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Evaluating the impact of ecological factors on the quality and habitat distribution of *Lonicera japonica* Flos using HPLC and the MaxEnt model

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Introduction: The quality of traditional Chinese medicine is based on the content of their secondary metabolites, which vary with habitat adaptation and ecological factors. This study focuses on *Lonicera japonica* Flos (LJF), a key traditional herbal medicine, and aims to evaluate how ecological factors impact its quality.

Methods: We developed a new evaluation method combining high-performance liquid chromatography (HPLC) fingerprinting technology and MaxEnt models to assess the effects of ecological factors on LJF quality. The MaxEnt model was used to predict suitable habitats for current and future scenarios, while HPLC was employed to analyze the contents of key compounds. We also used ArcGIS for spatial analysis to create a quality zoning map.

Results: The analysis identified 21 common chromatographic peaks, with significant variations in the contents of Hyperoside, Rutin, Chlorogenic acid, Cynaroside, and Isochlorogenic acid A across different habitats. Key environmental variables influencing LJF distribution were identified, including temperature, precipitation, and elevation. The current suitable habitats primarily include regions south of the Yangtze River. Under future climate scenarios, suitable areas are expected to shift, with notable expansions in southern Gansu, southeastern Tibet, and southern Liaoning. The spatial distribution maps revealed that high-quality LJF is predominantly found in central and southern Hebei, northern Henan, central Shandong, central Sichuan, southern Guangdong, and Taiwan.

Discussion: The study indicates that suitable growth areas can promote the accumulation of certain secondary metabolites in plants, as the accumulation of these metabolites varies. The results underscore the necessity of optimizing quality

based on cultivation practices. The integration of HPLC fingerprinting technology and the MaxEnt model provides valuable insights for the conservation and cultivation of herbal resources, offering a new perspective on evaluating the impact of ecological factors on the quality of traditional Chinese medicines.

KEYWORDS

Lonicera japonica Flos, species distribution, HPLC fingerprint, MaxEnt model, quality evaluation

1 Introduction

Traditional Chinese medicine (TCM) is highly esteemed for its outstanding pharmacological effects and holistic treatment principles. Its value is evident not only in the prevention, treatment, and management of various diseases but also in the relatively low side effects and comprehensive body regulation (Wang et al., 2021; Zhang et al., 2024). The uniqueness of Chinese medicine lies in its roots in millennia of practical experience, accumulating a wealth of clinical data and forming a distinctive therapeutic system. However, the intricate composition and dynamic changes in TCM ingredients pose challenges to quality control (Xing et al., 2023). The quality of TCM is closely related to its genetic and environmental factors. Genes regulate the expression of enzymes in the metabolic pathway of active ingredients, which is the internal factor that determines the quality of TCM (Yang et al., 2022). The ecological environment is an extrinsic factor that directs effects not only on the growth, development, and distribution of plants but also on internal compositions (Neugart et al., 2018). Different environmental factors have different effects on the quality and efficacy of TCM, such as climate, soil, and altitude. Concerningly, the impacts of climate warming and more severe weather extremes, such as intensified droughts, heavy rainfall, heat waves, and cold snaps, may potentially modify the existing habitat suitability, distribution, and phenology of species, posing a threat to their survival (Aguirre-Liguori et al., 2019; Ramirez-Preciado et al., 2019). Therefore, developing effective analytical methods to study the relationship between TCM and ecological factors is of great significance for the selection and quality control of artificial cultivation areas for TCM.

Lonicera japonica Flos (LJF), a TCM with a significant historical usage, was initially recorded in the “MIN YI BIE LU” during the Liang Dynasty (Zheng et al., 2022a). It is also recognized as a food substance in the “Homologous Catalog of Medicine and Food (2018)” by the National Health Commission (Yang et al., 2019). Recognized for its therapeutic effects, LJF demonstrates properties such as heat-clearing, detoxification, antibacterial, and anti-inflammatory actions (Han et al., 2016; Nam et al., 2016). It serves as a pivotal treatment for ulcers and a foundational remedy for febrile diseases. Additionally, LJF can be applied in addressing various conditions, including respiratory infections and bacterial

dysentery (Shang et al., 2011; Zang et al., 2022). Renowned for its exceptional antibacterial and anti-inflammatory efficacy, LJF is acclaimed as the “plant antibiotic” and has played a vital role in TCM for preventing and treating atypical pneumonia, novel coronavirus infections, and similar conditions (Li et al., 2019; Zhao et al., 2021; Yeh et al., 2022). The high medicinal value of LJF comes from its rich content of bioactive compounds, encompassing volatile oils, phenolic acids, cyclic terpenes, and flavonoids (Wang et al., 2016; Zheng et al., 2022a). Specifically, flavonoids are pivotal active components in LJF, contributing to its ability to resist bacterial and viral invasions and reduce the risk of cellular carcinogenesis (Ge et al., 2018). Key flavonoids found in LJF include rutin, hyperoside, and luteolin (Liu et al., 2020). Phenolic acid compounds, classified as organic acids, play a crucial role in the heat-clearing and detoxifying effects of LJF (Jeong et al., 2023). LJF exhibits strong adaptability, thriving in various conditions such as sunlight, shade, sandy soil, and slightly acidic to alkaline environments (Wang et al., 2023a). Its wide distribution spans from the northern regions of the three eastern provinces to the southern areas of Guangdong and Hainan Island, extending eastward to Shandong and westward to the Himalayas. Investigating whether regional differences result in variations in the quality of medicinal plants is a worthwhile endeavor.

With the advancement of chromatographic technology and computer software, the detection method has emerged as a focal point for researchers. These methods can qualitatively and quantitatively analyze the chemical components of TCM with characteristics and integrity. High-performance liquid chromatography (HPLC) stands out as a significant and contemporary separation and analysis technology, offering advantages such as efficient separation, high detection sensitivity, rapid analysis, wide applicability, and user-friendly operation, making it widely utilized in research (Yu et al., 2006; Yang et al., 2017; Arabi et al., 2018). This method encompasses the analysis of both known and unknown components, providing a comprehensive overview of the chemical composition and serving as a robust quality control approach. HPLC has become an essential tool for the quality control of Chinese medicinal materials.

