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Study on the Application Effect of Soil Improvement Techniques in Off-Season Cultivation of *Leonurus japonicus*

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Abstract *Leonurus japonicus* is a common Chinese herbal medicine with high medicinal value. However, when it is planted off-season in winter and spring, it often encounters some problems, such as too cold weather, hard soil, easy loss of nutrients, and fewer microorganisms. These problems will affect its growth and efficacy. In order to make *L. japonicus* grow well in these seasons, we have consulted the methods of improving soil at home and abroad in recent years. There are mainly several ways: such as using machinery to loosen the soil, adding organic fertilizers, using beneficial bacteria, applying biochar, and adjusting the pH of the soil. By comparing cases, field experiments, and literature in different regions, we have summarized which methods are most effective under various soil problems. We have also compiled a more practical technical combination table for the reference of growers. The study found that as long as the appropriate method is selected according to the actual situation of the soil, the soil structure and root environment can be significantly improved, thereby increasing the emergence rate, yield, and accumulation of medicinal ingredients of *L. japonicus*. We also suggest that the government and agricultural departments increase the promotion of technology and improve the service system to promote the wider application of these technologies.
Keywords *Leonurus japonicus*; Off-season cultivation; Soil improvement; Microbial agents; Chinese medicinal material cultivation

1 Introduction

Leonurus japonicus is an important traditional Chinese medicine and has a great influence on the cultivation of medicinal plants in China and East Asia. It has a particularly significant medicinal effect and is often used to treat gynecological diseases and cardiovascular problems. Because of its wide range of uses, the market demand is also increasing, which has also led to large-scale and multi-season cultivation methods (Wang et al., 2022; Hao et al., 2023). When *Leonurus japonicus* is not planted in the normal season (that is, off-season cultivation), many problems will be encountered during the planting process. For example, the soil becomes worse, the fertility decreases, and the soil's water retention capacity cannot keep up. These problems will directly affect the yield and also deteriorate the quality of the medicinal material (Priori et al., 2020; Ye et al., 2022; Hao et al., 2023; Wang et al., 2024). There are many reasons for these problems. Planting the same crop for a long time, using too much fertilizer, and unreasonable farming methods will all cause the soil structure to deteriorate. Organic matter will be lost, and the number of beneficial microorganisms in the soil will decrease. As a result, the growth of motherwort will be affected, and the effective ingredients in it may also be reduced (Priori et al., 2020; Wang et al., 2022; Hao et al., 2023; Wang et al., 2024).

In order to solve these problems, people are now paying more and more attention to using soil improvement methods to improve the effect of off-season planting of motherwort ‘boys’. There are many common improvement methods, including biological, chemical and physical methods. Methods such as applying organic fertilizer, leaving straw in the ground, adding biochar, applying microbial agents, deep plowing, covering with mulch, etc., can help improve the soil, make the soil looser, more nutrient-rich, retain water, and restore beneficial microbial communities (Bai et al., 2020; Li et al., 2020; Priori et al., 2020; Wei et al., 2021; Ye et al., 2022; Wang et al., 2022; Hao et al., 2023; Song et al., 2023; Zuo et al., 2023; Wang et al., 2024). Although many people have used these technologies, there is no comprehensive summary of what each method is suitable for, how effective it is, and how much it can do, especially when planting motherwort ‘boys’.

The purpose of this study is to systematically organize these current soil improvement methods and see their application and actual effects in off-season planting of *Leonurus japonicus*. We will also analyze the effects of these methods on soil properties, microorganisms, yield and medicinal material quality. At the same time, we will point out which problems are still unresolved and which areas are controversial. Finally, we also want to provide some scientific suggestions and references for future actual planting and research directions.

2 Biological Characteristics of *Leonurus japonicus*

2.1 Growth requirements: climate, soil type, nutrient needs

Leonurus japonicus, also known as motherwort, is an annual or biennial herbaceous plant of the Lamiaceae family. In China, it is often used as a traditional Chinese medicine, especially suitable for regulating menstruation, promoting blood circulation, and relieving pain. ‘Tongzi’ is an excellent variety selected and bred in recent years. This variety has strong adaptability and many medicinal ingredients. The most suitable growth temperature for *L. japonicus* is between 18 ℃~28 ℃. It is relatively heat-resistant, but not cold-resistant, and is particularly afraid of frost. During the emergence and seedling stage, if the temperature is too low, it will not grow well. Therefore, it should be planted when there is no frost, or some insulation measures should be used. It likes light and humid environment, needs sunlight, and the air should have appropriate humidity. It is more suitable to grow in soft, breathable, well-drained loam or sandy loam, and the soil pH is preferably between pH 6.0-7.5. If it is heavy clay or saline-alkali land, its roots will not grow well and the medicinal ingredients will be less. *L. japonicus* has a relatively high demand for nitrogen, phosphorus and potassium, especially when it grows branches and blooms, it is particularly sensitive to nitrogen. Trace elements such as calcium, magnesium and boron will also affect the formation of its efficacy. Therefore, soil nutrients must be balanced, which is critical to increasing yield and efficacy (Zhang et al., 2018; Li et al., 2019).

