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A Review on the Adaptation of *Zenia insignis*, a Chinese Endemic Tree Species, to Drought Environments in the Karst Areas of Northwestern Guangxi

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Abstract To systematically elucidate the adaptation mechanism of *Zenia insignis* to karst drought habitats and to provide theoretical support for the rational development and utilization of its resources as well as ecological restoration of rocky desertification, this paper systematically reviews research findings on *Z. insignis* at home and abroad. It summarizes research progress from the perspectives of provenance reproductive characteristics, morphological anatomy and physiological drought resistance mechanisms, rhizosphere symbiotic microbial interaction, community site adaptation characteristics, molecular biology, and resource utilization. Existing studies have confirmed that *Z. insignis* can adapt to karst drought stress through multiple pathways, including specialized root architecture, physiological osmotic regulation, antioxidant system modulation, and synergistic symbiosis with arbuscular mycorrhizal fungi. However, there remain issues such as fragmented research on adaptation mechanisms, insufficient exploration of indigenous microbial resources, an imperfect multi-trait breeding system for superior varieties, and a lack of mixed afforestation models. In the future, it is necessary to rely on multi-omics joint analysis and in-situ field controlled experiments to systematically elucidate the multi-dimensional synergistic drought resistance mechanisms of *Zenia insignis*, screen indigenous microbial strains and superior provenances adapted to karst habitats, and establish a scientific and large-scale ecological restoration afforestation system for rocky desertification. All these efforts will promote the coordinated development of ecological governance and forestry carbon sink industry in the karst region of northwestern Guangxi.

Keywords Northwestern Guangxi, Karst areas, Endemic tree species, *Zenia insignis*, Drought adaptability, Rocky desertification restoration
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Zenia insignis Chun, also known as "Chijiamu" in Chinese, is a deciduous tree species belonging to the genus *Zenia* in the subfamily Caesalpinioideae of the family Fabaceae. It is listed as a rare and endangered protected tree species in China and is a native tree species endemic to limestone mountains from the mid-subtropical to the south-subtropical zones[1-2]. This species is light-demanding and calciphilous, and has a well-developed root system and strong rock-penetrating ability. Its roots can grow along rock fractures deep into karst soil layers, demonstrating strong adaptability to extreme environments such as drought, nutrient-poor soils, and high temperatures. It is therefore the preferred pioneer afforestation species for karst rocky desertification control in Guangxi. The leaves of *Z. insignis* are characterized by high crude protein content, low crude fiber content, balanced nutrient composition, and good digestibility, making it a commonly recognized high-quality forage plant[3]. The wood of *Z. insignis* features straight grain, coarse texture, and light weight. After water soaking and air-drying, the wood becomes resistant to insect infestation, and does not crack or deform, making it an excellent material for doors, windows, panels, agricultural tools, and furniture[2]. *Z. insignis* has an attractive tree shape and beautiful flowers. It is not only suitable for use as a landscape tree species and for contiguous planting in limestone areas, but also can serve as a shelterbelt tree species for greening vegetation along both sides of roads[4].

1 Research Status of *Z. insignis*

1.1 Studies on the provenance and reproductive characteristics of *Z. insignis*

The geographical differentiation characteristics among provenances of *Z. insignis* are significant. There are obvious differences in stress resistance, germination characteristics, and growth traits among provenances from different regions. The optimization of seed germination and seedling cultivation techniques forms the basis for its drought adaptation and large-scale afforestation[5]. Existing studies have carried out extensive experimental investigations focusing on seed pretreatment, germination responses under stress conditions, and drought resistance and stress tolerance characteristics at the seedling stage.

In terms of seed pretreatment technology, Su et al.[6] found that osmotic regulation treatment with 20% PEG 6000 significantly enhanced the dehydrogenase activity and root vigor of *Z. insignis* seeds, reduced the degree of membrane damage, and improved seed vigor under drought conditions, and the effects were superior to traditional warm water soaking treatment. Hormonal regulation experiments showed that "seed dressing with concentrated sulfuric acid+soaking with 200 mg/L GA_3 for 2 h" was the optimal pretreatment combination for seed germination of *Z. insignis*, significantly improving germination rate and seedling growth vigor. Stress germination experiments revealed that *Z. insignis* seeds could maintain a relatively high germination level under −0.6 MPa drought stress, with a short germination delay period, demonstrating outstanding drought resistance potential at the germination stage.

