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Discussion on High-efficiency Cultivation Technology of Legume Crops under Different Soil Types

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Abstract Soil type is one of the key factors affecting the growth and yield of legume crops. This study reviews the physical and chemical properties of major soil types such as clay, loam and sandy soil, as well as the limiting effects of soil pH, permeability and nutrient status on nitrogen fixation and growth of legume nodules. In response to the problems existing in different soils, the study discusses the farming measures of improving soil structure, increasing organic matter, and adjusting pH, as well as the strategies of optimizing fertilization formula and inoculating microbial agents such as rhizobia according to soil type. At the same time, the study summarizes the practical cases of improving the yield and quality of legume crops in typical ecological regions (black soil area in Northeast China, alkaline soil area in Huanghuai, and red soil area in Southwest China), including the integrated application of technologies such as straw return to the field, application of soil conditioners, water-fertilizer integration, and mulching. The study shows that there are significant differences in high-yield cultivation of legumes under different soil conditions, and corresponding soil management and cultivation regulation technologies need to be adopted according to local conditions. This study proposes a prospect for the integrated innovation and regional promotion of legume crop cultivation technology in the future, in order to provide a scientific basis for achieving high yield and high efficiency of legume crops.
Keywords Legume crops; Soil type; Rhizobium; Soil improvement; Cultivation techniques

1 Introduction

Pulse crops include soybeans, peas, broad beans, peanuts and mung beans, etc., which play an important role in providing plant protein and improving soil fertility. According to statistics, pulses account for about a quarter of global crop production and contribute nearly 50% to human dietary protein. Through biological nitrogen fixation, legumes can fix a large amount of nitrogen for farmland every year, which not only reduces dependence on chemical fertilizers, but also increases the yield of subsequent crops. Therefore, legume crops are widely planted all over the world and are the second largest food crop after cereals. They play an important role in food security and sustainable agriculture (Ciampitti et al., 2021). Especially in China, with the improvement of people's living standards and the growth of livestock feed demand, expanding the planting of legume crops is of great strategic significance.

The soil types in legume-producing areas in different regions vary significantly, forming different limiting factors for crop production and also containing corresponding potential for increasing production. High-latitude regions such as the Northeast are dominated by black soil (clay loam) rich in organic matter, with high natural fertility, but excessive tillage has led to soil structure degradation; calcareous soil and tidal soil are widely distributed in the Huanghuai region of North China, with a sticky texture and strong alkalinity, prone to compaction and nutrient imbalance problems; the south is mostly red soil with strong weathering, sandy texture and severe acidity, low fertility and poor water and fertilizer retention. Soil conditions directly affect the development of legume roots and rhizobia colonization. For example, the high salt and high pH environment of saline-alkali land will inhibit soybean nodulation and nitrogen fixation, limiting yield (Ren et al., 2023). Correspondingly, various types of soil also provide improvement potential for legume cultivation: for example, organic matter can be maintained through conservation tillage in black soil areas, improving pH and supplementing trace elements in alkaline soil areas can improve nutrient effectiveness, and strengthening water conservation and fertilization in red soil areas can significantly increase legume yields (Amer et al., 2023; Al-Tawarah et al., 2024).

In view of the limiting factors of different soil types on the production of legume crops, this study will explore the corresponding efficient cultivation and management techniques, classify and introduce the soil types and physical and chemical characteristics of the main legume producing areas, and then analyze the influence mechanism of soil factors such as pH, permeability and nutrient imbalance on legume growth. On this basis, this study will focus on soil management measures to improve soil structure, increase organic matter and adjust pH, as well as strategies such as soil-based fertilizer formula optimization and microbial inoculation. Next, the practice of cultivation and regulation technology for different soil types is introduced, combined with the experience of typical case analysis in the three major regions of Northeast Black Soil, Huanghuai Alkaline Soil and Southwest Red Soil, summarize the key technical differences in efficient cultivation of legumes under different soil conditions, emphasize the importance of adapting measures to local conditions, and look forward to the future direction of technology integration and regional promotion to promote high yield and efficiency of legume crops.

2 Classification of Soil Types in the Main Bean Planting Areas

2.1 Physical and chemical properties of clay, loam and sand

According to texture and composition, farmland soil can be divided into three categories: clay, loam and sand, and there are obvious differences in their physical and chemical properties. Clay has a fine texture, high clay content, small pores and poor connectivity. It has high water retention and nutrient adsorption capacity, but poor ventilation and drainage, and poor tillage. Clay usually has a large cation exchange capacity and good buffering performance. It is mostly neutral and alkaline. Its advantage in nutrient supply is that it is rich in potassium and trace elements, but it is prone to phosphorus deficiency and fixation. Loam is between clay and sand, with good structure, balanced water and fertilizer retention and permeability, and is regarded as an ideal farming soil. The organic matter content in loam is moderate, the pH is generally neutral, the nutrient supply is relatively balanced, and it is suitable for the root growth of most grain crops. Sandy soil has a coarse texture, high sand content, large and straight pores, excellent ventilation and drainage, but poor water and fertilizer retention. Sandy soil has low organic matter and clay content, is often acidic and thin, and is prone to drought and nutrient leaching. Clay is prone to waterlogging and hypoxia but has high fertility, sandy soil is well-ventilated but prone to drought and barrenness, and loam medium conditions are the best (Alemneh et al., 2020). These physical and chemical differences profoundly affect the root environment and nutrient acquisition ability of legume crops, and are the basis for consideration when formulating cultivation strategies.

2.2 Relationship between typical soil distribution and climate in different regions

Legumes are widely planted in China, and soil types and climate conditions in different regions are coupled to form a unique ecology. In the high-latitude cold areas of Northeast China and Inner Mongolia, typical soils are black soil and dark brown soil, with deep soil layers and high organic matter, but affected by low temperatures and seasonal waterlogging, the farming period is short and soil erosion is prone to occur. In the temperate semi-humid area of the Huanghuaihai Plain, calcareous tidal soil and brown soil are the main soils, with drought in winter and spring and heavy rain in summer. The soil is heavy and the groundwater level is high, and it is necessary to improve aeration through drainage and the addition of organic matter (Zhang et al., 2022). In the southern monsoon region, red soil and yellow soil are widely distributed. The climate is hot and humid with abundant precipitation. Strong weathering and leaching make the soil acidified and barren, the arable layer is thin and scattered, and the ability to retain water and fertilizer is weak. Gray-calcium soil and saline-alkali soil are distributed in the arid northwestern region. Precipitation is scarce and evaporation is strong. Soil salt easily accumulates to toxic levels, limiting the growth of legume crops. It can be seen that the soil types in different regions are shaped by the climate, water and heat conditions, and pose different challenges to legume crop production. For example, the cold and easy waterlogging of black soil, the compaction and salinization of alkaline soil, and the acidity, thinness and drought of red soil need to be targeted in response to these regional characteristics. Management measures should be taken to tap the production potential of each soil.