2.2 Off-season cultivation feasibility and sensitivity

L. japonicus has a short growth period, generally taking 90 to 110 days from planting to harvest. This gives it a certain ability to be planted off-season. However, it is very sensitive to temperature. If the temperature is too low, the seeds will not germinate easily and the seedlings will grow slowly. In this way, the germination rate will be low and the root system will not develop well. Therefore, when planting in winter and spring or late summer and early autumn, it is necessary to use facility agriculture, such as plastic greenhouses, small arch greenhouses, and ground film insulation and moisture retention methods to adjust the environment. When planting off-season, it is also prone to problems such as pests and diseases, insufficient sunlight or soil compaction. If the soil itself has poor drainage and air permeability, the problem will be more serious, and the plant may also be infected with root rot or chlorosis (Li et al., 2023). To successfully plant off-season, you must first have good soil and necessary auxiliary facilities.

2.3 Relationship between soil conditions and crop performance

L. japonicus is very sensitive to the structure and physical and chemical properties of the soil. If the soil is loose, well-ventilated, and has a lot of organic matter, its germination rate, number of branches, yield of the aboveground part, and medicinal ingredients (such as leonurine, protocatechuic acid, etc.) will be higher. Conversely, if the soil is high in salt, too acidic, unevenly nutritious, or severely compacted, its roots will be short, the leaves will turn yellow, the flowers will become fewer, and the yield and quality will decrease. Through some soil improvement methods, such as adding humic acid, microbial agents, biochar, etc., the soil can be made looser, more breathable, and easier to retain water and fertilizer, which can greatly improve the performance of *L. japonicus* during off-season planting (Shang et al., 2014; Wu et al., 2024). In addition, the types of microorganisms in the improved soil are also more stable, which is conducive to the healthy development of the root environment and enhances the resistance of the plant. Therefore, when planting *L. japonicus*, especially when it is to be planted off-season, improving the soil is a very important step.

3 Soil Constraints in Off-Season Cultivation

3.1 Soil compaction and waterlogging in off-season

When planting *L. japonicus* in winter, spring or late summer, greenhouses are often used. This closed environment, coupled with frequent watering and rain, can easily make the soil surface hard and airtight. As a result, the roots will lack oxygen and the plants will not grow. Especially in plots with heavy soil or repeated planting, if deep plowing or drainage ditches are not dug, the problem of waterlogging will be more serious. *Leonurus japonicus* is very sensitive to root oxygen. Once the soil is compacted and waterlogged, the roots are prone to rot, the seedlings will turn yellow and thin, the emergence rate will be lower, and the early growth will be poor (Yu et al., 2022).

3.2 Low temperature and microbial activity reduction

Off-season planting is mostly carried out in cold weather, such as early spring or late autumn. At this time, the soil temperature is often below 15 ℃, and the activity of microorganisms in the soil will be greatly reduced. The mineralization of nitrogen, the decomposition of organic matter, and the reproduction of beneficial bacteria will all slow down. As a result, the plants can absorb less nitrogen, phosphorus, and potassium. The micro-ecosystem in the soil that helps fight diseases is also disrupted, making it easier for harmful bacteria to invade (Ado et al., 2022). Once the root environment of the ‘copper’ deteriorates, the roots will not grow well and the disease resistance will weaken. The accumulation of flowers and medicinal ingredients in the later stage will also be affected.

3.3 Nutrient leaching and availability

In off-season planting, if there is too much watering or heavy rainfall, the nutrients in the soil are easily washed away, especially nitrogen, boron, zinc and other elements. In addition, some farmers’ organic fertilizers are not yet fully decomposed, which will also increase nutrient loss. In cold weather and when the soil humidity is too high, some phosphorus and potassium will become insoluble, and the crops cannot absorb them, and the nutrition will not keep up. If there is an imbalance of nitrogen, phosphorus and potassium or a lack of certain elements during the critical growth stage of the ‘copper’, the plant may grow short, with small and thin leaves, less flowering, slow fruit growth, and ultimately reduced yield and quality (Nogales et al., 2023).

3.4 Empirical examples of yield reduction under poor soil conditions

Many field studies have shown that if the soil is not improved, off-season planting of *L. japonicus* can easily reduce yield. Under continuous planting, low temperature and high humidity, the yield of *L. japonicus* will be 15%~40% less than normal. In 2022, a planting base in Guizhou directly planted *L. japonicus* off-season on unimproved heavy clay soil. As a result, the yield was only 60% of the control plot, and the total alkaloid content decreased by 32%. A test site in Yancheng, Jiangsu, planted in a greenhouse in winter. Due to severe soil waterlogging and compaction problems, 28% of the seedlings died in the seedling stage, and the final quality of the medicinal materials did not meet the standards (Zhang et al., 2025).