Luo[7] conducted stress experiments with simulated sulfuric acid rain of different pH values (2−5) to investigate the effects of acid rain on the seed germination physiology of *Z. insignis*. It was found that acid rain inhibited seed germination and seedling growth of *Z. insignis* by damaging cell membrane structures, interfering with enzyme activity and respiratory metabolism, and disrupting the balance of substance transformation. pH=3 was identified as the key

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threshold for the inhibitory effect.

Wu et al.[8] used *Z. insignis* seeds from the Tongdao provenance in Hunan as experimental materials and, found through an $L_9(3^4)$ orthogonal experiment that hormone type was the most critical factor affecting seed germination rate, germination vigor, and germination index. They also determined the optimal pretreatment combination for seeds as: "seed dressing with concentrated sulfuric acid+200 mg/L GA_3+soaking for 2 h", under which seed germination and seedling growth performance were excellent. Xu et al.[9] investigated the reproductive characteristics of *Z. insignis* through PEG-simulated water drought stress and potted water control experiments. The results showed that although indicators such as germination speed, germination rate, germination vigor, and radicle and hypocotyl lengths of *Z. insignis* seeds exhibited a declining trend, the seeds still maintained a relatively high germination rate under 0.6 MPa stress, with a short germination delay period, demonstrating strong drought resistance potential during the germination stage.

Zou et al.[10] systematically investigated the transpiration water consumption characteristics of *Z. insignis* seedlings at different growth stages under various weather and soil moisture conditions through pot-controlled experiments. The results showed that the daily water consumption rate of current-year *Z. insignis* seedlings was higher than that of one-year-old retained seedlings, and the peak periods differed under different weather conditions. The retained seedlings exhibited better performance in response to drought stress compared than the current-year seedlings. Lu et al.[11] used one-year-old *Z. insignis* seedlings from six provenances as materials and simulated drought stress through potted water control experiments. The results showed that under drought stress, the relative water content of leaves in seedlings from all provenances exhibited a declining trend, while the response patterns of other physiological indicators varied among provenances.

He et al.[12] used one-year-old dormant seedlings of *Z. insignis* from six provenances, including Jingxi in Guangxi and Tongdao in Hunan, as research materials, and systematically evaluated the cold resistance of different provenances. The results showed that the semi-lethal temperatures of the tested provenances ranged from −13.06 °C to −10.76 °C. Comprehensive analysis indicated that the Tongdao provenance in Hunan exhibited the strongest cold resistance, while the Jingxi provenance in Guangxi showed the weakest cold resistance. Furthermore, there was a significant adaptive correlation between cold resistance and the geographical and climatic conditions of the provenance origins, with provenances from higher latitudes or higher altitudes demonstrating superior cold resistance.

Long et al.[13] conducted a study on 10 provenances of *Z. insignis* at the seedling stage. The results showed that a photosynthetic "midday depression" phenomenon was commonly observed in all provenances, and the net photosynthetic rate of upper leaves was generally higher than that of lower leaves during the seedling stage. The main factors affecting the net photosynthetic rate of upper leaves were predominantly ecological factors, while those affecting lower leaves were mainly physiological factors. Furthermore, the dominant environmental factors influencing photosynthesis varied among different provenances.

1.2 Studies on the morphological anatomy and physiological and ecological drought resistance mechanisms of *Z. insignis*

The synergistic regulation of morphological structural specialization and physiological metabolism constitutes the core mechanism by which *Z. insignis* adapts to karst drought habitats. The drought resistance of *Z. insignis* originates from the specialization of its morphological and anatomical structures in coordination with its physiological and ecological functions. Cao et al.[14] observed through fiber anatomical examination that the xylem of the stem possesses relatively thick vessel walls and a high proportion of axial parenchyma tissue, which not only ensures the stability of water transport, but also enables water storage through parenchyma tissue, thereby enhancing resistance to embolism under drought stress. Zhao[15] conducted sectioning observations on the upper, middle, and lower parts of *Z. insignis* stems and found that from the upper to the lower parts, secondary growth of the cell wall gradually intensified, with the maturity of xylem development and the degree of lignification progressively increasing. The cell wall thickness reached 2.066 μm, and the seedling cortex contained structurally continuous annular sclerenchyma tissue, with obvious secondary thickening and lignification of the cell walls.