The MaxEnt model, a component of the species distribution model (SDM), has been extensively employed for predicting the potential distribution range of species. This is attributed to its

advantages, including high modeling accuracy, stability, and effectiveness (Phillips and Dudík, 2008; Leanza et al., 2021; Lu et al., 2024). A Geographic Information System (GIS) possesses robust spatial analysis capabilities, enabling the quantitative study of ecologically suitable habitats and providing an intuitive representation of these habitats (Leanza et al., 2021). In recent years, the integration of GIS and MaxEnt has emerged as a crucial method for assessing the impact of environmental factors on the distribution and quality of medicinal plants. It facilitates the spatial quantification of TCM quality (Zhan et al., 2022).

In recent years, researchers have utilized representative secondary metabolites and ecological factors in certain plants as indicators to assess the impact of ecological factors on plant quality and forecast suitable distribution or planting areas. For instance, Wan et al. employed the MaxEnt model and ultrahigh-performance liquid chromatography (UPLC) to assess the potential habitat suitability distribution of *Codonopsis pilosula* in Dingxi, establishing a relationship between environmental factors and active ingredient content (Wan et al., 2021). In a similar vein, Zheng et al. utilized UPLC-MS/MS to determine amide concentrations and, in conjunction with the MaxEnt model and 19 environmental factors, predicted the suitable distribution region of Red huajiao (Zheng et al., 2022b). Consequently, establishing an evaluation method for chemical composition content and ecological factors is essential for the quality assessment of TCM.

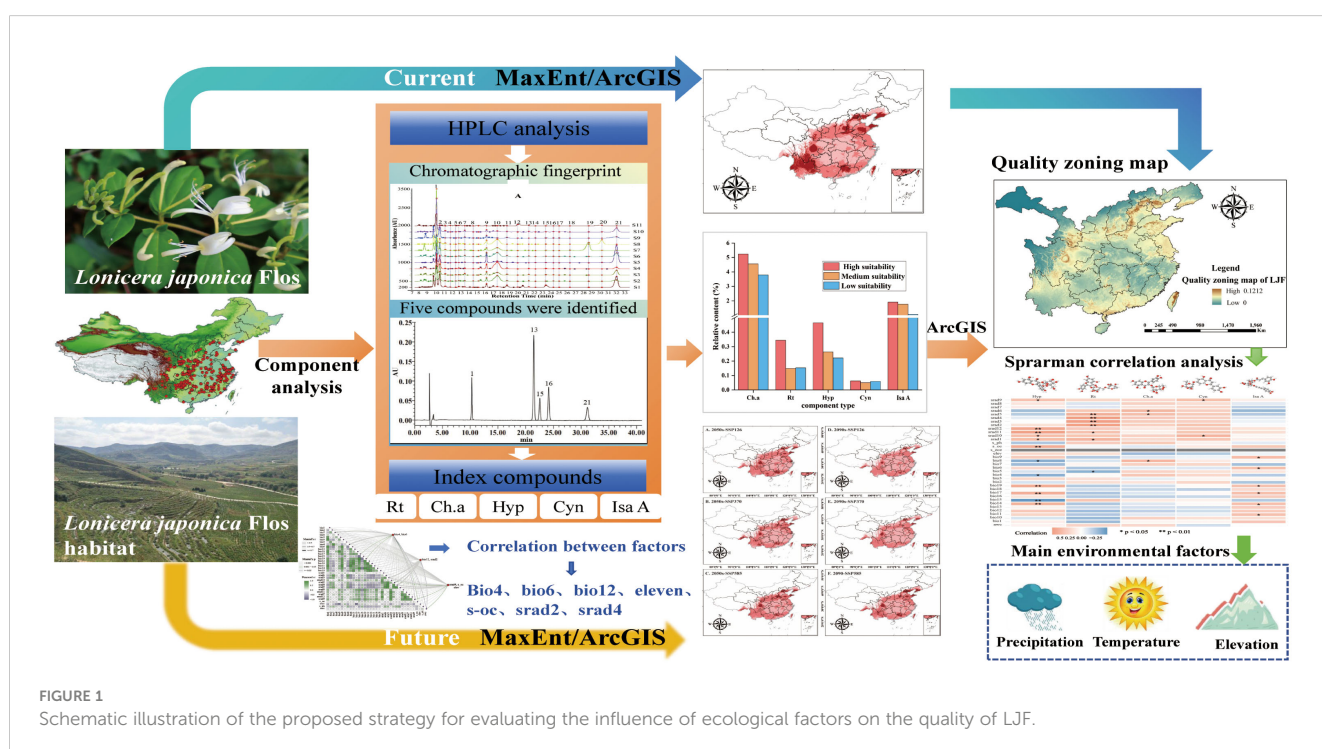
Ecological factors not only affect the suitable cultivation areas of Chinese medicinal materials but also influence the formation and accumulation of chemical components in TCM. The primary objectives of this study are as follows: (1) establish a MaxEnt model to predict the distribution and delineate suitable habitats, and identify the key ecological factors influencing the distribution of

LJF; (2) utilize HPLC fingerprinting technology to analyze the impact of habitat adaptability on the quality of medicinal herbs, and develop correlation models between ecological factors and medicinal efficacy components; and (3) based on the correlation models and utilizing ArcGIS software, create a quality zoning map for LJF, visually illustrating the regions where high-quality LJF is distributed. The obtained results can serve as a scientific reference for future quality control and cultivation area selection of LJF. The proposed strategy is visually represented in Figure 1.

2 Materials and methods

2.1 Geographic distributions of species

Species distribution data for LJF were collected through field surveys conducted in major growing areas in China from 2023. These sample areas included Gansu, Shanxi, Sichuan, Hunan, Hubei, Hebei, Henan, Shandong, Guangdong, Jiangxi, and Yunnan. The selection of these sample sites aimed to comprehensively cover the primary LJF-producing regions. These samples were identified by Professor Chen Yuan of Gansu Agricultural University. Additionally, we complemented by resource survey reports and literature reports, as well as various online databases, including the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/>), the Chinese Virtual Herbarium database (CVH, <http://www.cvh.ac.cn/>), Flora of China, and regional flora databases, to obtain distribution points of LJF. In cases where specific geo-coordinates were lacking in certain records, Google Earth 7.0 was utilized to estimate latitude and longitude based on the described geographical locations. Subsequently, a geographic distribution map was created using



