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Research on the Promotion and Application of Efficient Off-Season Cultivation Technology in the Industrialization of *Leonurus japonicus*

Shiying Yu [1], Lian Chen [2]
1 Biotechnology Resarch Center, Cuixi Academy of Biothchnology, Zhuji, 311800, China;
2 Institute of Life Science, Jiyang College of Zhejiang A&F University, Zhuji, 311800, China
Corresponding email: shiying.yu@cuixi.org
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Abstract *Leonurus japonicus* is a widely used medicinal plant in traditional Chinese medicine, known for its therapeutic effects such as regulating menstruation and promoting blood circulation. However, conventional open-field cultivation is often limited by seasonal changes, temperature, and rainfall, making the supply of medicinal materials unstable and unable to meet the growing demand for high-quality raw materials. By using greenhouses, adjusting light exposure, and controlling temperature and humidity, cultivation can be extended beyond traditional seasons. This study focuses on the growth characteristics of *L. japonicus*, examining its basic environmental requirements for temperature, light, and humidity. Experiments were conducted to adjust the cultivation substrate and manage environmental conditions. Changes in active compounds under different treatments were recorded. In addition to experimental data, the study reviewed real-world applications in various regions and assessed the input-output ratio of off-season cultivation. Common obstacles encountered during technical implementation were identified, and suggestions such as reducing the entry cost and improving the workflow were proposed. The research further explored how this cultivation model supports the entire industry chain by aligning well with downstream processing enterprises, promoting integration across planting, processing, and distribution. Based on actual production conditions, this study proposes practical improvements to optimize cultivation efficiency and enhance the medicinal quality of *L. japonicus*, offering useful insights for its broader application in the medicinal plant industry.
Keywords *Leonurus japonicus*; Off-season cultivation; Environmental control; Industrial development; Active compounds

1 Introduction

Leonurus japonicus is a commonly used medicinal plant in traditional Chinese medicine, often applied to regulate menstruation, promote blood circulation, and assist in treating cardiovascular conditions (Wang et al., 2023). Its therapeutic effects mainly come from leonurine, alkaloids, and flavonoids, which are known for their anti-inflammatory, antioxidant, and cardioprotective properties. These compounds give the plant strong potential in the pharmaceutical and health product industries.

In recent years, due to the continuous increase in the market demand for natural medicinal materials, wild resources have been overexploited, accelerating the rate of resource depletion. Therefore, it is necessary to rely on artificial cultivation to stabilize the supply (Xiao et al., 2017). However, traditional planting methods rely on seasonal changes, are vulnerable to climate impact, have short planting cycle, unstable yield and quality, and are difficult to achieve large-scale production (Zhang et al., 2022).

In order to solve these problems, off-season planting technology has been applied to the cultivation of *Leonurus japonicus*. Through greenhouse planting, environmental control and three-dimensional cultivation, the temperature, humidity and light can be adjusted, so that the plant can grow normally throughout the year. This method not only improves the yield per unit area, but also increases the content of active ingredients, while reducing the uncertainty caused by natural conditions (Miao et al., 2019; Wang et al., 2022a).

This study focuses on optimizing key factors such as temperature, light, and growing substrates in off-season cultivation of *L. japonicus*, aiming to improve yield and quality while ensuring a stable long-term supply. The limitations of conventional methods are discussed, and practical solutions are proposed to support scaled-up production and promote the development of the *L. japonicus* industry.

2 Growth Characteristics and Environmental Requirements of *Leonurus japonicus*

2.1 Biological traits and active compounds

Leonurus japonicus is an annual or biennial herbaceous plant that grows quickly and adapts well to various environments. It is widely distributed across many regions in China. The main medicinal compound is leonurine, known for its cardioprotective properties. The plant also contains various alkaloids and flavonoids with anti-inflammatory and antioxidant effects (Farooq et al., 2022). These active components are mainly concentrated in the aerial parts, particularly the leaves and flowers.

The full growth cycle typically ranges from 90 to 120 days. The plant is sensitive to changes in environmental conditions. Factors such as light intensity, soil quality, and nutrient availability directly influence both growth and the accumulation of active compounds (Calzadilla et al., 2019).