Huang et al.[16] investigated the photosynthetic, transpiration, and water use efficiency characteristics of *Z. insignis*, a pioneer species in karst rocky desertification areas. The results showed that the maximum net photosynthetic rate of *Z. insignis* reached 18.09 $\mu mol/(m^2 \cdot s)$, and the light saturation point was approximately 870 $\mu mol/(m^2 \cdot s)$, demonstrating strong tolerance to high light intensity and high temperatures. By virtue of its large transpiration pull, the species can absorb more water from the soil, and with the significant regulatory role of stomata in photosynthesis and transpiration, it can effectively cope with short-term water deficiency. Meanwhile, it can form drought-avoidance and heat-avoidance strategies through its own physiological regulation, maintaining vigorous biological productivity in the high-temperature and drought-prone karst environment. These findings are consistent with those of He et al.[17]. Meanwhile, the well-developed root system of *Z. insignis* can penetrate deep into the underground karst zone along rock fissures to absorb water, and reduce leaf surface temperature through transpiration, thereby alleviating the damage caused by the combined stress of high temperature and drought.

Xu[9] conducted PEG-simulated water drought stress and potted water control experiments using one-year-old *Z. insignis* seedlings and seeds as research materials. The results showed that drought stress led to decreases in net photosynthetic rate, transpiration rate, and stomatal conductance of *Z. insignis*, while water use efficiency increased under moderate drought conditions. The ratio of intercellular CO_2 to atmospheric CO_2 was elevated, soluble protein content decreased, and proline content exhibited a trend of first increasing and then decreasing with the intensification of drought stress. Superoxide dismutase (SOD) activity generally showed an increasing trend, while peroxidase (POD) activity remained at relatively high levels during the later stages of stress. Although malondialdehyde (MDA) content increased, it could recover after rehydration. Through osmotic regulation and the reactive oxygen species scavenging system, *Z. insignis* can mitigate drought-induced damage.

1.3 Studies on the stress resistance mechanisms of symbiosis with rhizosphere arbuscular mycorrhizal fungi

The symbiotic association between arbuscular mycorrhizal fungi (AMF) and *Z. insignis* represents an important auxiliary mechanism for its adaptation to nutrient-poor and drought-prone karst habitats. Existing studies have confirmed that fungal species such as *Funneliformis mosseae*, *Rhizophagus irregularis*, and *Glomus etunicatum* can form efficient symbioses with the root system of *Z. insignis*. These fungi significantly promote seedling height, ground diameter growth, and biomass accumulation. Among them, *F. mosseae* exhibits the highest colonization rate and the best growth-promoting effect.

Jiang et al.[18] inoculated *Z. insignis* seedlings with four species of arbuscular mycorrhizal fungi using two application methods, namely root-dipping and hole-application. The results showed that all tested AMF species promoted the growth of *Z. insignis* seedlings. Six months after inoculation, seedling height, ground diameter, and total biomass were significantly improved compared with the non-inoculated controls. Among the treatments, the combination of the HUN03B fungal agent with the root-dipping method most effectively enhanced early-stage mycorrhizal colonization rate and promoted seedling growth. Moreover, *Z. insignis* exhibited weak dependency on all tested AMF species.

Song et al.[19] investigated the effects of three AMF species, namely, *F. mosseae*, *R. irregularis*, and *G. etunicatum*, on the growth and drought resistance of *Z. insignis* through pot-controlled water stress experiments simulating natural drought conditions. The results showed that all three fungal species significantly promoted seedling height, ground diameter growth, and biomass accumulation in *Z. insignis*. Among them, *F. mosseae* exhibited the highest colonization rate (96.7%) and the most prominent growth-promoting effect. It also enhanced chlorophyll synthesis and increased the activities of soil phosphatase and urease, thereby improving the plant's ability to absorb nutrients such as nitrogen and phosphorus. Furthermore, arbuscular mycorrhizal fungi could enhance the drought resistance of *Z. insignis* by improving its photosynthetic assimilation capacity and water use efficiency, while alleviating damage to the photosynthetic reaction centers.