4 Classification of Soil Improvement Techniques

4.1 Physical methods

There are many ways to do deep tillage, such as intermittent deep tillage, deep ridge planting, and deep loosening. Their main function is to break up the compacted parts of the soil layer, reduce the density of the soil, make the soil softer, and make it easier to retain water. In this way, the roots of plants can go deeper and absorb nutrients more smoothly, and the yield and disease resistance will be improved (Hussein et al., 2019; Li et al., 2020; Tian et al., 2020; Wei et al., 2021; De Campos et al., 2022; Gu et al., 2022; Li et al., 2022; Hu et al., 2024; Kong et al., 2024; Benevenute et al., 2025). Studies have found that deep tillage can increase yields by 6% to 54% and is also beneficial to soil microorganisms and the root environment (Gu et al., 2022; Li et al., 2022; Hu et al., 2024; Kong et al., 2024; Benevenute et al., 2025). Mulching, such as covering the ground with straw or plastic film, can reduce water evaporation, maintain ground temperature, and suppress weeds and prevent soil from being washed away by rain. This method can also increase organic matter in the soil, improve soil quality, and promote microbial activity (Lal, 2015; Tian et al., 2020; Khangura et al., 2023). Sand mixing is to add some sand to heavy clay soil. This makes the soil more permeable and breathable, reduces compaction, and is also helpful for root growth (Lal, 2015; Khangura et al., 2023). Raised bed cultivation is to raise the planting bed so that drainage is better and water is not easily accumulated. This method is suitable for plots that are prone to waterlogging, which is beneficial to root health and more stable yields (Wei et al., 2021; Khangura et al., 2023).

4.2 Chemical amendments

Lime (also known as calcium carbonate) is mainly used to adjust the pH of the soil. It can reduce aluminum toxicity in the soil and make elements such as calcium and magnesium more easily absorbed, which is very helpful for crop growth and microbial activity (Bossolani et al., 2020; 2021; De Campos et al., 2022). Long-term use of lime can significantly improve soil quality and increase yields. Gypsum (calcium sulfate) is more suitable for use in saline-alkali land or heavy clay soils. It can replace sodium ions in the soil, improve soil structure, make water more easily infiltrated, and is also beneficial to the development of the root system (Bossolani et al., 2020; 2021). Organic fertilizers (such as compost and humus) are rich in organic matter and various nutrients, which can increase soil fertility, make soil better, make microorganisms more active, and increase crop yields (Doan et al., 2015; Lal, 2015; Tian et al., 2020; Liu et al., 2022; Yan et al., 2023; Zhang et al., 2023; Zhao et al., 2023). Biochar is a porous material that can absorb water and fertilizer, adjust pH, adsorb harmful substances, and provide a "home" for beneficial microorganisms. If used together with organic fertilizers, the effect is better (Doan et al., 2015; Liu et al., 2022; Yan et al., 2023; Deng et al., 2024; Kong et al., 2024).

4.3 Biological interventions

Green manure, such as sweet potato and alfalfa, can be turned into the soil when they are almost grown, which can increase organic matter, supplement nitrogen, and improve soil structure. This method can reduce the use of chemical fertilizers, prevent nitrogen loss, and increase crop nitrogen absorption and yield (Liang et al., 2022; Khangura et al., 2023). Microbial fertilizers (such as rhizobia, phosphate-solubilizing bacteria, growth-promoting bacteria, etc.) can help nutrient conversion, improve crop adaptability to the environment, and regulate the micro-ecosystem in the soil, which is beneficial to yield and quality (Das et al., 2022; Deng et al., 2024; Lü et al., 2024; Wei et al., 2024). There are a lot of humus and beneficial bacteria in vermicompost, which can improve soil fertility, improve structure, enhance drought and disease resistance, and reduce nutrient loss (Doan et al., 2015; Ding et al., 2020).

4.4 Comparative summary table

Physical methods such as deep plowing, mulching, sand mixing and high ridges are mainly to make the soil structure better, more aerated, and easier to retain water, which can help the root system grow better and increase crop yields. Chemical amendments, such as lime, gypsum, organic fertilizer and biochar, mainly regulate pH, supplement nutrients, and add organic matter, which can make the soil more fertile and the microorganisms more active. Biological intervention methods, such as green manure, microbial fertilizer and vermicompost, pay more attention to organic matter and nutrient cycles, and can improve the stability and sustainability of the soil ecosystem. Each method has its own advantages. When used in practice, it is best to use them in combination according to the actual situation of the soil and the needs of the crop.