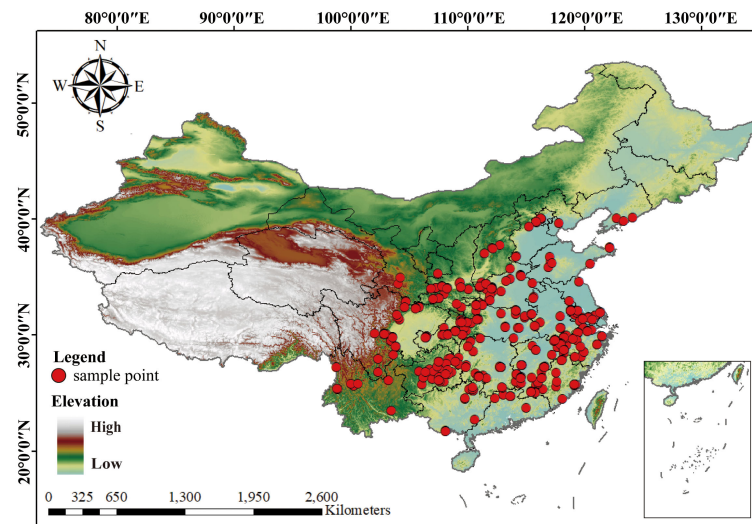


FIGURE 2
LJF included in this study, their collection sites and geographical coordinates.

ArcGIS 10.8. with map data sourced from the National Basic Geographic Information Center (<http://www.ngcc.cn/ngcc/>). In total, 298 specimen record points for LJF were ultimately identified and screened (Figure 2).

2.2 Environmental variables

We utilized a total of 36 environmental factors, comprising 19 bioclimatic variables, 3 soil variables, elevation, awc (AWC Range), and solar radiation variables (Table 1). The 19 bioclimatic variables, solar radiation, and elevation data were presented in grid format with a spatial resolution of 2.5 arcmin, approximately 1 km², obtained from the WorldClim database (<https://www.worldclim.org>) (Fick and Hijmans, 2017). Soil data were sourced from the Harmonized World Soil Database (HWSD, <http://www.fao.org/soils-portal/>) (Sanchez et al., 2010). For predicting future distributions, three shared socioeconomic pathways (SSP126, SSP370, and SSP585) were downloaded (BCC-CSM2-MR), representing radiative forcing levels in 2100 (Reddy and Saravanan, 2023). SSP126 (radiation intensity of 2.6 W/m²) reflects a low-emission scenario, SSP370 (radiation intensity of 7.0 W/m²) represents a medium-emission scenario, and SSP 585 (radiation intensity of 8.5 W/m²) corresponds to a high-emission scenario (Zheng et al., 2022b). We utilized the 2050s and 2090s to predict the future potential distribution of LJF. High correlation among environmental variables can lead to overfitting of the model. To avoid high correlation among variables, a correlation analysis was performed on the initial set of 36 environmental variables. Variables with a correlation coefficient $|r| \geq 0.8$ were considered, and among them, those with significant contribution values were selected (Dong et al., 2022; He et al., 2021a; Herrando-Moraira et al., 2019). Ultimately, seven factors were identified and retained: bio4, bio6, bio12, eleven, s-oc, srad2, and srad4 (Figure 3).

2.3 Species distribution modeling process

The MaxEnt 3.4.1 software integrates environmental variables and distribution data for predicting species distribution and habitat (Tang et al., 2021). Prior to model establishment, the TIFF (tag image file format) format of each variable is converted to the ASC (action script communication) format. The training set is set to 75%, and the test set is set to 25% in the model (Zhang et al., 2021). We employed 100 repetitions in “Bootstrap” mode with the output format set to “Logistic,” maintaining default settings for other parameters (500 iterations, 0.00001 convergence threshold, and 10,000 background points) (Shen et al., 2022). The weights of each factor in the suitable area of LJF were assessed using the knife-cutting method, identifying key limiting factors influencing the distribution of LJF. Model accuracy was evaluated using the ROC (receiver operating characteristic curve) and the area under the curve (AUC) value. The AUC value, ranging from 0.5 to 1.0, is widely used to assess the accuracy of prediction models, with higher values indicating greater accuracy (Vanagas, 2004; Wang et al., 2019). Based on the MaxEnt model results, the suitability distribution range of LJF in China was extracted using ArcGIS software.

The suitability was divided into four grades by Jenks’ natural breaks, namely, no suitability (0–0.2), low suitability (0.2–0.4), medium suitability (0.4–0.6), and high suitability (0.6–1), to obtain the potential distribution area of LJF (Zheng et al., 2022b; Shen et al., 2022).

2.4 Centroid migration in the core distribution

The SDM toolbox, integrated into ArcGIS, is a software package designed to calculate changes in the suitable area for species. It helps determine the migration direction and distance of species over time.

TABLE 1 Ecological factor variable information.

Abbreviation	Ecological factors	Unit
bio1	Annual mean temperature	°C
bio2	Mean diurnal range	°C
bio3	Isothermality	1
bio4	Temperature seasonality	1
bio5	Max temperature of warmest month	°C
bio6	Min temperature of coldest month	°C
bio7	Temperature annual range	°C
bio8	Mean temperature of wettest quarter	°C
bio9	Mean temperature of driest quarter	°C
bio10	Mean temperature of warmest quarter	°C
bio11	Mean temperature of coldest quarter	°C
bio12	Annual precipitation	mm
bio13	Precipitation of wettest month	mm
bio14	Precipitation of driest month	mm
bio15	Precipitation seasonality	mm
bio16	Precipitation of wettest quarter	mm
bio17	Precipitation of driest quarter	mm
bio18	Precipitation of warmest quarter	mm
bio19	Precipitation of coldest quarter	mm
elev	Elevation	m
s_ph	Subsoil pH	-log(H ⁺)
s_cec	Subsoil CEC	cmol·kg ⁻¹
s_oc	Soil organic carbon	% weight
srad (1-12)	Solar radiation	kJ·m ⁻² ·day ⁻¹
awc	AWC range	code

In this study, the core changes in LJF distributions were identified by converting predictions of species' suitable distributions into binary vectors, where the species suitability probability $p \geq 0.04$ is considered to be the total suitable region, while $p < 0.04$ is considered to be unsuitable. Then, using the Spatial Analysis Tools, the centroid coordinates of the LJF were precisely located based on different climate predictions. Finally, changes in the distribution were examined by tracking the shifts in the centroid across various SDMs

2.5 Preparation of sample solution

Weigh 1.0 g of LJF powder and place it in a stoppered conical flask. Add 50 mL of 50% methanol, record the mass, and perform ultrasonic extraction for 30 min. After cooling, compensate for the weight loss with 50% methanol, shake the mixture, and filter it. Then, filter the sample vial with a 0.22- μ m microporous membrane and store it in the sampling bottle for HPLC analysis.