2.3 Overview of the adaptability of legumes on major soil types

The growth performance of legume crops on different soil types is significantly different. In general, legumes are most suitable for loam environments with deep soil layers, good permeability and medium to high fertility. Under these conditions, the root system can fully penetrate and establish an effective symbiosis with rhizobia, thereby achieving high and stable yields (Li et al., 2024). On heavy clay soils, due to poor ventilation, the root system of legumes is susceptible to waterlogging, and improved tillage is needed to improve water permeability to adapt to this environment. However, the rich nutrient supply of clay is beneficial to legume crops. Practice has shown that soybeans and other crops can show high yield potential on improved black clay soil (Zhang et al., 2021). In poor sandy soil environments, legume crops often grow well during emergence and seedling stages, but are prone to drought and nutrient deficiency in the middle and late stages, resulting in reduced yields. At this time, water and fertilizer conservation measures can enhance their adaptability. Some barren-resistant legume varieties (such as mung beans and peas) have strong adaptability to sandy soils, short growth periods and relatively low nutrient requirements, but water and fertilizer management still needs to be strengthened to achieve high yields. Agronomic measures such as crop rotation and intercropping can also help legumes improve their adaptability in different soils. For example, intercropping legumes with grasses can improve soil nitrogen cycle efficiency and overall productivity. Therefore, selecting tolerant varieties and adjusting cultivation systems according to soil types are important means to unleash the potential of legume crops (Zhang et al., 2019).

3 Soil Factors Limiting Legume Growth

3.1 Soil pH and rhizobium activity

Soil pH directly affects the symbiotic nitrogen fixation efficiency of legume crops and rhizobia. Most rhizobia are most active in soils close to neutral, while their activity is significantly inhibited in strongly acidic soils with a pH below 5.5. Acidic soils often make it difficult for legume nodules to form and reduce nitrogenase activity, and the number and diversity of rhizobia are also significantly reduced (Han et al., 2020; Abulfaraj & Jalal, 2021). For example, studies have shown that when soil pH drops from 6.8 to 5.0, the number of soybean nodules and the amount of nitrogen fixed per plant drop significantly by more than 50% (Kollie and Semu, 2022; Lai et al., 2024). Acidic conditions not only produce aluminum and manganese toxicity that hinders root growth, but also inhibit the infection and colonization process of rhizobia, leading to symbiotic failure. On the other hand, too high pH (>8.0) in calcareous soil is not conducive to the growth of some legumes, and may cause a deficiency of trace elements such as iron and zinc, which in turn affects leaf photosynthesis and nitrogen fixation. However, compared with acid resistance, rhizobia are slightly more adaptable to weak alkaline environments, and some legumes such as alfalfa can still nodulate and fix nitrogen in soils above pH 7.5. Excessive acidity or alkalinity will limit the efficiency of the legume-rhizobium symbiotic system, and it is necessary to optimize its growth environment by adjusting the soil pH. Applying lime is a traditional measure to improve acidic soils, which can raise the pH to the appropriate range for legumes, thereby significantly increasing the number of nodules and nitrogen fixation. At the same time, inoculation of acid-tolerant rhizobia or combined use with growth-promoting bacteria has also been shown to alleviate the effects of acid stress on nitrogen fixation to a certain extent (Alemneh et al., 2020). Therefore, reasonable regulation of soil pH is one of the primary measures to ensure efficient nitrogen fixation and normal growth of legume crops.

3.2 Effects of drainage and aeration on root health

The root system of legume crops is very sensitive to soil oxygen supply. An overly humid and oxygen-deficient environment will lead to restricted root growth and obstructed respiration. In severe cases, root rot and premature aging of plants will occur. When heavy clay soils and low-lying areas are overly waterlogged, the nitrogen fixation activity of legume nodules almost stops, and the plants may show symptoms of nitrogen starvation. Studies have shown that soybeans are extremely sensitive to field waterlogging. Waterlogging for more than 10 days during the growth period can cause yield losses of up to 60% (Figure 1) (Gangana Gowdra et al., 2025). Excessive water causes soil pores to be filled with water, reducing the oxygen diffusion rate, and the root system is metabolically disordered due to lack of oxygen, resulting in growth point necrosis and root hair shedding. At the same time, the anaerobic state will also lead to increased soil reductiveness and the production of reducing substances that are harmful to the root system. Legumes usually have taproots and require a well-ventilated soil environment to take root deeply and coexist with rhizobia. Once the soil permeability is poor, rhizobia infection and nodulation will also be inhibited. For example, if the soil in pea continuous cropping fields is compacted and anoxic, the yield-increasing effect of rhizobia inoculation is significantly reduced. Improving soil drainage and aeration can effectively promote the healthy growth of legume roots. In high rainfall areas, measures such as digging trenches to drain moisture and adopting high-bed cultivation can reduce field waterlogging and increase soil oxygen content (Zaman et al., 2018). Deep plowing and deep loosening can break the plow bottom layer, increase soil macroporosity, and significantly improve the water permeability of clay (Wang et al., 2020). Experiments have shown that the use of straw mulching and no-tillage in the black soil area of Northeast China can reduce topsoil runoff and water evaporation, while improving the aeration of the 0 cm-20 cm soil layer, thereby playing a dual role of "moisture conservation and ventilation" in the middle and late stages of soybean growth. Therefore, for poorly drained soils, optimizing tillage and field engineering to improve its aeration is a necessary condition to ensure the health of legume roots and stable and high yields.