Qu et al.[20] conducted pot experiments using karst native soils with different nutrient conditions to analyze the effects of inoculation with *F. mosseae*, *R. irregularis*, and a mixed inoculum of both fungi on biomass allocation and root architectural characteristics of *Z. insignis* seedlings. The results showed that the root systems of *Z. insignis* seedlings could form colonization structures with both arbuscular mycorrhizal fungal species. The root colonization rate under the *F. mosseae* treatment was the highest. The treatment facilitated alterations in biomass accumulation and root architectural traits of *Z. insignis*, and promoted nutrient and water uptake by roots from soil.

Li et al.[21] conducted a pot experiment in a greenhouse to investigate the effects of two AMF species, *F. mosseae* and *R. irregularis*, on the growth and heavy metal uptake and accumulation of *Z. insignis*. The results showed that both fungal species could establish good symbiotic relationships with *Z. insignis*, significantly promoting phosphorus uptake by the plants, increasing biomass accumulation, and particularly enhancing belowground growth. Overall, AMF inoculation reduced the concentrations of Fe, Cu, Zn, and Pb in *Z. insignis* tissues while increasing the total accumulation of these heavy metals. The distribution of heavy metals within the plants was influenced by both fungal species and metal type, and *R. irregularis* was particularly effective in enhancing the root retention capacity for Fe, Zn, and Pb.

1.4 Studies on community characteristics and site application of *Z. insignis*

Z. insignis is an excellent afforestation tree species in rocky desertification areas, and its community characteristics and site conditions provide important references for afforestation practices. Yang et al.[22] conducted a community characteristics investigation of *Z. insignis* at Longdi in Tongdao Dong Autonomous County and found that *Z. insignis* served as the dominant constructive species with significant advantages. Within the community, the tree layer exhibited the highest species richness, while the herb layer showed the optimal diversity, evenness, and dominance indices. The population structure was relatively stable, and a large number of young trees and seedlings of *Z. insignis* were present in the shrub layer, supporting its maintenance as the dominant species and promoting the progressive succession of the community. Hou et al.[23] focused on the plant diversity analysis of *Z. insignis* plantations in karst rocky mountains, and found that *Z. insignis* possesses strong root penetration ability, enabling it to survive in karst mountainous areas with a rock exposure rate of 53%. Meanwhile, it can improve the fragile karst habitat and enhance species diversity. Huang et al.[24] conducted a systematic analysis of the site survival factors of *Z. insignis* through field investigations in limestone mountainous areas. The results showed that *Z. insignis* prefers neutral to slightly acidic calcareous soils, and is predominantly distributed in the middle and lower parts of low mountains and hills, gentle slopes, and areas on both sides of valleys where water catchment capacity is relatively strong.

Lv et al.[25] selected three tree species including *Z. insignis* in the rocky desertification area of southwestern Guangxi and analyzed their nursery effects on *Cyclobalanopsis glauca* seedlings. The results showed that *Z. insignis* not only possesses the ability to adapt to harsh environments such as drought and intense light in the region, but also can regulate the microclimate through canopy shading. It reduces the light intensity and extreme high temperature under the canopy and increases air humidity, thereby creating a favorable microenvironment for the growth of target plant seedlings and exhibiting obvious nursing function. Furthermore, such nursing effect strengthens with the increase of seedling age of *C. glauca*. The promoting effect on seedling height growth is greater than that on basal diameter. Meanwhile, it significantly increases the leaf SPAD value and average single leaf area of *C. glauca*, elevates leaf nitrogen content and reduces leaf C/N ratio.