2.6 HPLC analysis

To establish HPLC fingerprints, the chromatographic conditions were optimized and the established method was verified. (1) Method Establishment: On the HPLC detection platform, the analytical conditions were set as follows: (a) Column, Symmetry C18 (5 μ m, 4.6 mm * 250 mm); (b) Mobile phase: Acetonitrile (Merck) as mobile phase A, ultrapure water with 0.3% methanoic acid (Aladdin) as mobile phase B; (c) The gradient elution program is shown in Table 2; (d) Wavelength, column temperature, flow rate, and injection volume: 245 nm, 38°C, 1 mL min⁻¹, and 10 μ L, respectively. (2) Method Validation: Evaluate precision by injecting the same sample solution six times in a row, and assess repeatability by analyzing six different sample solutions prepared in parallel with the same procedure and batch of LJF. Stability tests of the sample solutions are conducted by analyzing them at 0-, 2-, 4-, 8-, 16-, and 24-h intervals (Jin et al., 2009; Wan et al., 2021).

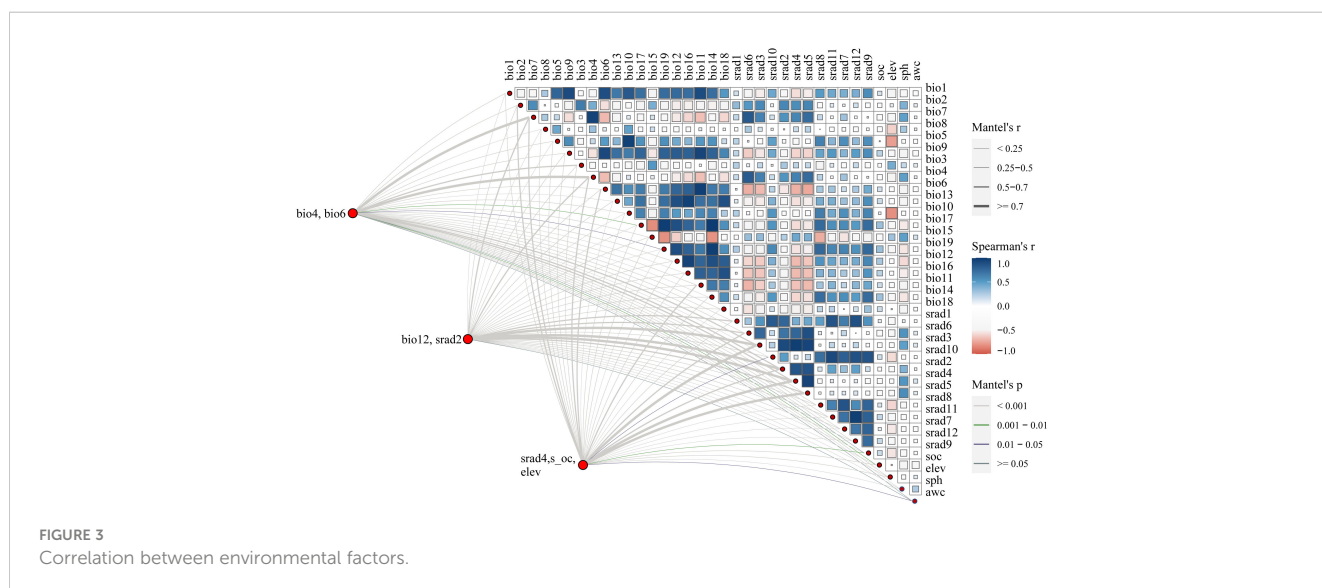


TABLE 2 Gradient elution program of HPLC fingerprints.

Time (min)	Flow rate (mL min ⁻¹)	A%	B%
Initial	1	9	91
10	1	15	85
15	1	17	83
20	1	17.5	82.5
30	1	17.8	82.2
35	1	19	81
40	1	22	78
50	1	9	91

2.7 Correlation analysis between ecological factors and chemical components

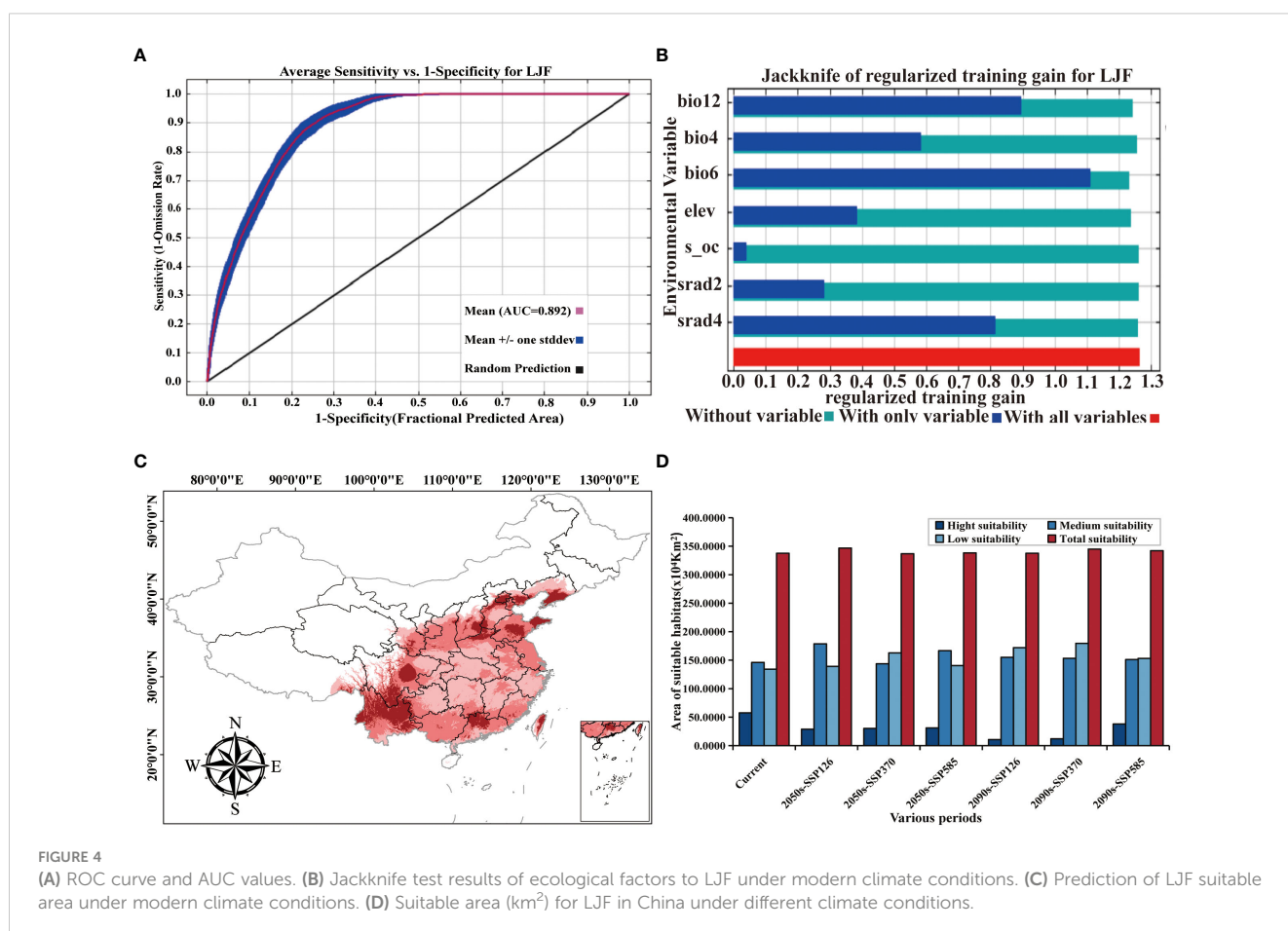
For the sake of studying the effect of habitat suitability on the accumulation of ecological factors, we extracted the ecological factor values of the sampling points by ArcGIS based on the longitude and latitude information of LJF. Then, the stepwise regression method was performed using R 4.3.2 software to

