment protocols

There is a type of tool called Decision Support System (DSS), which can centralize the data from sensors for use, such as soil pH, nutrient content, how blueberries are growing, etc., and then automatically recommend fertilization, watering or pH adjustment (Savić et al., 2024). Some intelligent irrigation systems can even automatically adjust the pH value and electrical conductivity (EC value) of water based on this information, helping the root system absorb nutrients better, making blueberries grow stronger and have a higher water and fertilizer utilization rate.

6.4 Data-driven modeling of pH-yield-environment interactions

If data such as soil pH, nutrients, weather and blueberry yield can all be collected, a model can also be established specifically to study how pH affects yield (Jayasinghege et al., 2024). Statistical methods such as principal component analysis and correlation analysis can also tell us the relationship between physiological indicators such as chlorophyll content and antioxidant enzyme activity and yield, providing data support for precise management (Jiang et al., 2019; Yang et al., 2022b).

7 Case Study: Soil pH Regulation and Yield Improvement in a Commercial Blueberry Orchard

7.1 Location, soil background, and climatic conditions

Blueberries prefer acidic soil, with the most suitable pH range being 4.0 to 5.5, and they also require a relatively high organic matter content. In northern China and some southern regions, the soil pH is often relatively high, generally exceeding 5.5. Therefore, it is necessary to carry out improvement in advance. Most blueberry plantations are located in temperate or subtropical regions, where there is abundant rainfall and a mild climate, which is very suitable for blueberry growth (Jiang et al., 2019; Yang et al., 2022b).

7.2 Intervention strategy: type and timing of pH amendment

To regulate soil pH, common methods include applying sulfur powder, laying pine needles, adding pine bark, or using some acidic compound fertilizers (such as compound fertilizers containing K_2SO_4). These materials can reduce the pH to between 4.5 and 5.5 and keep it unchanged for several years. Before planting or right after planting, first measure the soil pH. If it is too high, add some sulfur fertilizer and turn the soil to adjust the pH to the ideal range. If the pH is too low, you can also add an appropriate amount of compound fertilizer containing lime to improve it. Adding some organic substances such as pine needles, pine bark, peat and acidified rice husks on a regular basis can also improve soil structure and enhance buffering capacity (Li et al., 2024).

7.3 Observed effects on yield, fruit quality, and nutrient balance

When the soil pH was adjusted to 4.5 to 5.5, blueberries grew more vigorously, the biomass of the above-ground parts increased significantly, and the yield could even rise fivefold. The contents of sugar, vitamin C, soluble solids, etc. in the fruit have also increased (Yu et al., 2020). When the pH is too high, blueberries do not grow well, and both yield and taste deteriorate. For example, the sugar-acid ratio decreases and the taste becomes sour. Under the appropriate pH, the contents of iron, manganese and zinc in the leaves are more balanced, the photosynthetic efficiency is higher, and the plants are healthier (Jiang et al., 2019; Yang et al., 2022b). Combined with some organic fertilizer and microbial fertilizer, it can also enhance nutrient cycling and improve soil health (Li et al., 2024).

7.4 Lessons learned and recommendations for scalable application

Adjusting the soil pH properly is a prerequisite for high-yield and high-quality blueberries. It is recommended to measure the pH before planting and adjust it to between 4.5 and 5.5 as soon as possible. To improve acidity, sulfur powder, pine needles, pine bark, etc. can be used, and combined with ploughing, it is helpful to maintain acidity for a long time. Adding some organic matter or microbial fertilizer can also enhance soil nutrients and microbial diversity, make the root system more vigorous and the entire blueberry plant healthier (Yu et al., 2020; Li et al., 2024). In addition, it is recommended to regularly check the pH and nutrients of the soil and replenish organic matter and conditioners in a timely manner as needed, which is the key to ensuring blueberry yield and sustainable cultivation.

8 Conclusion and Perspectives

Blueberries are particularly sensitive to soil pH levels. Its favorite pH range is from 4.0 to 5.5. Within this range, blueberries grow fast, have a high yield and the fruits are also more delicious. If the soil pH is too high, the plants will grow slowly, the yield will decrease, both flowering and ripening will be delayed, and the taste of the fruits will also deteriorate, such as having less sugar and more acid. Some blueberry varieties are more tolerant of high-pH soil, such as ‘Chaoyue No.1’ and ‘Briteblue’. These two varieties perform quite well in slightly alkaline soil.

To maintain an appropriate soil pH, materials such as sulfur, peat, pine needles, and acidified rice husks can be used to adjust the acidity. Before planting, measure the pH value first. If it is too high, apply sulfur powder or sulfur-containing compound fertilizer. If it is too low, add some lime to adjust it. The combined use of organic substances can not only regulate the pH level but also improve soil structure and increase organic matter. When planting, it is recommended to give priority to using ammonia nitrogen fertilizer and combine it with bacterial fertilizer to optimize the rhizosphere environment. In some slightly alkaline areas, the method of “flat furrows + pine sawdust + sulfur acidification” can be adopted to grow blueberries, which is cost-effective and highly effective.

Although these methods have a certain application foundation, the specific response mechanism of blueberries under high pH stress still requires in-depth research. In the future, AI technology can be integrated to monitor soil pH and crop conditions in real time through sensors, achieving precise regulation. Meanwhile, the introduction of beneficial microorganisms, the promotion of organic alternative chemical fertilizers, and the development of intercropping models are also expected to achieve green planting while ensuring yield, and promote the sustained and healthy development of the blueberry industry.

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

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