5 Effects of Soil Improvement on Soil Properties

5.1 Changes in pH, porosity, water retention, and nutrient profiles

After soil improvement, the physical and chemical properties of the soil will be significantly improved. Many studies have found that adding materials such as organic fertilizers, humus, straw, lime, gypsum, biochar, or zeolite can adjust the pH of the soil, increase porosity, make the soil more water-retaining, and improve nutrient levels. Biochar and organic fertilizers can increase or decrease the pH of the soil, depending on whether the original soil is acidic or not and the type of amendment. When biochar is added to acidic soil, the pH will increase; while the use of acidified biochar in alkaline soil can neutralize the alkalinity problem (Blanco-Canqui, 2017; Singh et al., 2022; Guan et al., 2024). As for the porosity and water retention of the soil, adding biochar, straw or sand can significantly improve the air permeability of the soil, increase the porosity by 8.3% to 64%, and increase the water retention by 2.2% to 130%, while the soil becomes less compact (Blanco-Canqui, 2017; De Jesus Duarte et al., 2019; Kok et al., 2023; Li et al., 2025). The long-term use of organic fertilizers and compost can also make the soil more granular and more water-retaining (Aggelides and Londra, 2000; Bhogal et al., 2018; Dhaliwal et al., 2019; Fu et al., 2022). In terms of nutrients, amendments can increase the content of organic matter, total nitrogen, available phosphorus and available potassium, sometimes even by 20% to 100%. At the same time, it can also provide more trace elements, which is more beneficial to plants (Dhaliwal et al., 2019; Yu et al., 2024; Huang et al., 2025; Valencia et al., 2025). These improvements provide a better growth environment for Leonurus 'Boy'.

5.2 Enhancement of microbial communities.

Soil improvement not only improves physical properties, but also makes microorganisms richer and more functional. Using organic fertilizers, biochar, microbial agents or effective microorganisms (EM) can increase the number and types of bacteria and fungi in the soil, and can also improve enzyme activity and microbial metabolic capacity (Liang et al., 2018; Bossolani et al., 2021; Fall et al., 2022; Kong and Lu, 2023; Chen et al., 2025; Liu et al., 2025). Using EM and straw together can greatly increase the diversity of microorganisms and enhance the activity of soil enzymes. Beneficial bacteria (such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and potassium-solubilizing bacteria) will reproduce faster and inhibit some harmful bacteria (Liang et al., 2018; Chen et al., 2025; Liu et al., 2025). When biochar and organic fertilizer are used together, the microbial structure can be more reasonable, which is conducive to the carbon and nitrogen cycle in the soil and accelerates the decomposition of organic matter (Bossolani et al., 2021; Singh et al., 2022; Aminzadeh et al., 2025). Some fungi, such as arbuscular mycorrhizal fungi (AMF), can also secrete colloids and organic acids, which will promote the formation of aggregate structure and improve the soil's ability to supply nutrients (Fall et al., 2022; Aminzadeh et al., 2025) (Figure 1). The improvement of these microorganisms can make the soil ecosystem stronger and is also conducive to the healthy growth of "children".