conduct a correlation analysis of the chemical composition of medicinal materials, including Hyperoside (Hyp), Rutin (Rt), Chlorogenic acid (Ch.a), Cynaroside (Cyn), Isochlorogenic acid A (Isa A), and ecological factors. Finally, a correlation analysis was constructed to assess the relationship between the chemical composition and ecological factors. This analysis was superimposed with the habitat suitability distribution map of LJF to create a medicinal quality zoning map.

3 Results and discussion

3.1 Accuracy of model analysis

The AUC value (area under the ROC curve), being unaffected by the threshold, is widely used to assess the accuracy of prediction models (Zheng et al., 2022b). An AUC between 0.9 and 1 signifies an “excellent” model, while an AUC between 0.8 and 0.9 indicates a “good” model (Swets, 1988). In the context of ecological factors, the ROC curve generated by the MaxEnt model illustrates an AUC value of 0.892 for the LJF distribution model based on 36 environmental variables (Figure 4A). This value surpasses 0.8, indicating the model’s good accuracy, and the prediction results can be used for studying the division of LJF suitable areas.



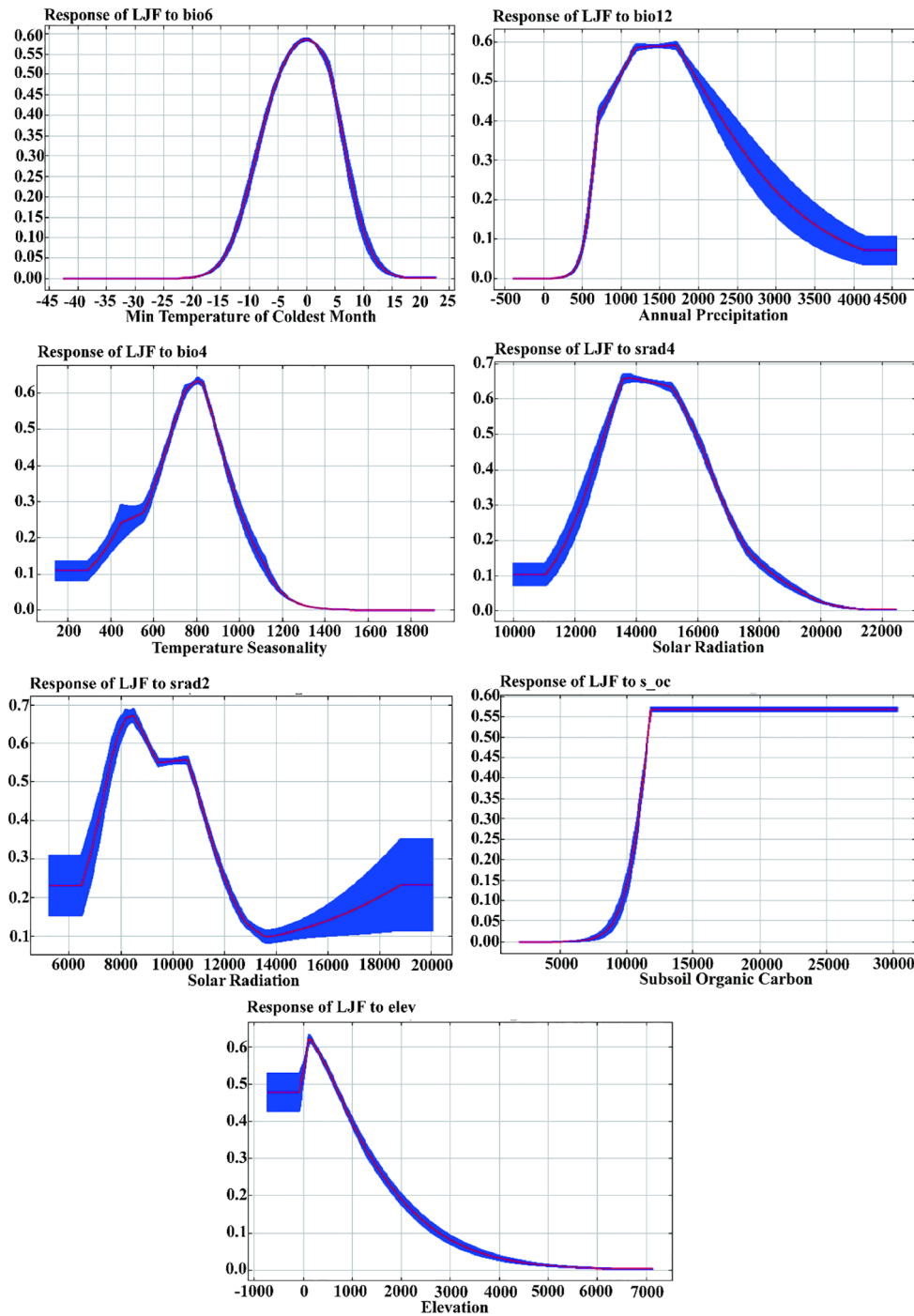


FIGURE 5 Response curves of the current existence probability of LJJ to the environmental variables.