2.2 Key environmental factors affecting growth

The growth of *Leonurus japonicus* depends on suitable climatic conditions, and the optimum temperature is between 20 ℃ and 28 ℃. More light is needed during the growth period, and insufficient light will inhibit photosynthesis, thereby affecting the yield and synthesis of active ingredients. Slightly acidic or neutral loam soil is suitable for planting, which requires good drainage, medium fertility, and pH value between 6.0 and 7.5. The water supply must be balanced, neither long-term ponding nor long-term drought, otherwise it is easy to cause root rot or growth restriction (Kaducová et al., 2019).

When environmental conditions remain stable, the plant maintains good development and compound production. However, large fluctuations in temperature or humidity may reduce overall yield and quality.

2.3 Limitations of traditional cultivation

The traditional planting method mainly depends on the natural climate. Not only the sowing and harvesting time is limited, but also the yield and efficacy are difficult to ensure. In extreme weather, such as continuous rain or drought, it is more likely to affect the normal development of plants and cause losses.

This planting method needs to occupy a large area of arable land, and the utilization efficiency of land resources is low. If continuous cropping is encountered, soil degradation or disease accumulation may occur (Calzadilla et al., 2016). Due to the unstable planting conditions, the concentration of active ingredients in each batch of medicinal materials is prone to fluctuate, which is difficult to meet the requirements of traditional Chinese medicine enterprises for the consistency of the content of ingredients.

These practical problems show that the traditional mode has not adapted to the development needs of the current medicinal industry. In order to improve the stability of yield and efficacy, more and more studies began to pay attention to the application of off-season planting technology in the production of *Leonurus japonicus* to alleviate the limitations brought by the traditional mode (Shah et al., 2020) (Figure 1).

3 Principles and Advantages of Off-Season Cultivation Technology

3.1 Basic principles of environmental control

Off-season cultivation relies on adjusting environmental conditions so that crops can grow outside their natural seasons. This method is typically carried out in greenhouses or controlled growth chambers, where temperature, humidity, and light can be carefully managed. By setting suitable temperature ranges, regulating air moisture, and using artificial lighting, growers can maintain favorable conditions for plant growth. This approach helps ensure stable growth even in colder months or in areas with large day-night temperature differences, reducing the risk of yield loss caused by unpredictable weather (Weidner et al., 2021).

3.2 Advantages of greenhouse and vertical cultivation

Greenhouse planting can effectively isolate adverse weather such as wind, rain and frost, reduce the occurrence of diseases and pests, and reduce the frequency of pesticide use. The plants are protected in the greenhouse, with higher survival rate and more centralized management. Stereoscopic planting arranges crop growth by stacking up and down, which can expand the cultivation area on limited land, especially suitable for cities and land tension areas. This method can not only save space, but also improve the utilization efficiency of water and fertilizer, help to improve the yield per unit area and increase the planting efficiency (Koukounaras, 2020).