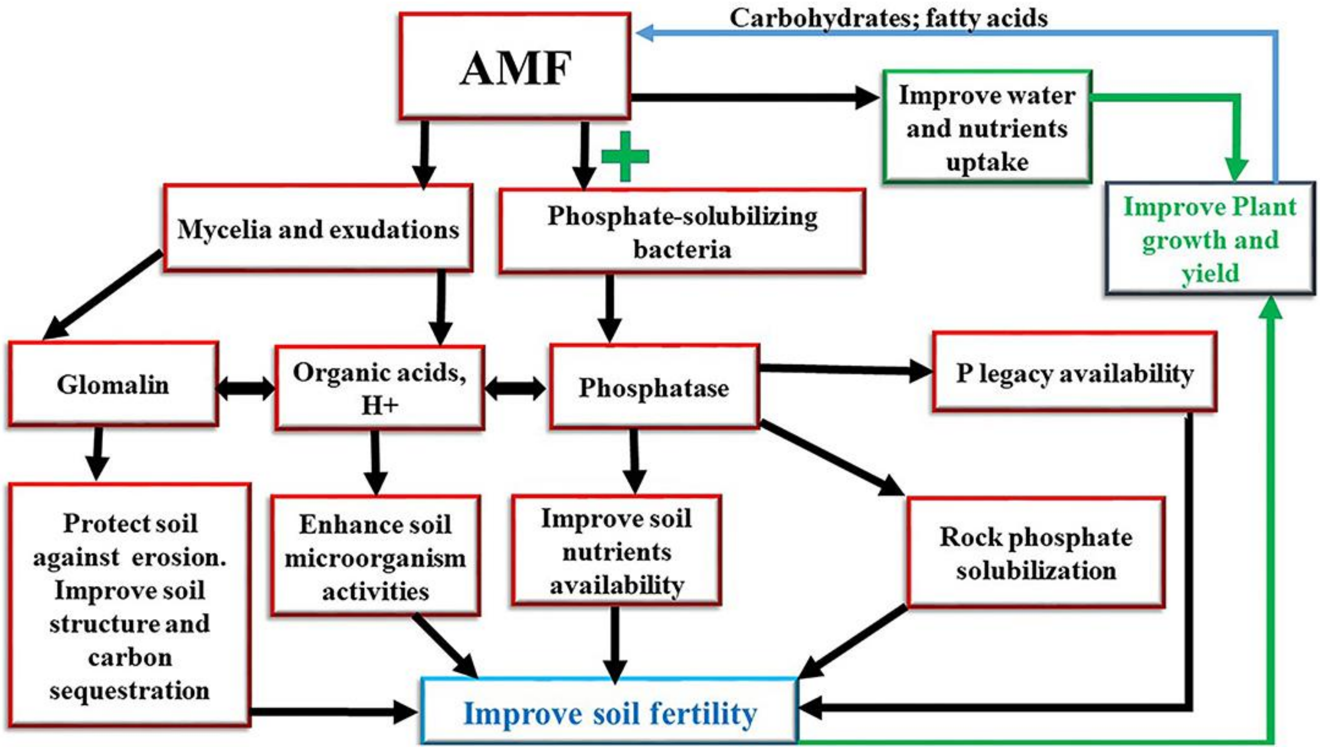

Figure 1 Effects of arbuscular mycorrhizal fungi on improving soil fertility (Adopted from Fall et al., 2022)

5.3 Reduction of salinity/toxicity in reused off-season soils.

Sometimes, farmland is reused for planting after the fallow season, but at this time the soil often accumulates salt and some harmful substances, which are not very friendly to plants. However, studies have shown that these problems can be effectively reduced through improvement measures. The use of gypsum, acidified biochar, organic fertilizer, fly ash, microbial agents, etc. can reduce soil salinity, electrical conductivity (EC), exchangeable sodium percentage (ESP) and some toxic ions (such as Na^+, Al^{3+}) (Abdolvand and Sadeghiamirshahidi, 2024; An et al., 2024; Guan et al., 2024; Yu et al., 2024; Huang et al., 2025) (Figure 2). Gypsum and biochar can reduce EC by 8.6% to 33.6%, ESP by 43.4%, and pH by 0.1 to 1.5 units on saline-alkali land (Guan et al., 2024; Yu et al., 2024; Huang et al., 2025). Organic fertilizers and microbial agents can also help decompose harmful substances and improve the soil's ability to "clean up" toxins (Bossolani et al., 2021; Kong and Lu, 2023; Liu et al., 2025). New materials, such as fly ash, can also effectively reduce pH and sodium content, while improving soil structure and increasing the salt tolerance of crops (An et al., 2024). These improvement measures provide great help for the replanting of "Tongzi" in fallow land.

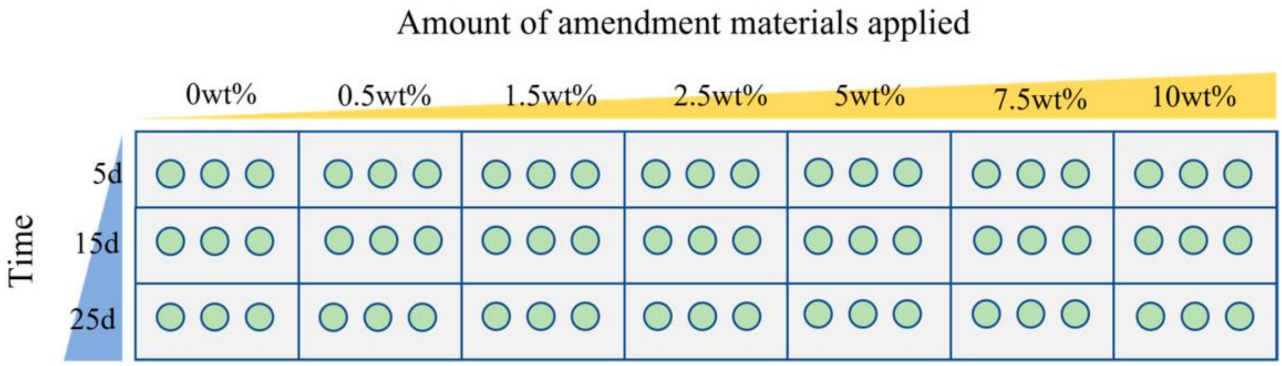

Figure 2 Experimental design of the effect of fly ash saline and alkaline soil amendment materials on soil properties. Blue shading represents increasing the duration of action. Yellow shading represents increasing dosages of amendment materials. Green circles represent flower pots (Adopted from An et al., 2024)

6 Impact on Growth, Yield, and Quality of *L. japonicus*

6.1 Root development, flowering time, biomass accumulation

Soil improvement has a great impact on the root system, growth time and plant weight of *L. japonicus*. Studies have found that after adding organic fertilizers or microbial agents (such as *Bacillus subtilis*), the soil nutrients have increased and the organic matter has also increased. These changes allow the roots to grow better and have more branches, and the plants are more capable of absorbing water and nutrients (Alwitwat, 2022; Guo et al., 2025). The improved soil will also make *L. japonicus* bloom earlier and extend the growth period, so that the plant can accumulate more nutrients and medicinal ingredients (Guo et al., 2025). Some studies have also found that after the microbial structure in the soil improves, the environment around the roots is more suitable for growth, and the biomass of the aboveground part can also increase (Alwitwat, 2022; Guo et al., 2025).