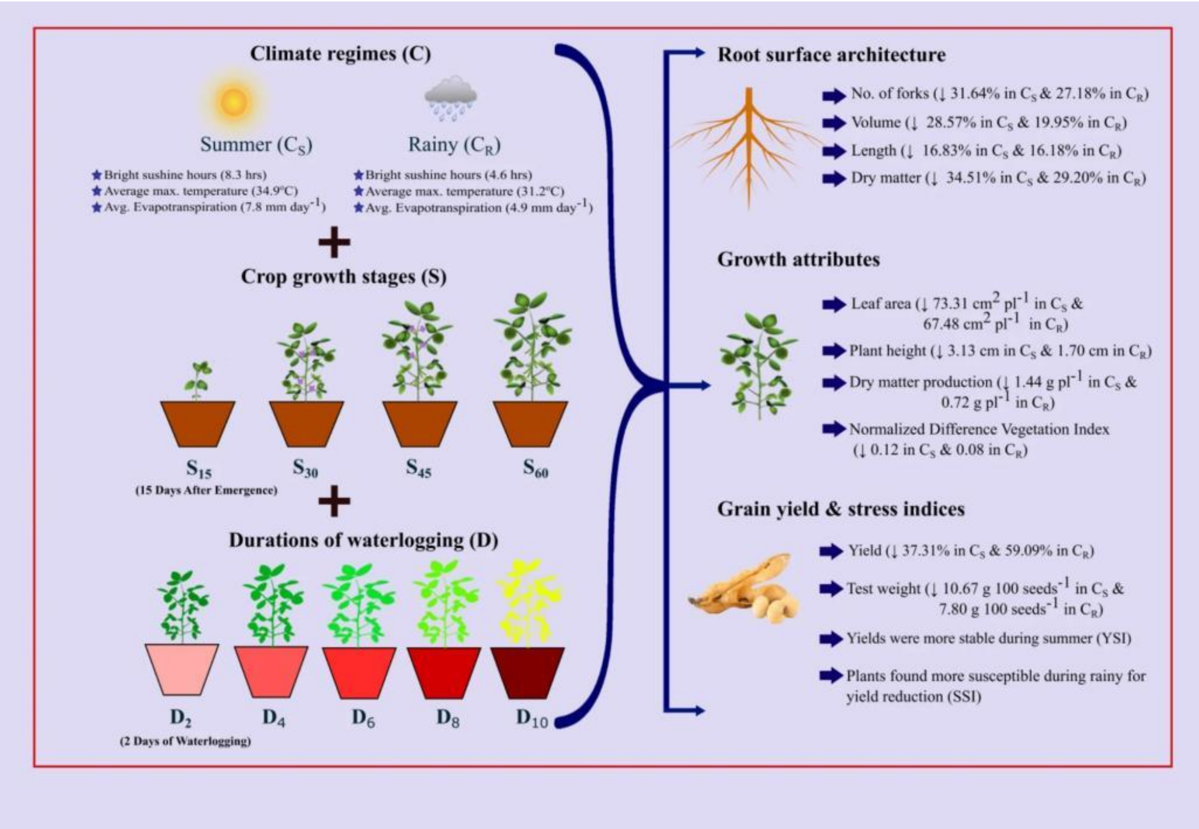

Figure 1 Response of soybean to waterlogging stress at different growth stages under climatic regimes (Adopted from Gangana Gowdra et al., 2025)

3.3 Soil nutrient imbalance and salinity stress

The imbalance or excess or deficiency of soil nutrient supply will have an adverse effect on legume crops. Imbalance of macronutrients such as nitrogen, phosphorus and potassium is common in farmland with long-term improper fertilization management. For example, excessive application of nitrogen fertilizer may inhibit the nitrogen fixation of legume nodules, resulting in a decrease in the nitrogen utilization efficiency of legumes (Ciampitti et al., 2021). Studies have found that high nitrogen environments reduce the expression of symbiotic nitrogenase in soybeans, thereby reducing the nitrogen contribution rate of nodules to plants. Therefore, in the legume-rhizobium system, the amount of chemical nitrogen fertilizer needs to be controlled to give full play to the biological nitrogen fixation function (Clovis et al., 2023). On the other hand, insufficient nutrients such as phosphorus and potassium or lack of trace elements also limit legume yields. For example, low available phosphorus in acidic red soil leads to poor root development of legumes and reduced flowering and pod setting. In response to the problem of nutrient imbalance, soil testing and formula fertilization should be implemented to replenish the deficient nutrients in time and avoid excessive fertilization to maintain the dynamic balance of soil nutrients (Ren et al., 2022). The stress of salinized soil on the growth of legume crops should not be ignored. Excessive salt can cause osmotic stress and ion toxicity, reduce the germination rate of legume seeds and the survival rate of seedlings, make the plants short, and the leaves turn yellow. In severe cases, no grains can be harvested. A field experiment showed that when soybeans were planted on saline-alkali land, the plant height, number of pods, and grain yield were 25%, 26.6%, and 33% lower than those in normal soil, respectively (Ren et al., 2023). Salt-alkali stress can also destroy the living environment of rhizobia, inhibit their infection of legume roots, and thus weaken the nitrogen fixation ability of legumes (de Almeida et al., 2022). To alleviate the harm of salinity, soil salt concentration and exchangeable sodium content can be reduced by adding soil, washing salt and using improvers (such as gypsum) to create a suitable root zone environment. At the same time, breeding salt-tolerant varieties and inoculating salt-tolerant and efficient rhizobia are also effective measures (Gao et al., 2022). In recent years, functional microorganisms that promote plant salt tolerance have received widespread attention. For example, certain Streptomyces can increase the survival and yield of soybeans in soda saline-alkali soils. In response to nutrient imbalance and saline-alkali stress, comprehensive soil improvement and cultivation management methods are needed to ensure that legume crops obtain a balanced nutrient supply and a suitable rhizosphere environment to achieve normal growth and development.

4 Targeted Soil Management Measures

4.1 Tillage methods to improve soil structure

Good soil structure is the basis for high yields of legume crops. For soils with poor structure, the tillage method can be adjusted to improve it. For heavy and compacted soils, deep plowing and deep loosening are one of the common measures. By increasing the tillage depth (such as >25 cm) and breaking the plow bottom layer, the soil bulk density can be significantly reduced, the macroporosity can be increased, and thus the ventilation and water permeability can be improved (Wang et al., 2020). Experiments in the Huanghuaihai Plain have shown that compared with traditional plowing, deep loosening rotation can reduce the soil density of the 0 cm-20 cm soil layer by about 0.1 g/cm^3, increase the root depth of soybeans by 15%, and increase the final yield by about 8%. No-tillage straw mulching is also an important method of conservation tillage, which is suitable for soils with high organic matter. For example, the promotion of no-tillage mulching technology in the black soil area of Northeast China can reduce soil disturbance and maintain aggregate structure, which can improve soil stability and erosion resistance in the long run. Studies have shown that after 8 years of straw mulching and no-tillage on sloping farmland, the water-stable aggregates of black soil > 0.25 mm increased by more than 10%, the soil infiltration rate increased, and the rainfall utilization efficiency and yield of soybean planting increased. Reasonable crop rotation can also help improve soil structure. The rotation of legumes and grasses can improve the pore distribution of the soil layer by utilizing the root characteristics of different crops. The deep roots of legumes loosen the soil, and the fibrous roots of grasses increase viscosity. Alternating the two can fertilize the soil and increase organic matter (Chalise et al., 2019). For example, the rotation of soybeans and corn not only increases the organic carbon content in soil aggregates, but also reduces the compaction of shallow soil, which is conducive to the rooting of subsequent soybeans (Zhang et al., 2021). Selecting appropriate tillage systems according to soil structure conditions, such as deep ploughing and loosening, no-till mulching, and crop rotation, can significantly improve the physical structure of the soil and create good conditions for the growth of legume roots.