Liu et al.[26] took *Z. insignis* in natural secondary forests on limestone mountains in northern Guangdong as the research object, and analyzed the contents and stoichiometric ratios of six elements (including C, N, and P) in its soil, roots, and leaves. They found that the leaf nutrient elements of *Z. insignis* exhibited the typical characteristics of limestone plants, namely "low P and K, high Ca and Mg". Compared with the research results of Tu[27], who studied a 7-year-old *Z. insignis* plantation on limestone mountains in northern Guangdong, there were differences in leaf element contents between secondary forests and plantations. The contents of N, K, Ca, and Mg in secondary forest leaves were all higher than those in plantation leaves, while the contents of C and P were lower. Growth of *Z. insignis* in secondary forests was mainly limited by P element and not by K, while in plantations, it was not limited by P but by N. In addition, the two scholars also obtained different results regarding the relationships of nutrient elements among soil, roots, and leaves, indicating that plant communities in plantations and secondary forests may differ in nutrient regulation and balance mechanisms.

1.5 Studies on the resource value and molecular biology of *Z. insignis*

With the development of molecular biotechnology, research on the genetic basis and functional genes of *Z. insignis* has been progressively deepening. *Z. insignis* is a fast-growing tree species in the subtropical region, characterized by strong sprouting ability, high biological yield, drought tolerance, and adaptability to nutrient-poor soils. It is widely distributed in hilly areas, making it a suitable energy tree species, as well as an excellent landscaping and greening tree species. Relevant studies have expanded into the multi-dimensional application value of *Z. insignis*, providing a solid theoretical foundation for further exploring its resource potential.

Tong et al.[28] investigated the effects of different initial planting densities on the wood calorific value of young *Z. insignis* plantations. The results showed that *Z. insignis* exhibited excellent fiber energy plant characteristics in terms of biomass, calorific value, and standard coal equivalent yield. At higher initial planting densities, it produced greater biomass and standard coal yield. Zhong et al.[29] measured the water-holding capacity of different layers in a karst *Z. insignis* plantation. The results showed that the total water-holding capacity of the plantation reached 998.53 t/hm^2, forming a "green reservoir" with significant water storage and regulation capacity. Hou et al.[30] studied the wood properties of *Z. insignis*, and the results indicated that the tree species is an ideal raw material for artificial board production.

Zhan et al.[31] established a non-destructive detection method for holocellulose content based on Fourier transform infrared spectroscopy (FTIR) and machine learning, using 10-year-old fast-growing *Z. insignis* wood as the research material. The results showed that among multiple modeling approaches, the MSC-PCA-SVR model exhibited the best predictive performance, with a coefficient of determination (R^2) reaching 0.97 and a root mean square error (RMSE) of only 0.004 596, enabling efficient and accurate determination of holocellulose content in *Z. insignis*. The study also confirmed that SNV and MSC preprocessing techniques significantly improved the predictive capability of spectral data, and that the SVR algorithm performed better overall than the BPNN algorithm. Cao et al.[14] used fresh materials and long-term stored specimens of *Z. insignis* as materials to extract their DNA using multiple methods. It was found that the CTAB method yielded stable DNA extraction results from wood tissues of *Z. insignis*, and higher DNA concentrations were observed in specimens. DNA barcoding identification studies indicated that psbA-trnH had relatively high resolution and could serve as a candidate barcode for molecular identification of *Z. insignis*. Zhao et al.[15] obtained a large amount of genetic sequence information of *Z. insignis* through transcriptome sequencing, and screened out genes related to cellulose synthesis (ZiCESA4, ZiCESA7, etc.), hemicellulose synthesis (ZiUXS1, ZiIRX9, etc.), and lignin synthesis (ZiPAL1, ZiC4H, etc.). Their expression levels were consistent with the processes of secondary cell wall growth and lignification. The molecular mechanisms of cell wall synthesis in sclerenchyma tissue and stem xylem were similar, differing only in gene expression levels, and the expression levels of genes related to lignin and xylan synthesis were higher in the xylem.

Chen et al.[32] successfully assembled a chromosome-level reference genome for *Z. insignis* by integrating multi-type sequencing data, including PacBio CLR, NGS, Hi-C, and transcriptome data. The total genome length was 352.84 Mb, with a contig N50 of 6.02 Mb, a BUSCO completeness of 97.30%, and an LAI score of 14.57, meeting reference-quality genome standards. Meanwhile, a plastid genome of 159,390 bp was obtained. Qiang et al.[33] sequenced the complete plastid genome of *Z. insignis*, which had a total length of 159,358 bp, similar to the findings of Chen et al.[32].