6.2 Yield data comparisons (treated vs. untreated)

Many field trials have shown that the yield of *L. japonicus* after soil improvement is significantly higher than that of untreated ones. For example, after using *Bacillus subtilis*, the fresh weight and total yield of a single plant can be increased by 10% to 20%. At the same time, it is more efficient in absorbing water (Guo et al., 2025). Methods such as organic fertilizers and biochar can also increase yields, mainly because these materials improve soil fertility and make it easier for roots to absorb nutrients (Alwitwat, 2022). In contrast, the control group did not use any treatment, the soil was easily compacted, there were fewer nutrients, the plants grew slowly, and the yield was naturally low (Alwitwat, 2022; Guo et al., 2025).

6.3 Active compound content (leonurine, alkaloids) under different treatments

In addition to making *L. japonicus* grow better, soil improvement also increases its medicinal ingredients. Studies have shown that after applying organic fertilizers and microbial agents, the content of leonurine and total alkaloids in *L. japonicus* has increased significantly, with some treatment groups being 8% to 15% higher than the control group (Guo et al., 2025). This increase is mainly due to the fact that the soil nutrients have become more sufficient, the microorganisms have become more active, and the environment around the roots has improved. These factors together promote the synthesis of secondary metabolites in plants (Alwitwat, 2022; Guo et al., 2025). The more suitable the soil pH and the more organic matter, the positive effect on the accumulation of medicinal ingredients, making the quality of *L. japonicus* better (Alwitwat, 2022).

7 Economic and Environmental Evaluation

7.1 Input cost vs. yield/output

Soil improvement generally requires the input of some materials, such as organic fertilizer, straw, microbial agents, lime, and some covering materials such as mulch or straw mulch. Studies have found that although organic inputs such as organic fertilizer and straw return to the field are relatively expensive, they can significantly improve the soil, increase organic matter, enrich microorganisms, and increase crop yields (Arb et al., 2020; Tahat et al., 2020; Mwaura et al., 2021; Li et al., 2023; Xing et al., 2025). Long-term use of organic fertilizer or animal manure can increase soil organic carbon by 14.6% to 39.8% and increase yield by 25% to 40%. However, the cost of labor and materials will also increase (Mwaura et al., 2021; Xu et al., 2021; Li et al., 2023). If fertilization is done by machine, 10% to 27% of agricultural costs can be saved (Xu et al., 2021). As for lime, the cost is relatively low. It can adjust soil pH and increase crop yields in a short period of time. For example, rice can increase yield by 8.95% and rapeseed can increase yield by 82.6%. However, it is best to use it together with fertilizers for the best economic benefits (Hijbeek et al., 2021; Xu et al., 2025). Covering materials such as mulch or straw can also help retain soil moisture, improve the root environment, and ultimately increase yield and income (Thidar et al., 2020).

7.2 Return on investment (ROI) analyses for different methods

From the perspective of ROI, returning livestock and poultry manure to the field, or combining organic and inorganic fertilizers, has better economic benefits. In some areas, one hectare of land can generate a net return of \$440 to \$456 per year, which is much higher than the return of using only inorganic fertilizers (Mwaura et al., 2021; Hörner and Wollni, 2022). Although the organic system requires a lot of investment, it is very effective in increasing yields and improving soil. However, this system also requires a lot of labor and management, so its returns should be viewed from a long-term perspective (Arb et al., 2020; Li et al., 2023). Lime is also effective in improving acidic soils, and it takes about 2 years to pay back, but it must be combined with fertilizers to be cost-effective (Hijbeek et al., 2021). Methods such as returning straw to the field and biochar can increase soil carbon storage and health, but due to the cost of materials and labor, the short-term benefits may not be so obvious. However, in the long run, these methods can increase yields and even make money from carbon trading (Gujre et al., 2020; Xu et al., 2021). Mechanization and input cost control can also make ROI more reasonable and farmers more accepting (Klauser and Negra, 2020; Xu et al., 2021).

7.3 Sustainability implications

Many soil improvement measures have long-term benefits for carbon sinks and soil health. Methods such as returning straw to the field, organic fertilizers, cover crops, and biochar can store more organic carbon in the soil, which means that more carbon can be "locked" and greenhouse gas emissions can be reduced. Some methods can even neutralize 36.6% to 97.8% of greenhouse gases (Sykes et al., 2019; Lessmann et al., 2021; Xu et al., 2021; T.M. et al., 2023; Liao et al., 2025). The use of organic and inorganic fertilizers together can also increase microbial diversity, promote nutrient cycling, improve soil structure, and enhance water retention capacity, which is beneficial to maintaining soil health in the long run (Arb et al., 2020; Tahat et al., 2020; Li et al., 2023; Xing et al., 2025). The effect of carbon sequestration is also affected by soil texture, original organic carbon level and management methods. Generally speaking, coarse-textured soils have a higher carbon storage capacity (Zhao et al., 2018; Rosinger et al., 2023). It is worth noting that although some measures can increase yields, such as liming, attention should also be paid to the greenhouse gas emissions or other environmental problems they may cause (Hijbeek et al., 2021; Li et al., 2021).