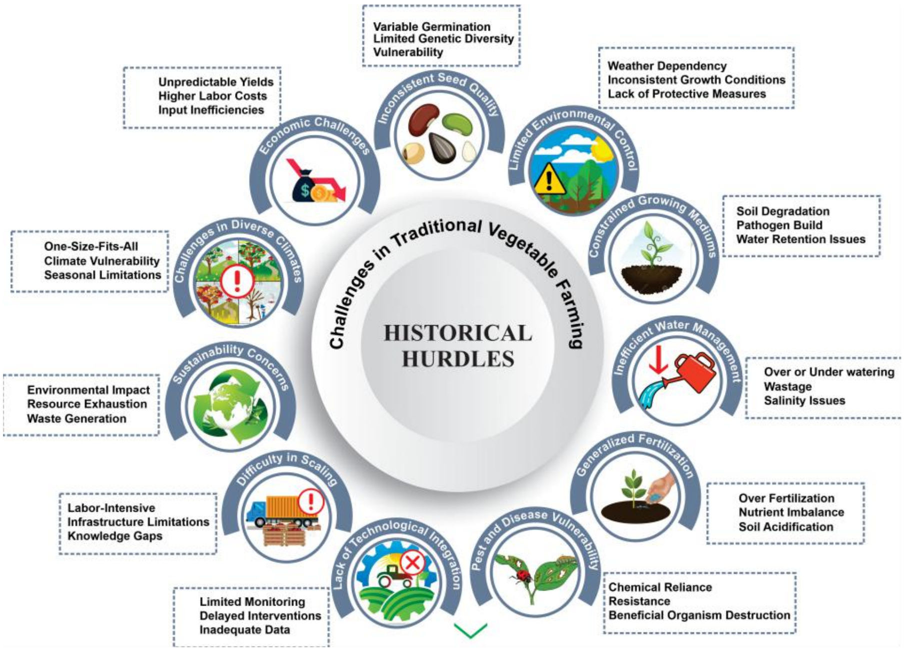

Figure 1 Challenges faced by traditional cultivation models of *Leonurus japonicus* (Adopted from Ahmed et al., 2024)

3.3 Effects on yield and quality

Off-season cultivation extends the growing period and often allows multiple harvests per year. With controlled conditions, plants grow more evenly and absorb nutrients more efficiently. This supports the accumulation of active compounds and leads to more consistent quality. Crops grown in these environments tend to have higher nutritional content, stronger medicinal properties, or better visual appearance. In addition, off-season techniques make it possible to grow climate-sensitive plants in regions where they normally wouldn't thrive, expanding crop variety and increasing market options (Duangpakdee and Sukpancharoen, 2024).

4 Optimization of Efficient Off-Season Cultivation Techniques

4.1 Substrate selection and fertilizer ratio

Choosing the right substrate and fertilizer combination is key to improving root development and balanced growth of *Leonurus japonicus* under off-season conditions. A mixture of peat, vermiculite, and perlite enhances water retention and aeration, supporting strong root systems and better seedling survival (Ahmed et al., 2024). Adding organic materials such as biochar or compost can further improve soil structure and boost microbial activity.

A nitrogen-phosphorus-potassium (N:P:K) ratio of 2:1:1 has been shown to promote growth and increase leonurine content. Using controlled-release fertilizers helps maintain a steady nutrient supply, reduces the need for frequent applications, improves nutrient use efficiency, and minimizes environmental impact (Zhang et al., 2018).

4.2 Temperature and light regulation

The suitable growth temperature of *Leonurus japonicus* is 20 ℃ to 28 ℃. High temperature is conducive to rapid growth, while appropriate low temperature stimulation is conducive to the synthesis of active ingredients, especially the accumulation of leonurine and flavonoids (Wang et al., 2022b).

Light has obvious effects on Photosynthesis and morphological regulation of plants. Red light can accelerate plant growth and promote biomass accumulation; Blue light is beneficial to leaf expansion and activation of secondary metabolic pathways. In the actual planting, the application of red and blue LED lights can effectively improve the photosynthetic efficiency. If the light duration and intensity are dynamically adjusted according to the growth stage, it can not only promote plant growth, but also reduce power consumption (Liu et al., 2022).

4.3 Environmental stress and metabolite regulation

Applying moderate stress conditions can stimulate the production of active compounds. For example, mild drought stress can activate plant defense responses and increase the content of flavonoids and alkaloids. Reducing certain nutrients also produces similar effects. In addition to managing water and nutrients, external inducers such as salicylic acid and jasmonic acid can trigger secondary metabolism without affecting overall growth (Yin et al., 2020).

Alternating light intensity has also been used to enhance metabolic activity. These strategies provide useful tools for increasing the medicinal value of *L. japonicus* and make large-scale off-season production more feasible.

5 Promotion and Application of Off-Season Cultivation Technology in Industrial Production

5.1 Cost-effectiveness and economic feasibility

Although the off-season planting of *Leonurus japonicus* has a large initial investment, such as greenhouse construction, equipment procurement and energy-saving system installation, it is feasible in the long run. Thanks to the annual planting, disease reduction and yield increase, the unit cost gradually decreased and the economic benefits began to appear (Krishna et al., 2024). At the same time, precision irrigation and nutrition management can also save water and fertilizer and reduce operating expenses.