3.2 Important environmental variables

Supplementary Table S1 provides an overview of the contribution and significance of Maxent model factor variables in shaping the distribution of LJJ. In the current period, the seven variables that contribute the most to LJJ are bio6, bio12, bio4, srad2, srad4, elev, and s_oc, with contribution rates of 44.6%, 40.3%, 8.5%, 3.2%, 2.4%, 0.8%, and 0.1%, respectively. The permutation

importance rates for these variables are 58.1%, 25.5%, 4.6%, 0.5%, 7.7%, 2.2%, and 0.4%, respectively. Jackknife test simulations for the current period demonstrated that when simulations were conducted with a single variable, bio6 had the highest regularization training gain, indicating its provision of more effective model simulation information (Figure 4B). When the bio6 variable was removed from the simulation, the variable with the greatest decrease in regularization training gain was also bio6,

suggesting that this variable had information about the other variables. Utilizing response curves (Figure 5), we determined thresholds (presence probability $p > 0.55$) for key biotic factor parameters. The identified thresholds for these parameters are as follows: Min temperature of the coldest month (bio6) ranges from -4 to 4°C , temperature seasonality (bio4) spans 700 to 900, annual precipitation (bio12) falls between 500 and 1,000 mm, solar radiation in February (srad2) varies from 7,500 to 9,000 $\text{kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, solar radiation in April (srad4) ranges from 13,500 to 14,500 $\text{kJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, subsoil organic carbon (s_oc) at 11,000, and elevation (elev) from 0 to 2,500 m. The results showed that temperature, precipitation, elevation, and soil characteristics are the primary ecological factors influencing the growth of LJF. LJF thrives in temperatures approximately 20°C (Zheng et al., 2022a). Extreme temperature will damage the photosynthetic activity of plants, affect the stability of proteins, accumulate excessive reactive oxygen species (ROS), and change the production and signal transduction of plant hormones, thus having a significant harmful effect on plant growth, development, quality, and so on (Ohama et al., 2017; Li et al., 2018; Huang et al., 2023). LJF typically thrives in precipitation ranging from 600 to 1,000 mm. Moreover, water availability significantly impacts seedling emergence and plant growth (Khaim et al., 2022). Long-term drought will restrict the growth and development of plants, and the photosynthesis of plant leaves will also begin to decline, and the accumulation of secondary metabolites will be weakened (Chaves et al., 2009; He et al., 2021b; Yang et al., 2007). Altitude emerges as the dominant ecological factor influencing the pharmacodynamic components of LJF. The content of components increases with the elevation of the planting area, ranging from 4 to 2,100 m (Seyis et al., 2020). LJF, being a vine or woody plant, exhibits a preference for deep soil. Research indicates that the ideal soil type for LJF is neutral or slightly alkaline, characterized by loose, deep, fertile sandy soil, and a higher soil exchange capacity (Yang et al., 2017).

3.3 Prediction of a suitable area for LJF under modern environmental variables

Initially predicted using the MaxEnt model, the distribution of LJF under current ecological factors is illustrated in Figure 4C. The identified distribution areas in northern Yunnan and Guangdong, central Sichuan and Hebei, central and eastern Shandong, and southern Liaoning align with relevant records (Sun et al., 2023). Subsequently, ArcGIS software was employed to reclassify the LJF distribution, leading to the determination of the potential suitable distribution area under the current ecological factors, as depicted in Figure 4D. The results indicate that the potential suitable distribution area of LJF covers $3,376,198 \text{ km}^2$, constituting 35.17% of the national land area. The highly suitable habitat area covered an expanse of $574,879 \text{ km}^2$, spanning the central and western parts of Sichuan (Chengdu and Ziyang), the southern part of Shandong (Linyi), the northern part of Henan (Xinxiang and Anyang), the southern and central eastern parts of Hebei (Xingtai and Chengde), the central and western parts of Guangdong (Qingyuan and Shaoguan), the southeastern part of Shanxi (Jincheng), the

southern part of Liaoning (Dalian), Yunnan, and Taiwan. Moderately suitable areas are primarily distributed in the Taihang Mountains, Hengduan Mountains, Wuyi Mountains, Loess Plateau, and the middle and lower reaches of the Yangtze River, covering an area of $1,460,417 \text{ km}^2$. This indicates that the modern potential distribution suitability areas simulated by MaxEnt largely align with contemporary distribution records. In summary, LJF exhibits high adaptability in the Huaihe River Basin, Qinling, and North China Plain. The warm and humid climate, along with sufficient rainfall in most areas of Sichuan, Yunnan, and Guangdong in the southwest and southern regions, creates a conducive ecological environment for the growth of LJF. These findings further emphasize LJF's adaptability to diverse ecological conditions.

3.4 Potential distribution of LJF under future climate change scenarios

The changes in the distribution of LJF under different future climate scenarios are depicted in Figure 6 and Supplementary Table S2. In comparison to the present conditions, the total suitable area is projected to increase in the future, although the area of high suitable habitat is expected to decrease. For the period from 2041 to 2060, the highly suitable habitat areas under the SSP126, SSP370, and SSP585 climate scenarios are $288,333 \text{ km}^2$, $302,170 \text{ km}^2$, and $311,684 \text{ km}^2$, respectively. These figures represent a reduction of 49.84%, 47.44%, and 45.78%, respectively, compared to the current climate scenarios. The moderately suitable habitat areas under these scenarios increased by 22.38%, decreased by 1.58%, and increased by 14.06%, respectively. For the period from 2081 to 2100, the highly suitable habitat area under SSP126, SSP370, and SSP585 was $106,024 \text{ km}^2$, $120,035 \text{ km}^2$, and $379,427 \text{ km}^2$, respectively. All these values significantly decrease compared to current conditions. In contrast, the area of moderately suitable habitat increased. This is believed to be attributed to the gradual increase in greenhouse gas emissions, where elevated temperatures will limit plant growth, leading to the gradual transformation of highly suitable habitat areas into moderately suitable ones (Wan et al., 2023). In the future, LJF high suitability areas are expected to expand in southern Gansu, southeastern Tibet, and southern Liaoning (Supplementary Figure S1). Compared with current climate conditions and future emission scenarios, the LJF high suitability area expands to higher-altitude areas. In future emission scenarios, rising temperatures associated with increased concentrations of CO_2 released can lead to species migration towards higher-altitude or -latitude areas (Bertrand et al., 2011; Pernicová et al., 2024).