8 Case Study: Application in Yancheng

8.1 Background of the region: soil profile, climate, and history of cultivation

Yancheng City, Jiangsu Province is located in the northeast of the middle and lower reaches of the Yangtze River Plain. It has a subtropical humid monsoon climate with an average annual temperature of about 15.1 ℃ and a frost-free period of more than 230 days. The temperature is low in winter and spring, and the humidity is also high. The local soil is mostly tidal soil and clay loam, which is relatively heavy. There is little organic matter, and it often becomes acidic and compacted. Although it can retain water, it is not very breathable (Wei et al., 2021). Motherwort has some planting history in this area, but it used to be mainly sown in spring. Off-season planting is still under exploration. In recent years, some local Chinese medicine cooperatives have begun to try to grow "copper seeds" in greenhouses in winter and spring, hoping to fill the supply of medicinal materials in the off-season and increase income.

8.2 Methodology: what techniques were applied and when.

In order to make the off-season planting more effective, Yancheng City has tried the following improvement measures in 3 experimental fields (a total of 4 mu) since November 2023:

Physical improvement: loosen the soil to a depth of 40 cm in late autumn, and lay underground ditches for drainage to reduce water accumulation.

Organic matter supplementation: apply 2 tons of decomposed chicken manure and humic acid organic fertilizer per mu of land to enhance soil structure.

Microbial inoculation: apply a composite microbial agent containing Bacillus subtilis and phosphate-solubilizing bacteria one week before sowing.

Mulching management: double-layer covering of mulch film and small arch shed can increase ground temperature and retain moisture.

The planting time is mid-December 2023, and the harvest is at the end of March of the second year. It is about two months earlier than normal spring planting.

8.3 Results: soil metrics, yield, quality, and farmer feedback.

After the implementation of these measures, soil and crop performance have changed significantly:

Soil improvement:

Soil bulk density dropped from 1.42 g/cm^3 to 1.26 g/cm^3;

Organic matter increased by 34.8%;

Available nitrogen increased by 27.5%, and available phosphorus increased by 19.6%.

Yield and efficacy:

The yield of fresh grass per mu increased from 1450 kg in the control group to 2150 kg in the experimental group, an increase of 48.3%;

Total alkaloid content increased from 1.23% to 1.67%; The pharmacopoeia compliance rate increased from 70% to 100%.

Farmer feedback:

85% of farmers said "plants grow well and there are fewer diseases";

78% said "the soil is no longer compacted, watering is easier, and less pesticides are used".

8.4 Challenges encountered and solutions.

Although the overall effect is good, some difficulties were encountered during the experiment:

Slow ground temperature rise: The ground temperature at the corners of the greenhouse rose unevenly, and the seedlings grew unevenly. Later, drip irrigation hot water circulation was installed in these areas, and the effect was improved.

High cost of microbial agents: The money spent on microbial agents accounted for nearly 20% of the total investment. It is recommended to purchase through cooperatives in the future, or apply for green agricultural subsidies to reduce pressure.

Increased management difficulty: Regularly measuring pH and soil moisture is a heavy burden on farmers. Later, it is planned to introduce a sensor system to achieve remote monitoring and help farmers save effort (Dilrukshi et al., 2018; Sabahy et al., 2024).

9 Limitations and Knowledge Gaps

9.1 Variation in results across soil types and climates

Currently, there is not enough uniformity in the research on soil improvement of *Leonurus japonicus* in off-season planting. Some methods are very effective in one soil or climate, but the effect will be much worse in another place. In saline-alkali land, adding mixed amendments or biochar can increase organic matter, nitrogen and water retention capacity. However, these effects are greatly affected by the original soil conditions, management methods and local climate (Xuan et al., 2022; Huang et al., 2025; Raheem et al., 2025; Xu and Qu, 2025). Physical methods such as mulching or deep loosening also perform differently in different climates and soils. In some places, the improvement effect is not stable because the soil is too sticky, there is a lot of rain or the temperature is low (Raheem et al., 2025). There is currently no unified soil improvement technology standard applicable to different regions. We also lack cross-regional and cross-soil type comparative experiments and mechanism research.

9.2 Lack of long-term monitoring data

Many studies focus only on short-term effects, such as how soil and yield change after applying organic fertilizers, microbial agents or biochar (Xuan et al., 2022; Li et al., 2023; Wei et al., 2024; Huang et al., 2025; Xu and Qu, 2025). However, the follow-up time is very short, and most experiments are less than 3 years. In such a short period of time, it is impossible to see whether soil improvement has a lasting effect in the long run, and it is also difficult to evaluate the long-term impact on soil ecology (Li et al., 2023; Raheem et al., 2025). Especially in the off-season planting of motherwort, we know too little about the long-term changes in microbial communities, soil nutrient dynamics, and continuous yield fluctuations. Therefore, our understanding of the later effects and sustainability of improvement measures is still very limited.