Large scale planting can usually recover the investment cost within 2 to 3 years (Pachiyappan et al., 2022). Due to the higher active ingredients, stable quality and better market price of medicinal materials planted out of season, the characteristics of "high quality+stable supply" enhance the market competitiveness of medicinal materials.

5.2 Demonstration bases and field results

Several demonstration sites for off-season cultivation of *L. japonicus* have been established to test and promote this method. These bases are equipped with systems for automatic temperature control, light regulation, and energy conservation, creating stable growth conditions. In eastern and southern China, yields have increased by around 40% under off-season conditions, and product quality is more consistent (Moraes et al., 2021).

A base in Zhejiang province uses precision irrigation and solar-powered systems to reduce water use by 30% and energy costs by about 20%. It also offers training programs for local farmers, helping them operate equipment and manage crops (Figure 2). These efforts have supported broader adoption in surrounding areas (Chen et al., 2020).

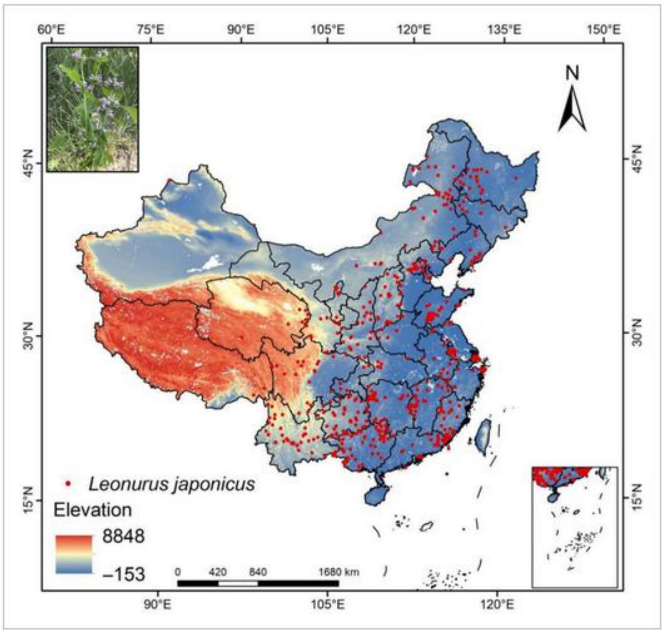

Figure 2 Off-season cultivation distribution map of *Leonurus japonicus* (Adopted from Wang et al., 2023)

5.3 Practical cases and challenges in promotion

At present, in some cooperatives and agricultural companies, off-season planting has brought remarkable results. The yield has increased by about 50% compared with the original, and the planting efficiency is also higher. These cases mainly rely on the cooperation between scientific research institutions and the government, with support from technical guidance to market docking (Schreinemachers et al., 2016).

But there are still many problems in the process of promotion. First, the pressure of facility investment is high, and some small farmers are difficult to bear the cost of greenhouse or control system. Secondly, some growers lack operation skills, are not familiar with equipment, and management is not in place. The relevant regulatory system is not unified enough, which is not conducive to the entry of products into the market.

In order to solve these problems, government subsidies and discount loans can be used to help farmers reduce the initial investment pressure. At the same time, technical training for farmers should be carried out to improve their operational ability. The establishment of a unified product quality standard and certification system can also simplify the sales process, improve consumers' trust in off-season medicinal materials, and promote the steady promotion of technology.

6 Challenges in Technology Adoption and Proposed Solutions

6.1 Farmer participation and technical training

The success of off-season cultivation largely depends on whether farmers are willing to adopt the technology. Many growers are used to traditional methods and are unfamiliar with greenhouses, automated systems, and other modern equipment. A lack of experience also makes them hesitant to try new practices (Luo et al., 2022).

To solve this problem, the government and agricultural departments can carry out targeted training to let farmers master the basic operation process, and focus on the yield and benefit advantages of off-season planting. By setting up a demonstration base, organizing on-the-spot observation, and building an exchange platform between farmers, it will help to enhance the confidence of farmers and improve their acceptance (movilla pateiro et al., 2020).