3.5 Changes in gravity center of the highly suitable distribution of LJF in the future

The SDM_Toolbox within ArcGIS 10.8 was utilized to calculate the centroid distribution of LJF suitable areas under various environmental scenarios and time periods, thereby deriving the centroid migration trajectory (Figure 7). Currently, the center of gravity of the suitable habitat for LJF is in Fancheng District, Fanyang

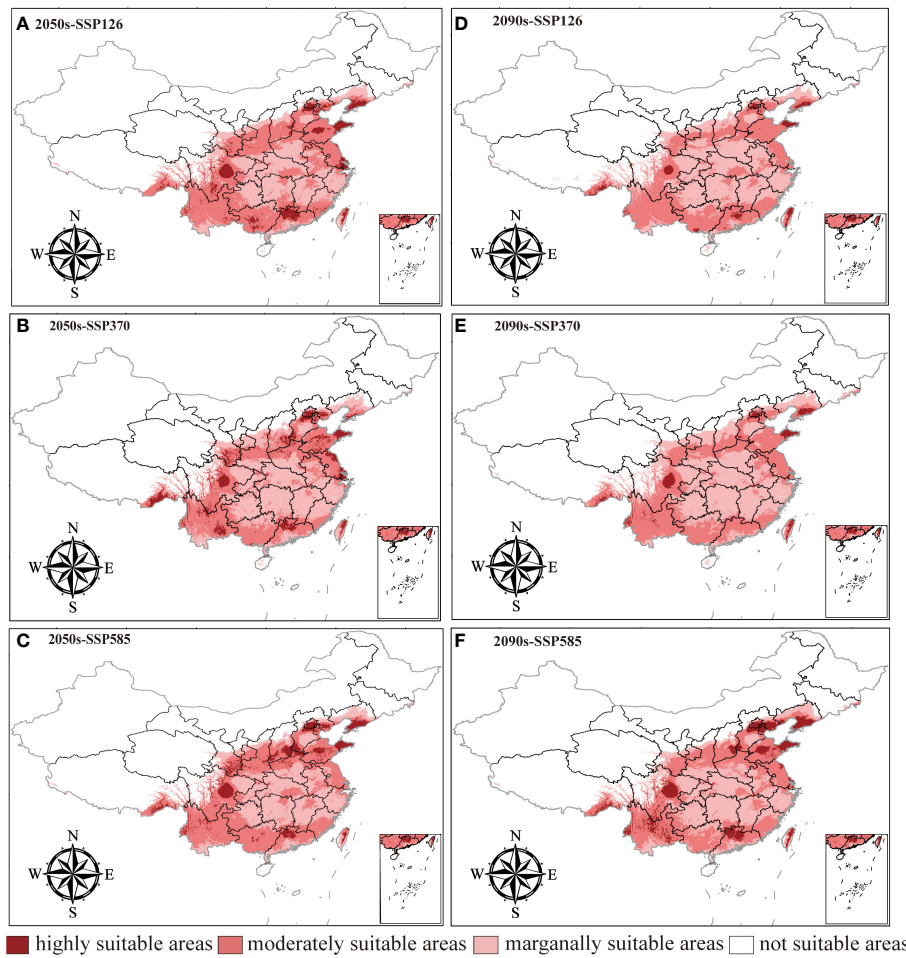


FIGURE 6 Prediction of LJF suitable area under future climate conditions. (A). 2050s-SSP126, (B). 2050s-SSP370, (C). 2050s-SSP585, (D). 2090s-SSP126, (E). 2090s-SSP370, (F). 2090s-SSP585.

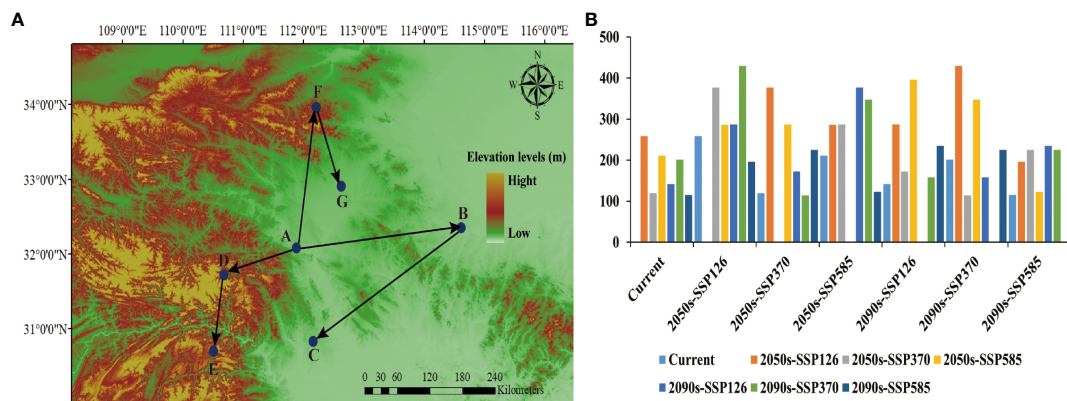


FIGURE 7 Interglacial period ((A) migration route; (B) migration distance). Among them, the meaning of the letters were (A) current, (B) 2050s-SSP126, (C) 2090s-SSP126, (D) 2050s-SSP370, (E) 2090s-SSP370, (F) 2050s-SSP585, (G) 2090s-SSP585.