4.2 Soil organic matter improvement strategy and green manure utilization

Increasing soil organic matter content is one of the effective ways to enhance soil fertility and stabilize soil structure. To this end, soil organic matter can be continuously supplemented by increasing the application of organic fertilizers, planting green manure crops, and returning straw to the field. Practice has shown that long-term application of organic fertilizers can significantly improve soil carbon and nitrogen conditions and microbial activity, which is beneficial to the nutrient acquisition and yield increase of legume crops (Yao et al., 2020). In a four-year experiment in the dry land of Northwest China, the introduction of legume green manure (such as pea green manure) and wheat rotation not only improved the organic matter and total nitrogen levels of the topsoil, but also improved the stability of soil aggregates. The economic benefits of the rotation system have obvious advantages over single planting. The biological nitrogen fixation function of green manure crops (such as sweet potato and astragalus) can provide part of the nitrogen for the next legume crop, and its large amount of organic residues can improve soil fertility after turning over and returning to the field. Studies have shown that the carbon and nitrogen release dynamics of different legume green manures after turning over are slightly different, but they can all decompose quickly in the soil and release nutrients for subsequent use. For example, planting green manure Astragalus in southern red soil can increase soybean production by about 10% in the next season, and the soil organic matter content is 0.2 percentage points higher than that of fields without green manure (Chalise et al., 2019). Returning straw to the field is also an important measure to increase soil organic matter. The promotion of crushing corn straw and returning it to the field to plant soybeans in Northeast China can add a large amount of organic carbon source to the soil every year, which will form humus and improve soil physical and chemical properties after microbial decomposition. Yao et al. (2020) reported that the use of a "legume green manure-corn-wheat" three-way rotation and returning green manure and corn straw to the field not only achieved an increase in soil organic matter input throughout the year, but also effectively improved soil nutrient balance and soybean yield. It can be seen that increasing soil organic matter through green manure planting and returning organic materials to the field is a long-term strategy to improve the productivity of legume crops on various soils. It is necessary to select appropriate green manure varieties and return methods according to regional conditions. For example, annual leguminous green manure is suitable for use in the north, and Chinese milk vetch is often planted in winter in the double-season rice areas in the south to achieve soil fertility improvement and nutrient circulation.

4.3 Soil conditioners and pH adjustment technology

For soil acidity and salinity problems, soil conditioners can be applied to adjust them. For acidic soils, lime (calcium carbonate or calcium oxide) is the most commonly used conditioner, which increases the pH value by neutralizing the active acid in the soil. Generally, applying 1~2 tons of lime per hectare can increase the pH of red soil from about 5.0 to above 6.0, and the number of nodules, plant height and biomass of soybeans on the improved soil are significantly increased (Li et al., 2021). In addition to lime, alkaline phosphate fertilizers containing calcium and magnesium (such as calcium magnesium phosphate fertilizers) can also partially neutralize soil acidity and supplement phosphorus, which is suitable for the fertilization plan of leguminous crops in acidic soils. For saline-alkali soils, the application of chemical gypsum (calcium sulfate) is an effective measure to control alkali damage. Ca^{2+} in gypsum can replace Na^{+} adsorbed on soil colloids, generating soluble Na_2SO_4 to be leached, thereby reducing the exchangeable sodium percentage of the soil and improving soil structure and permeability. Studies have shown that applying 2.5 tons of gypsum per hectare on sodic alkaline soil can significantly reduce soil conductivity and pH, and significantly increase soybean emergence rate and pod number (Yakuwa et al., 2022). New soil conditioners such as biochar and polymer water retainers are also beginning to be used in bean cultivation. Biochar has porosity and alkaline buffering capacity. Applying an appropriate amount of biochar to acidified soil can increase pH and provide a stable organic carbon source. A study applied biochar when planting peanuts in southern red soil and found that the soil pH increased by 0.5 units and the peanut yield increased by 9.8%. Water retainers can improve soil moisture retention capacity in sandy soils and reduce drought stress, which has a certain effect on improving the growth environment of drought-resistant legume crops such as mung beans. It should be noted that the use of amendments should be based on the soil test results to determine the reasonable dosage and frequency. Excessive application may cause secondary problems. For example, too much lime will lead to the fixation of trace elements and the decrease of biological activity, which requires supplementary organic fertilizer regulation. Soil amendments and pH adjustment technology are important measures to make up for the natural deficiencies of the soil and create an environment suitable for the growth of legumes. They should be scientifically implemented in combination with local soil types and crop needs. New technologies in recent years, such as bacterial agent regulation, have also shown potential. For example, some saprophytic fungal preparations can secrete organic acids to lower the pH of saline-alkali soils and promote the absorption of phosphorus by legume roots (Wen et al., 2024). Research in this area should be strengthened in the future to expand the technical means of soil improvement.