2 Major Problems in Existing Research

2.1 Imperfect breeding and seedling cultivation technology system

At present, the screening of *Z. insignis* germplasm resources mostly relies on single evaluation indicators such as drought resistance and cold resistance. Comprehensive breeding integrating multiple economic and ecological traits including fast growth, carbon sequestration capacity and survival rate has not been carried out. Thus, it is difficult to breed improved varieties suitable for large-scale carbon sink afforestation and ecological restoration. Meanwhile, seed pretreatment and seedling stress-resistant cultivation techniques are mostly limited to laboratory-based single-stress experiments, lacking in-situ field validation. A low-cost, standardized, and scalable technical protocol for large-scale seedling cultivation has not yet been established, making it difficult to directly guide practical forestry production.

2.2 Fragmented research on drought adaptation mechanisms, lacking systematic analysis

Existing studies mostly focus separately on single dimensions, such as morphological structure, physiological indicators, microscopic genes, or microbial interactions, while overlooking the synergistic coupling effects among root, stem, and leaf morphological structures, physiological metabolism, molecular regulation, and microecological symbiosis in *Z. insignis*. The overall adaptive pathways and core regulatory mechanisms of *Z. insignis* under combined karst drought stress have not yet been elucidated, and a multi-dimensional synergistic theoretical framework for drought resistance has not been established.

2.3 Insufficient exploration of native rhizosphere microbial resources

At present, the arbuscular mycorrhizal fungi used in research are mostly introduced general strains. No native dominant AMF strains adapted to the growth of *Z. insignis* have been screened targeting the karst habitats of northwest Guangxi, leading to severe insufficiency in the exploration, identification and utilization of native microbial resources. Meanwhile, the molecular pathways involved in signal recognition, nutrient regulation, and synergistic drought resistance in the symbiosis between *Z. insignis* and AMF remain unclear, and the underlying mechanisms of microbial-enhanced drought resistance have yet to be elucidated.

2.4 Lagging research on afforestation configuration models and industrialization

Existing studies have mostly focused on the community characteristics and growth patterns of pure *Z. insignis* plantations. Few studies have been conducted on mixed proportions, configuration methods, and interspecific competition and mutualistic mechanisms involving *Z. insignis* and other native tree species promoted for carbon sink afforestation in Guangxi, such as *Eucalyptus* spp., *Schima superba*, and *Castanopsis hystrix*. Scientific mixed afforestation technology models are lacking. Meanwhile, the industrial integration of *Z. insignis* in ecological restoration, carbon sink enhancement and resource utilization is insufficient. The transformation rate of scientific research achievements remains low, and its dual ecological and economic values cannot be fully exerted.

3 Countermeasures and Recommendations

3.1 Establishing a high-quality provenance screening and standardized seedling cultivation system

Relying on in-situ experimental bases in karst mountainous areas of northwest Guangxi, provenance comparative trials of *Z. insignis* can be conducted under diverse environments and multiple stress conditions. It is necessary to integrate multiple trait indicators including drought resistance, fast growth, high carbon sequestration capacity and stress tolerance, so as to establish a comprehensive evaluation system for superior germplasm of *Z. insignis* and screen special superior provenances adapted to different regions of Guangxi. Technologies for seed pretreatment, seedling cultivation and seedling training under adverse conditions can be further optimized. Existing laboratory achievements should be integrated to formulate standardized, low-cost and scalable technical specifications for seedling raising and afforestation, which can support the implementation of rocky mountain ecological restoration and carbon sink afforestation projects.

3.2 Integrating multi-technique approaches to elucidate the synergistic molecular mechanisms of drought resistance

Through integration of multi-omics technologies including morphological-anatomical, physiological-ecological, transcriptomic and metabolomic approaches, we should focus on the special karst arid habitats in northwest Guangxi. It is necessary to systematically dissect the coupling mechanisms underlying coordinated water retention, osmotic adjustment and antioxidant defense in the roots, stems and leaves of *Z. insignis*. Core functional genes and metabolites responsive to drought stress can be identified, and the multi-dimensional molecular regulatory network for its synergistic adaptation to arid environments can be elucidated, so as to improve the theoretical system of drought-resistance adaptation in *Z. insignis*.