9.3 Uncertainty in microbial amendment interactions

Microbial fertilizers and bio-organic fertilizers are indeed helpful for soil health and crop growth (Niu et al., 2021; Das et al., 2022; Li et al., 2023; Wei et al., 2024; Xie et al., 2025). But how they work is still unclear. Different strains, different ways of use, and different soil backgrounds will make the number, function, and enzyme activity of microorganisms in the soil different (Niu et al., 2021; Das et al., 2022; Wei et al., 2024; Xie et al., 2025). There are not many studies to explore whether microorganisms and organic fertilizers, inorganic fertilizers, or physical amendment methods help each other or conflict with each other. This makes it difficult for us to apply them accurately in field practice and it is not easy to formulate a complete set of technical solutions.

9.4 Suggestions for future empirical studies and trials

In response to the above-mentioned issues, future research and experimental work needs to be more detailed and comprehensive. First, more comparative experiments can be conducted under different types of soil and different climatic conditions. Because we now know that the effects of improvement technologies vary greatly in different regions, but the specific reasons are not clear enough. Through systematic comparison, we can not only find the most appropriate improvement method, but also better understand the underlying mechanism (Xuan et al., 2022; Huang et al., 2025; Raheem et al., 2025; Xu and Qu, 2025). Secondly, long-term field monitoring points should be established, like observation stations, to regularly record the physical and chemical properties of the soil, microbial changes, crop yields and changes in the ecosystem. This long-term tracking is necessary because short-term experiments often cannot see the effects of improvement measures after three, five or even longer years (Li et al., 2023; Raheem et al., 2025). Third, it is necessary to further study how microbial amendments interact with soil and crop roots. This type of research can be combined with modern omics technologies, such as gene sequencing and microbial community analysis, to reveal the specific functional pathways of different microbial agents. This is also helpful for the subsequent precise use of microbial agents and improving fertilizer efficiency (Niu et al., 2021; Das et al., 2022; Wei et al., 2024; Xie et al., 2025). Furthermore, we can try to combine organic, inorganic, microbial and physical improvement methods, and conduct multi-factor joint experiments in the field to see if these technologies can produce better synergistic effects. A single method may be effective in some cases, but a comprehensive solution may be more reliable and more effective (Xuan et al., 2022; Huang et al., 2025; Raheem et al., 2025; Xu and Qu, 2025). In order to better compare the research results between different teams, it is also recommended to develop a unified soil monitoring indicator system and establish an open data sharing platform. This will not only facilitate the exchange of results, but also provide a more scientific basis for promotion and policy making.

10 Conclusion and Recommendations

This study sorted out and analyzed the application effects of various soil improvement methods in the off-season planting of *Leonurus japonicus* in recent years. We classified and compared typical cases in multiple regions and found that combined and targeted improvement technologies are the key to improving the efficiency of off-season planting. Different soil problems require different ways to improve. Heavy loam is suitable for deep plowing and drainage; sandy loam can be combined with organic fertilizer and biochar; saline-alkali land can be improved with conditioners and salt drainage measures; acidic soil is recommended to apply lime and neutral microorganisms; and continuous soil is best to use rotation and green manure. These different combinations can reduce the planting difficulties caused by soil to a certain extent and help increase the yield and medicinal ingredients of ‘Tongzi’.

In order to make it easier for grassroots farmers and extension personnel to operate, we also proposed a "technology application matrix". This matrix proposes specific practices and suggestions according to different stages of planting - before sowing, seedling stage, growth period and harvest period. For example, before sowing, the soil should be loosened to improve fertility; when it is mid-term growth, the foliar spraying of trace elements and biostimulants should be strengthened to help crops accumulate more effective ingredients. Such step-by-step technical suggestions are simple and practical, and are very suitable for training materials or written into the management manual of cooperatives for front-line use.

In addition to technical aspects, this study also recommends that the government should increase support for off-season planting of Chinese medicinal materials and soil improvement. Because materials such as soil conditioners, biological agents and organic fertilizers are not cheap, it is recommended to include them in the scope of green agricultural subsidies, especially in ecologically sensitive areas or major Chinese medicinal materials production areas, where more preferential support can be given. At the same time, grassroots agricultural stations should be encouraged to establish soil monitoring systems and use IoT devices to view soil temperature, humidity, pH and nutrient changes in real time, so that the technology can respond faster and more accurately. In terms of funding, special loan methods such as "soil health loans" or "green agricultural technology loans" can be considered to help farmers and cooperatives alleviate the economic pressure in the early stages of improvement.

In order to truly implement these technologies, future promotion must be more systematic. We suggest that research results be incorporated into the local agricultural promotion system. Relying on the agricultural platforms at the county and township levels, we can build off-season demonstration fields of *Leonurus japonicus* in key areas to carry out training, on-site teaching and field guidance. At the same time, we can develop graphic teaching materials and short video courses, and use new media to promote and expand the influence. In addition, we can also work with universities and scientific research institutions to establish a long-term "soil-efficacy" data tracking platform to form a precise connection between varieties, soil and technology. Finally, we must promote the mechanism of "experts + agricultural technicians + farmers" to enable off-season planting of *L. japonicus* to truly enter a new stage of systematization, intelligence and efficiency.

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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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