5 Optimization of Fertilization and Inoculation Strategies

5.1 Soil type and fertilizer formula adjustment principles

Reasonable adjustment of fertilizer formula and dosage according to soil type is the key to the nutritional management of legume crops. Fertilizer management should take into account the fertilizer supply capacity and limiting nutrients of different soils. For example, for loam and black soil with high organic matter content, the amount of nitrogen fertilizer can be appropriately reduced, and more nitrogen can be provided by soil mineralization and leguminous nitrogen fixation to avoid excessive nitrogen inhibiting nitrogen fixation (Ciampitti et al., 2021). On the contrary, on poor sandy soil or red soil, it is necessary to increase the input of nitrogen, phosphorus and potassium in basal fertilizer and topdressing accordingly, and adopt the principle of small amounts and multiple times to prevent nutrient leaching. Generally speaking, clay has good fertilizer retention but often lacks effective phosphorus, and the proportion of water-soluble phosphorus should be increased in the phosphate fertilizer formula; sandy soil is prone to potassium deficiency, and the proportion of potassium and organic fertilizer in fertilizer should be increased. Soil testing and formula fertilization can adjust the fertilizer composition according to the nutrient abundance and deficiency conditions of different soils. For example, the effective iron and zinc in the alkaline soil of Huanghuaihai is low, so special compound fertilizers containing trace elements or foliar spraying of micro-fertilizers should be added to soybeans to prevent symptoms such as iron deficiency and chlorosis. Long-term positioning experiments have shown that balanced application of nitrogen, phosphorus and potassium in black soil combined with organic fertilizers can maintain stable soil fertility while ensuring yield (Zhang et al., 2021). The study by Ren et al. (2022) further pointed out that on loam with medium fertility, the best fertilization mode for high soybean yield is "organic fertilizer + appropriate fertilizer", in which organic sources of nitrogen account for 50%, and combined with a high planting density, high yield and high efficiency can be achieved. This result is of reference significance for similar soil types. In short, the principle of fertilization is: fertilizer input matches the soil fertility and adapts to crop needs, avoiding excessive fertilization waste due to high soil fertility and preventing insufficient nutrient input and reduced yield when the soil is barren. For some special soils, such as calcareous soils, acidic or neutral fertilizers can be used in combination with sulfur fertilizers and micro-fertilizers to improve nutrient utilization. For example, in red soil areas, attention should be paid to the combination of phosphorus and potassium fertilizers and organic fertilizers to improve soil acidity while providing a slow-release nutrient source. Through the above soil-based fertilization strategy, the soil's own potential and the benefits of exogenous nutrients can be maximized, and efficient coordination of nutrient management of legume crops can be achieved.

5.2 Inoculation effect of microbial preparations such as rhizobia and phosphorus bacteria

The application of microbial fertilizers (microbial preparations) is one of the effective measures to improve the nutrient utilization and adaptability of legume crops to adversity. For legume crops, inoculation of high-efficiency rhizobia has almost become a standard practice in the field of soybeans, peanuts, etc. The inoculation of excellent strains can significantly increase the number of nodules and increase the activity of nitrogenase, thereby providing more nitrogen nutrients for bean plants (Zhang et al., 2024). For example, Ma et al. (2020) reported that after inoculating suitable soybean rhizobia in acidic soils in the southwest, the photosynthetic rate and nitrogen fixation ability of soybeans were improved, and the final pod yield was more than 10% higher than that of the uninoculated control. In addition to rhizobia, functional bacterial agents such as phosphorus bacteria and nitrogen-fixing bacteria that have been promoted in recent years have also shown good results in bean cultivation. Phosphorus bacteria can dissolve insoluble phosphates in the soil and increase the absorption rate of phosphorus by legumes; autogenic nitrogen-fixing bacteria can provide additional nitrogen sources for crops in the rhizosphere. Field experiments have shown that inoculating phosphate-solubilizing bacteria on phosphorus-deficient red soil can increase the phosphorus accumulation of peanut plants by 15%, and inoculating nitrogen-fixing bacteria and rhizobia on saline-alkali soil can increase the number of soybean nodules and improve salt tolerance (de Almeida et al., 2022). However, it should be noted that the actual effect of microbial preparations is closely related to soil type and background microbial flora. Zhang et al. (2024) found that in two soils in the Huaihe River Basin of Anhui Province, inoculation with the same rhizobia resulted in completely different results: inoculation in the slightly acidic yellow-brown soil increased soybean nitrogen accumulation by

33.6%, while in the alkaline sand ginger black soil, nitrogen accumulation was reduced by 21.7%. The reason for the analysis may be related to the different competitiveness of the original symbiotic nitrogen-fixing bacterial communities in different soils and the opposite direction of the soil nitrogen cycle process affected by inoculation. When promoting microbial agents, the strain type should be selected according to the soil: when the abundance of inherent soil bacteria is high, strains with strong competitiveness should be selected; salt-alkali-tolerant strains should be selected for saline-alkali soil; acid-tolerant rhizobia should be selected for acidic soil. In addition, the "microbial community package" of combined inoculation of multiple functional microbial agents has gradually gained attention. For example, mixed inoculation of rhizobia with growth-promoting bacteria (PGPR) can synergistically promote the development of legume roots and nitrogen fixation efficiency. Studies have reported that co-inoculation of rhizobia and Pseudomonas on peas can significantly alleviate continuous cropping obstacles and increase plant dry weight and photosynthetic performance. For example, some Bacillus preparations can produce plant hormones, and co-inoculation with rhizobia can increase the number and yield of soybean nodules (Miljaković et al., 2022). The effectiveness of microbial preparations varies in different soils, but reasonable selection and application can significantly exert their yield-increasing potential and is an important auxiliary means for the green and efficient cultivation of legume crops.

5.3 Application examples of formula fertilizers and controlled-release fertilizers in different soils

The application of new fertilizers provides a technical approach for efficient management of legume nutrients under different soil conditions. Among them, formula fertilizers are customized according to the fertilizer requirements of crops and the characteristics of soil fertilizer supply. They generally contain a variety of macro- and micro-nutrients, which can meet the needs of legumes during the growth period at one time. The use of special formula fertilizers for legumes on alkaline soils lacking trace elements can effectively prevent nutrient deficiency and increase the pod setting rate and seed fullness. In recent years, special fertilizers for peanuts and soybeans developed in different regions have been promoted in production. For example, the application of special soybean fertilizers containing gypsum and boron and zinc on alkaline soils in North China has a significantly better yield-increasing effect than conventional NPK compound fertilizers. For example, the peanut fertilizer promoted on red soils in the southwest has increased the phosphorus and calcium content, which significantly promotes pod development. Controlled-release fertilizers slowly release nutrients through special coatings or slow-release technologies, which are also suitable for medium-fertilization crops such as legumes. Studies have shown that the application of controlled-release urea on soybeans can simultaneously increase yield and nitrogen utilization without weakening biological nitrogen fixation (Clovis et al., 2023). In a field trial, the application of controlled-release urea did not significantly differ from conventional urea in soybean nodulation number and nitrogenase activity, but increased grain yield by more than 6%. This is because controlled-release fertilizers slowly release nitrogen, avoiding the inhibition of nodule symbiosis by excess nitrogen in the seedling stage (Abulfaraj and Jalal, 2021). Controlled-release phosphate fertilizers also have potential in leguminous crops, slowing down the fixation of phosphorus in the soil and increasing the supply of effective phosphorus in the later stage. It is worth noting that new fertilizers are often more expensive and should be used in a targeted manner according to soil conditions to obtain the best input-output ratio. For example, the use of controlled-release fertilizers on sandy soils that are prone to leaching is more effective, while clay soils have a relatively weak response to the yield increase of controlled-release technology due to their strong buffering capacity (Ren et al., 2022). For example, the yield increase of formula fertilizers on nutrient-rich black soil is limited, but the effect is significant on barren red soil. Therefore, these new fertilizer technologies should be applied first to the soil types that need them most. A combination of various measures, such as the combined application of controlled-release nitrogen fertilizers, phosphorus bacteria agents and formula fertilizers, is expected to achieve a win-win situation of efficient nutrient management and high bean yields on difficult soils. With the development of fertilizer technology, new products that more accurately match soil nutrient supply and demand will continue to emerge, pushing the fertilization of bean crops from "balanced fertilization" to "intelligent fertilization."