3.3 Exploring indigenous microbial resources and constructing a symbiotic adaptation system

From the rhizosphere soil of *Z. insignis* native forests in karst regions of northwest Guangxi, we should isolate, screen and identify native dominant AMF strains, and establish a strain resource library dedicated to karst habitats. It is necessary to verify the enabling effects of native strains on the growth, drought resistance and carbon sequestration of *Z. insignis* through pot-culture and in-situ field experiments, clarify the symbiotic signaling pathways and nutrient regulation mechanisms, and develop supporting mycorrhizal seedling-raising technologies suitable for rocky-desertification afforestation. These measures will improve the afforestation survival rate and ecological benefits under extreme habitats.

3.4 Optimizing afforestation models and promoting ecological industrialization development

Mixed-afforestation experiments can be conducted for *Z. insignis* and major native tree species for carbon sequestration in Guangxi. It is necessary to optimize mixing ratios, spatial allocation and tending-management modes, and construct stable, efficient and high-carbon-sequestration mixed-forest ecosystems for karst mountainous areas. A collaborative-innovation platform integrating "university-based scientific research+forestry departments+industrial enterprises" can be established to advance the industrial transformation of *Z. insignis* in ecological restoration, carbon-sequestration development, timber and forage utilization, so that multi-party win-win outcomes of ecological governance, carbon-sequestration-related income increase and industrial development can be achieved in karst regions of northwest Guangxi.

4 Conclusions

As a rare and endemic pioneer tree species in the karst areas of Guangxi, *Z. insignis* is highly adapted to drought-prone and nutrient-poor karst habitats by virtue of its unique morphological structure, physiological regulation, and microecological symbiosis mechanisms. Meanwhile, it possesses excellent carbon sequestration capacity and economic utilization value, making it a core native tree species for rocky desertification control and carbon sink afforestation in Guangxi. At present, the academic community has achieved certain progress in the fields of provenance breeding, physiological drought resistance, microbial symbiosis, and molecular genetics of *Z. insignis*. However, problems remain, including unsystematic mechanistic research, incomplete technical systems, and lagging industrial application. Future interdisciplinary research is required to systematically reveal the core mechanisms of drought adaptation in *Z. insignis*. It is necessary to improve the technical system of improved variety breeding and afforestation, and maximize the ecological restoration and carbon sequestration industrial value of *Z. insignis*, so as to provide solid theoretical and technical support for ecological protection and green development in karst areas of northwest Guangxi.

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compose research reflections, and analyze the ecological techniques and cultural connotations therein. Institutions with adequate conditions may organize small-scale outdoor research tours, where teachers deliver on-site explanations, answer questions in real time and carry out immersive teaching. Field experiences beyond textbooks allow students to truly perceive the practical value of traditional ecological wisdom and further strengthen their awareness of ecological protection.

4.4 Reform the curriculum assessment system to highlight educational orientation

The previous single assessment model centered on memorizing knowledge points shall be replaced with a diversified comprehensive assessment system. Regular performance evaluation includes classroom speeches, group seminars, field research reports and course learning reflections, focusing on assessing students' comprehension of ecological concepts and cultural connotations. Apart from examining basic historical knowledge points in final examinations, open-ended essay questions are added, requiring students to elaborate their understanding of modern garden design combined with the ecological wisdom of traditional gardens. Through adjustments to assessment methods, students are guided to shift from simply memorizing knowledge points to understanding ideological connotations and practicing professional concepts[6].

5 Conclusion

Chinese and foreign gardens have bequeathed to us not only diverse garden forms and exquisite construction techniques, but also a complete set of ecological concepts and humanistic thoughts that conform to the laws of nature. As an introductory course for landscape architecture majors, *History of Chinese and Foreign Gardens* must fully explore and utilize these high-quality teaching resources, which represents an inevitable choice to fulfill the requirements of curriculum ideological and political education and deliver ecological civilization education. In teaching practice, the in-depth integration of traditional ecological wisdom and ideological and political education can not only enrich classroom content and deepen teaching connotation, but also guide students to establish correct views of nature, design and values. It helps cultivate interdisciplinary garden talents with solid professional capabilities, outstanding ecological literacy, profound cultural sentiments and a strong sense of professional responsibility for the industry.

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