6.2 Energy use and resource efficiency

Greenhouse systems require significant energy and water, which can hinder large-scale expansion. Heating, ventilation, and lighting systems increase electricity demand and raise operating costs. They may also have environmental impacts if not managed properly (Jia et al., 2023).

One solution is to incorporate renewable energy, such as solar power, to reduce reliance on conventional electricity. Precision irrigation systems and automated fertigation equipment can help save water and nutrients. Using energy-efficient LED lighting can also cut electricity costs and improve resource use efficiency (Geels et al., 2020).

6.3 Policy support and industry collaboration

Policy support plays a key role in technology promotion. The government can reduce the investment pressure of farmers and enterprises and encourage them to try out the off-season production mode through subsidies, tax cuts and low interest loans. Promote the cooperation among universities, scientific research institutions and enterprises, jointly develop new varieties and new equipment, and improve the technical level of the whole system.

In addition, it can promote the local construction of a number of off-season planting demonstration parks, and pilot the promotion of management standards and certification mechanisms. The implementation of a special quality identification system for products helps to enhance consumer trust and promote market recognition (Liu et al., 2019).

7 Impact of Off-Season Cultivation on Industrial Development

7.1 Stable supply and improved market competitiveness

The off-season planting technology can make *Leonurus japonicus* grow and harvest all year round, avoiding the problem of supply interruption caused by seasonal changes. This continuous supply mode makes the quality of raw materials more consistent, which is conducive to meeting the demand of pharmaceutical enterprises for stable supply (Wang, 2024). *L. japonicus* cultivated under controlled conditions has higher content of active ingredients, more guaranteed quality of medicinal materials and easier to sell at a good price. This way reduces the dependence on wild resources, protects the ecological environment and promotes the sustainable development of the industry (Nara et al., 2021).

7.2 Strengthening upstream–downstream collaboration

With off-season cultivation, growers can produce standardized, high-quality raw materials that meet the requirements of pharmaceutical and processing companies. This reduces supply fluctuations and improves coordination across the supply chain (Zhao, 2024). Better integration also encourages joint development of new products, such as standardized extracts and functional health supplements, which expand the value chain and increase the commercial potential of *L. japonicus* (Gargaro et al., 2023).

7.3 A Model for other medicinal plants

The off-season planting of *Leonurus japonicus* not only solves the problem of insufficient yield, but also provides ideas for the planting mode of other traditional Chinese medicine plants. Many medicinal plants also face problems such as short growth cycle and lack of wild resources, and this set of technical system, including greenhouse management, light regulation, precision fertilization, etc., can be properly transplanted and applied (Singh et al., 2024).

For plants with narrow natural distributions or strict growth requirements, off-season cultivation offers a way to ensure stable production and easier quality control. It can also support export efforts by helping meet the demand for high-quality botanical products in international markets (Vernon et al., 2023).

8 Concluding Remarks

By adjusting the proportion of cultivation substrate and fertilizer, controlling temperature and light, and using inducers to promote the accumulation of effective components, the experiment has achieved remarkable results. Under different environmental conditions, the growth performance and quality of *Leonurus japonicus* were improved. Using these technologies, growers can achieve year-round production, and solve the problem of large seasonal impact in the traditional mode. The demonstration bases established in many regions have also proved that these methods have the possibility of promotion. The production in the base is improved and the resource utilization efficiency is higher.

Future work can focus on two main areas. First, improving greenhouse systems to boost energy efficiency and lower operating costs. Second, integrating smart technologies—such as IoT sensors and AI-based prediction tools—to monitor and manage environmental conditions like temperature, moisture, and light in real time, improving overall control and reducing waste. It can also be considered to screen out *Leonurus japonicus* varieties with more disease resistance, stronger stress resistance and higher medicinal ingredients through genetic improvement. Adjust the anti season technical scheme according to the planting environment in different climate regions.

The adoption of off-season cultivation has enhanced both yield and quality while reducing reliance on wild harvesting and helping protect natural ecosystems. As demand for high-quality medicinal herbs continues to grow, this method offers a more sustainable production approach and provides a useful reference for improving the cultivation of other medicinal plants.

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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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