6 Cultivation and Regulation Technology for Soil Types

6.1 Reasonable close planting and water-fertilizer integration on loam

For loam with good fertility and suitable structure, its high-yield potential should be fully utilized, and measures such as reasonable close planting and water-fertilizer integration should be taken to increase the yield per unit area of legume crops. Loam has medium fertility and good water and fertilizer storage capacity, so the legume planting density can be appropriately increased to improve the group light energy and land utilization rate (Ren et al., 2022). Studies have shown that when summer soybeans are planted in loam, when the density increases from 90 000 plants per hectare to 120 000~150 000 plants per hectare, the dry matter accumulation and net photosynthetic rate of the group both increase, but when the density is too dense to 180,000 plants, the group is closed, resulting in insufficient light in the lower part. Therefore, it is generally recommended that summer soybeans be planted densely to about 120 000 plants per hectare on suitable loam, which can significantly increase yield without excessive competition. Dense planting requires sufficient water and fertilizer supply to support a higher group biomass. This requires the use of efficient management methods such as water-fertilizer integration, and fine regulation according to the laws of crop water and fertilizer requirements. In some soybean demonstrations in Northeast China and North China, the drip irrigation + solution fertilizer application technology was promoted to achieve water and fertilizer supply on demand in stages during the growth period, saving more than 30% of water compared with traditional irrigation and fertilization and increasing yields (Zhang et al., 2021). Loam itself has moderate water permeability and fertilizer retention. Combined with drip irrigation and fertilization, it can further reduce deep leakage and nutrient fixation, allowing more water and fertilizer to be used for crop growth. The experiment of Ren et al. (2022) pointed out that when soybeans on loam soil were managed with "organic and inorganic combined fertilization + higher density + water and fertilizer integration", the net photosynthetic rate and PSII light system efficiency of soybeans were significantly improved, and the final grain yield increased by more than 12% compared with traditional management. In fields with good loam soil, mechanized precision sowing and real-time monitoring can also be implemented, and the irrigation and fertilization cycle can be dynamically adjusted according to soil moisture conditions to ensure that soil moisture and nutrients are in the optimal range (Alemneh et al., 2020). On relatively ideal loam soil, the yield potential of legume crops should be fully tapped through advanced and applicable cultivation techniques, so as to achieve high yield and high efficiency by making the cultivation dense but not weak and the fertilizer and water coordinated.

6.2 Drainage and deep tillage management in heavy clay soil

For soils with heavy texture and poor drainage (such as tidal soil, clay black soil, etc.), the focus of cultivation regulation is to improve field water management and soil tillage mode to prevent waterlogging and promote rooting. A complete field drainage system should be established. Timely removal of field waterlogging during rainy seasons or during the critical period of crop growth can significantly reduce the incidence of clay soil waterlogging. In practice, ditching and soil management technology is often used, that is, the combination of ridge ditch and side ditch, so that the field can basically drain the surface water within 24 hours after rain. For low-lying and flood-prone plots, pre-digging drainage ditches before rain and adding water collection pits on the edge of the field are also effective measures. Through these engineering measures, the soil oxygen content is guaranteed and the root system of legumes is maintained healthy. Secondly, deep tillage and reasonable crop rotation are implemented in autumn to improve the tillage layer. In clay regions, plowing the soil after autumn harvest when it is dry can break the bottom layer of the plow and loosen the soil by freezing and thawing. Deep plowing can promote the taproots of soybeans to penetrate deep into the soil layer to absorb water and nutrients, thereby enhancing stress resistance. Studies have shown that deep plowing combined with deep loosening on heavy clay soil can make the soil three-phase ratio of the 15~25 cm soil layer approach an ideal state, increase the growth space of soybean roots and the depth of root nodule distribution. Rotating legumes with moisture-tolerant rice or flood-tolerant crops can also alleviate the problem of soil structure deterioration caused by continuous bean planting. On clay, it is advisable to select flood-tolerant varieties and appropriately postpone the sowing period to avoid the rainy period during the seedling stage. In breeding practice, a number of flood-tolerant soybean lines have been cultivated, and the survival rate under 24-hour waterlogging conditions is significantly higher than that of ordinary varieties (Gangana Gowdra et al., 2025). These varieties can be planted in flood-prone clay plots to reduce the risk of waterlogging and yield reduction. Ridge cultivation can be considered to increase the bed height, which is also conducive to drainage and warming. Combining the above measures, a multi-pronged management approach such as drainage, deep plowing, crop rotation and selection of tolerant varieties can be adopted for heavy clay soils, which can significantly improve the growth environment of bean crops, reduce the occurrence of root rot and seedling death, and ensure yield formation.

6.3 Water retention and mulching technology in light sandy soil environment

Light loam and sandy soil are prone to drought stress due to their poor water retention capacity, which is a key problem to be overcome in bean cultivation. On this type of soil, the cultivation technology of "water retention and moisture increase" should be emphasized, including mulching to retain moisture, zoned irrigation and soil fertilization. Mulching technology has been widely used in crops such as peanuts and mung beans in northern dry farming areas. By covering with plastic film, soil moisture evaporation is reduced and the water use efficiency of crops is significantly improved. Studies have shown that planting mung beans with mulching on semi-arid sandy land can increase soil water storage by more than 20% during the growing period compared with no mulching, and increase yield by 15% to 25% (Wang et al., 2022). Mulch can also increase soil temperature, accelerate the growth of bean seedlings, and have a certain weed suppression effect. However, long-term use of mulch can also cause residual film pollution problems, which require measures such as residual film recycling. In addition to mulch, organic mulching is also an effective moisture conservation measure. For example, spreading straw and rice straw on mung bean fields can cool and retain moisture and reduce surface runoff. Chalise et al. (2019) found that covering crop residues can increase soil water content from 0 cm to 10 cm, reduce soil temperature and improve the yield structure of soybean populations. In areas where water resources permit, the "small water frequent irrigation" method can be used to make up for the defect of sandy soil that is easy to lose water. The application of drip irrigation or micro-sprinkler irrigation in sandy peanuts shows that segmented and multiple irrigation saves more than 50% of water than traditional flooding, while increasing the number of crop pods and 100-grain weight. Therefore, it is advisable to promote water-saving irrigation technology on light sandy soil to improve water use efficiency. On the other hand, in view of the problem of easy loss of nutrients in sandy soil, it is necessary to pay attention to increasing the application of organic fertilizers and planting green manures to improve soil fertility and gradually improve soil texture and structure. Through continuous fertilization for several years, the organic matter and clay content of sandy soil can be significantly increased, thereby enhancing the soil's ability to retain water and fertilizer (Chalise et al., 2019). For example, in an experiment in the Northwest Irrigation Area, 5 tons/hectare of organic fertilizer was added to the mung bean field for three consecutive years, and the organic matter content of sandy loam increased by 0.3 percentage points, the field water holding capacity increased by 2 percentage points accordingly, and the average yield of mung beans increased by 12% compared with the control. On light sandy soil, a three-pronged approach of "covering + water conservation + fertilization" is needed: covering to retain moisture is a temporary solution, improving soil quality is a fundamental solution, and reasonable irrigation can ensure that legumes can grow normally and obtain higher yields in a dry and leaky soil environment.

7 Analysis of Typical Application Cases in Different Ecological Zones

7.1 Northeast black soil region: combination of high-yield soybean cultivation and straw return to the field

The soil in the black soil region of Northeast China is fertile, but long-term cultivation has caused problems such as organic matter decline and soil erosion. In order to ensure the continued high yield of soybeans, the local area has explored a technical system of "high-yield cultivation mode + straw return to the field". On the one hand, by breeding soybean varieties that are resistant to dense planting and lodging, and supporting dense planting and fine management, a breakthrough in yield is achieved; on the other hand, the straw of crops such as corn is crushed and returned to the field, fertilizing the soil and improving the soil structure year by year. Taking the high-yield research field in Hailun City, Heilongjiang Province as an example, high-yield varieties are selected with dense planting of 250 000 plants per hectare, and the soybean yield exceeds 4 tons/hectare. At the same time, the full amount of straw is returned to the field and the no-till mulching technology is implemented. The organic matter content of black soil has increased from 3.5% to more than 4% within 5 years, and the soil's ability to store water and retain fertilizer has been enhanced. The 30-year positioning experiment of Zhang et al. (2021) also showed that under the conditions of long-term organic + inorganic fertilization of black soil and straw return to the field, the wheat-soybean rotation system not only has stable yield, but also achieves continuous accumulation of soil organic carbon pool and reduces net greenhouse gas emissions. It can be seen that in the black soil area, returning straw to the field to maintain soil fertility lays the foundation for high soybean yield. In terms of cultivation management, attention is also paid to reasonable rotation and integrated pest and disease control to avoid continuous cropping obstacles and disease outbreaks. Soybean seedlings suffering from root rot often show browning and rotting of the root system, necrosis of the stem base, wilting and even death of the plant (Figure 2). The promotion of the "soybean-corn-soybean" rotation model breaks the pest and disease cycle and reduces the incidence of soybean root rot by 40% (Liu et al., 2025). The typical model in the Northeast Black Soil Area is to combine soybean high-yield cultivation technology with soil fertilization and improvement. Through returning straw to the field and scientific rotation, a virtuous cycle of "improving soil fertility-increasing yield" is achieved, which provides a demonstration for the protection and utilization of black soil. This experience is also of reference significance to other high-fertility soil areas (such as black brown soil areas).

Figure 2 Soybean plants with root rot symptoms in the field (Adopted from Liu et al., 2025)

7.2 Huanghuai region: alkaline soil improvement and microbial synergistic root promotion

The soil in some areas of the Huanghuai Plain is alkaline and heavy in texture, and the growth of legume crops is often troubled by problems such as iron deficiency, chlorosis, and poor root development. In response to this situation, local demonstrations of combining soil improvement with biotechnology have been carried out. By applying gypsum to improve alkaline soil, the soil pH and exchangeable sodium content are reduced, creating a soil environment suitable for root growth. After applying 3 tons of phosphogypsum per hectare at a certain test site, the pH of the 0~20 cm soil layer dropped from 8.5 to 7.8, the soil became loose, and the average soybean yield increased by 15% after three years. The introduction of microbial agents to promote root growth, such as inoculating a mixed agent of stress-resistant rhizobia and phosphate-solubilizing bacteria, enables legume root nodules to fix nitrogen smoothly in saline-alkali soil and improves nutrient utilization. The study by de Almeida et al. (2022) proved on saline soil that the simultaneous inoculation of rhizobia and growth-promoting bacteria can significantly reduce the growth inhibition of soybeans under salt damage, increase yield and nitrogen accumulation. In a demonstration in Xinxiang, Henan, a multi-strain bio-organic fertilizer was applied when peanuts were planted in alkaline tidal soil. As a result, the root length and number of nodules of peanuts increased by more than 30% compared with conventional treatment, and the pod yield increased by 12% (Zhang et al., 2023). These effects are due to the production of organic acids, plant hormones and other substances by beneficial microorganisms in the rhizosphere, which promote the release of insoluble nutrients and the expansion of the root system (Abulfaraj and Jalal, 2021). In addition, the Huanghuai region also promotes the drip irrigation and fertilization technology of beans, which improves the soil moisture conditions while accurately supplying nutrients to avoid the secondary salinization of the soil caused by traditional flooding. The case of Huanghuai alkaline soil treatment highlights that the synergistic effect of "chemical improvement + biological root promotion" can effectively solve the problems of weak root system and yellowing of beans, and achieve increased production and efficiency. In this region, the application of these technologies in the wheat-soybean rotation system not only ensures that the soil does not compact during the wheat growth period, but also creates good soil conditions for soybeans. At present, this model has been promoted in some alkaline soil soybean fields in Henan and Hebei, becoming a typical representative of efficient cultivation of beans in this type of soil.

7.3 Southwest red soil area: high-quality mung bean production management under medium- and low-fertility soil conditions

Red soil and yellow soil in the southwest region generally have strong acidity and low nutrient content, and are considered to be "medium- and low-yield fields" that are not conducive to high yields. However, high-quality and efficient production of bean crops can also be achieved in this region through comprehensive measures. Taking the cultivation of mung beans in red soil in a certain place in Guangxi as an example, the technical route includes: improving soil acidity, providing nutrients in a balanced manner, selecting stress-resistant varieties and strengthening management. Applying 1.5 tons of lime per hectare and combining it with organic fertilizer can increase the pH of red soil from 5.0 to about 6.0, greatly reduce aluminum toxicity and increase calcium and magnesium supply. Subsequently, phosphorus, potassium and boron fertilizers are added according to the soil nutrient status to make up for the lack of available phosphorus and trace elements in red soil. After soil testing and formulation, N-P_2O_3-K_2O (10-30-20 kg/ha) and a small amount of borax were applied to the red soil mung bean field at one time to ensure the nutrients required for root development and flowering and podding in the seedling stage. In terms of variety selection, mung bean varieties that are resistant to barrenness and diseases and have good commercial properties are used, such as "Guilu X", which has a well-developed root system and strong adaptability to acidic soil. Combined with the above-mentioned soil improvement measures, the yield potential of this variety can be brought into play. In terms of field management, ridge planting is implemented to improve drainage, and straw is added to retain moisture and reduce temperature, thereby reducing the adverse effects of high temperature and drought in red soil on mung bean grain filling. The results show that the red soil mung bean field that has undergone soil improvement and fine management has excellent mung bean grain quality and an increase of more than 20% in yield compared with ordinary management (Ma et al., 2020).

Similarly, in some hilly red soil areas in Yunnan and Guizhou, the soybean-corn strip intercropping technology was promoted, using corn shading to reduce soil temperature and improving soil structure through root complementarity, which also achieved the successful practice of "increasing soybean production without reducing corn production". These areas also attach great importance to the application of biofertilizers. For example, the application of biofertilizers in red soil peanut fields significantly promoted nodule development and root absorption capacity, proving the yield-increasing potential of microbial inputs in low-fertility soils (Liu et al., 2021). The high-quality and efficient production of beans in the red soil area of Southwest China embodies the combination of "soil improvement + good varieties and good methods": by improving soil acid and fertilizer conditions, selecting varieties with good stress tolerance, and adopting cultivation techniques such as mulching and intercropping, higher bean yields and quality can be obtained on originally medium- and low-yield soils. This provides a demonstration for the development and utilization of low-fertility soils in southern China, which is of great significance to improving the level of grain and bean production in these areas.

8 Concluding Remarks

Soil type has a decisive influence on the efficient cultivation of legumes, and different management techniques need to be adopted under different soil conditions. In heavy clay soils, the key is to improve ventilation and drainage conditions to prevent waterlogging and root damage, which can be achieved by deep ploughing and loosening and improving the drainage system; on sandy soils, attention should be paid to water conservation and fertilization, and measures such as mulching and increasing organic matter should be adopted to reduce drought and nutrient loss. In acidic and barren soils, pH adjustment and supplementation of deficient nutrients are the key points. Usually, lime or biochar should be applied to neutralize acidity, and balanced fertilization should be applied; on the contrary, in alkaline saline soils, gypsum is applied to reduce alkalinity, and salt-resistant varieties and salt-tolerant bacteria are used to alleviate salt damage. For loam with sufficient fertility, its advantages can be fully utilized to implement dense planting and high-yield cultivation, while paying attention not to apply excessive nitrogen to avoid inhibiting nitrogen fixation. In all soil types, improving soil organic matter and reasonable crop rotation are common measures to promote stable yield of legumes. Therefore, soil texture, pH and nutrient status should be comprehensively considered to formulate a matching cultivation plan to achieve the goal of adapting to the soil. Through the above typical cases, we can see that the three major regions of black soil, alkaline soil and red soil have formed representative high-efficiency bean cultivation technology models, and the core of these models is to manage the soil limiting factors in a targeted manner.

A large number of practices have shown that only by optimizing cultivation management according to local conditions based on soil conditions can the yield potential of bean crops be fully utilized. A single model cannot be applied to all soils, and inappropriate management may be counterproductive or even damage the soil ecology. For example, excessive deep plowing on well-drained sandy soil will aggravate water loss; excessive nitrogen application on fertile black soil will not only waste but also inhibit the nitrogen fixation of soybean nodules. On the contrary, precise improvement of soil shortcomings, such as applying lime to acidic soil, gypsum to alkaline soil, and increasing organic matter in barren soil, and matching cultivation measures can achieve significant results. Adapting to local conditions also means adapting to crops. Different legume varieties have different tolerance to soil stress, and varieties and matching strains that are adapted to soil conditions should be selected. For example, acid-tolerant rhizobia are specifically used for highly acidic red soils, and salt-tolerant strains are used for coastal saline soils to improve the effectiveness of inoculation. Therefore, agricultural technology promotion and farmers' planting need to establish the concept of "looking at the soil and the dish", and choose appropriate technology according to soil characteristics instead of "one size fits all". Only in this way can we ensure both bean yields and soil health and achieve sustainable agricultural development.

Looking to the future, bean crop cultivation technology for different soil types will develop in the direction of integrated innovation and precision management. On the one hand, it is necessary to organically integrate soil improvement, fertilizer and water management, variety selection and biotechnology to form a comprehensive supporting solution. For example, the combination of acid-resistant varieties, lime improvement, bacterial agent seed dressing and water conservation mulching for red soil mung bean production is expected to have better results than the simple superposition of single measures. This kind of technical integration requires experts in different fields to work together to develop modular cultivation technology models for farmers to choose. On the other hand, regional customized promotion will be more important. Localities should promote suitable and efficient bean cultivation models based on local soil resources and planting traditions. For example, soybean conservation tillage technology is promoted in the Northeast Black Soil Conservation Area, salt-tolerant bacterial fertilizer + deep loosening and soil improvement model is demonstrated in the Northwest saline-alkali land, and lime + organic fertilizer is promoted in the southern red soil area to improve the planting of high-quality soybean seeds. Government agricultural departments and scientific research and promotion units should strengthen the zoning evaluation of soil types, formulate regional bean production increase plans based on soil conditions, and strengthen training and guidance to enable farmers to master soil management methods. With the development of technologies such as soil sensing, big data and artificial intelligence, it is expected that real-time monitoring and precise policy implementation of soil in different fields can be achieved in the future, such as guiding irrigation and fertilization through soil sensor networks and using drones to monitor growth and timely remedies.

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