City, Hubei Province (111.881004 E, 32.083149 N). Under the 2050s-SSP126 climate scenario, the center of gravity for highly suitable areas will shift eastward to Xixian County, Xinyang City, Henan Province (114.613104 E, 32.35066 N), with a migration distance of 258.73 km. Under the 2090s-SSP126 climate scenario, the center of gravity of the suitable habitat will migrate to the Duodao District in Jingmen City, Hubei Province (112.161545 E, 30.829002 N), with a migration distance of 141.97093 km. In the scenario of 2050s-SSP370, the center of gravity of the highly suitable area will migrate westward to Shennongjia District of Hubei Province (110.682713 E, 31.722339 N), covering a migration distance of 120.02 km. In the 2090s-SSP370 scenario, the gravity center moves southwest to Changyang Tujia Autonomous County, Yichang City (110.507134 E, 30.702936 N), covering a distance of 201.38847 km. Under the 2050s-SSP585 scenario, the center of gravity of suitable habitat will migrate eastward to Songxian County, Luoyang City, Henan Province (110.682713 E, 31.722339 N), with a migration distance of 210.94 km. Under the 2090s-SSP585 scenario, the center of gravity of suitable habitat moves to Yuancheng District, Nanyang City, Henan Province (112.624916 E, 32.90641 N). Simulation of future distributions indicates that under three different climate scenarios (SSP126, SSP370, and SSP585), the suitable distribution areas for LJF are decreasing. This phenomenon is also observed in other plants such as *Leonurus japonicus* and *Leucanthemum vulgare* (Wang et al., 2023b; Ahmad et al., 2019). In the high emissions scenario for 2050, temperatures are projected to rise by approximately 1.3°C and by over 2.79°C in the 2090s (Ford et al., 2012; Brouziyne et al., 2021). Consequently, the population of LJF is expected to generally decline, and habitat fragmentation is anticipated to become more severe than it is currently. Under the emission scenarios for the 2050s and 2090s, the predicted suitable areas are projected to shift towards southern regions at higher elevations. Studies have shown that the altitudinal distribution of species is largely driven by temperature gradients (Lenoir et al., 2008; Ashraf et al., 2016; Kumar et al., 2022). However, besides the impact of temperature changes, the suitable distribution of species may also involve biological characteristics, geological factors, or other disturbance factors (Dong et al., 2022). LJF thrives in moist, warm climates. Therefore, there is a tendency to migrate to the south.

3.6 Chromatographic fingerprint analysis

Chromatographic fingerprinting enables the qualitative and quantitative assessment of TCM quality by analyzing chemical information and depicting the peak distribution of specific components. At a detection wavelength of 245 nm, there is high separation between chromatographic peaks, elevated response, symmetrical peak shapes, and a stable baseline, facilitating fingerprint establishment. The results of method validation showed that the relative standard deviation (RSD) for the precision of Rt, Ch.a, Hyp, Cyn, and Isa A were 2.3%, 2.2%, 3.6%, 3.5%, and 1.9%, respectively. The RSD for reproducibility were 2.0%, 3.7%, 3.2%, 3.1%, and 2.7%, respectively, and the RSD for stability were 3.0%, 3.2%, 2.8%, 3.1%, and 2.5%, respectively. These results indicate that the established method is suitable for the development of HPLC fingerprints of LJF. The Chromatographic Fingerprint is imported into the Similarity Evaluation System for Chromatographic Fingerprint of TCM (version 2012). Subsequently, the reference spectrum and time width are set, peak areas are normalized, multi-point correction is conducted, peaks are automatically matched, and the standard fingerprint is generated. The standard fingerprints of LJF in 11 different regions are presented in Figure 8A. Based on chromatographic peak matching information, 21 common peaks were selected. The similarity values ranged between 0.817 and 0.989, indicating that the chemical composition of LJF from different locations varied to some extent (Table 3). Five compounds, Ch.a, Rt, Hyp, Cyn, and Isa A, were identified through the control (Figure 8B). Subsequently, a quantitative analysis of the five components in LJF from different origins was conducted (Supplementary Figure S2). The results revealed that the average contents of Ch.a, Hyp, and Isa A were higher in medium and high suitable areas than in low suitable areas. The contents gradually decreased from high suitable areas to low suitable areas, whereas the contents of Rt and Cyn in low suitable areas were higher than those in medium suitable areas. This indicates that the suitable growth area is not necessarily conducive to the accumulation of all secondary metabolites. Research indicates that certain species, under the influence of environmental stress, produce specific secondary metabolites to

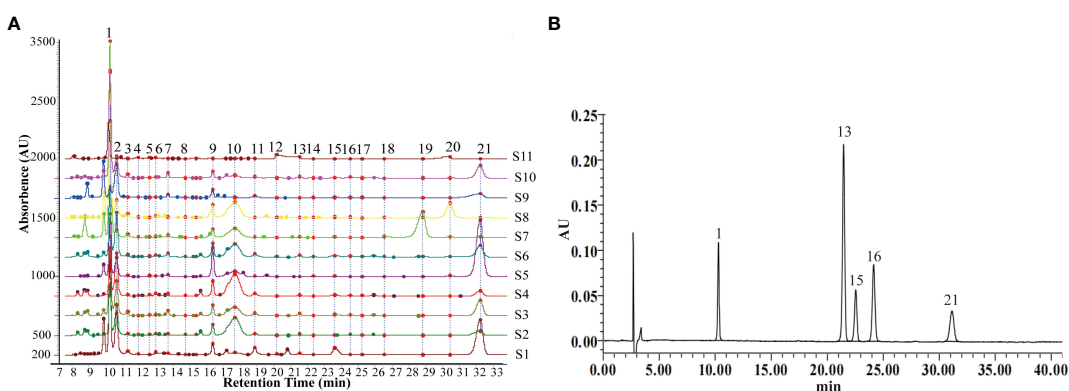


FIGURE 8

(A) Standard fingerprints of LJF in eleven regions. (B) Reference fingerprint. The serial numbers S1-11 represent Guangdong, Shandong, Yunnan, Hubei, Henan, Jiangxi, Hebei, Sichuan, Shanxi, Hunan and Gansu province, respectively. The numbers 1, 13, 15, 16, 21 represent Ch.a, Rt, Hyp, Cyn, Isa A.

TABLE 3 The similarity values of LJJ in 11 regions.

No.	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	C
S1	1											
S2	0.583	1										
S3	0.915	0.806	1									
S4	0.543	0.993	0.756	1								
S5	0.861	0.395	0.647	0.387	1							
S6	0.827	0.917	0.951	0.900	0.590	1						
S7	0.854	0.644	0.919	0.56	0.622	0.772	1					
S8	0.800	0.846	0.950	0.783	0.562	0.892	0.948	1				
S9	0.675	0.553	0.671	0.579	0.450	0.766	0.355	0.439	1			
S10	0.909	0.659	0.97	0.588	0.611	0.852	0.958	0.922	0.578	1		
S11	0.767	0.503	0.847	0.406	0.472	0.658	0.955	0.866	0.293	0.935	1	
C	0.926	0.826	0.989	0.781	0.724	0.949	0.919	0.957	0.63	0.943	0.817	1

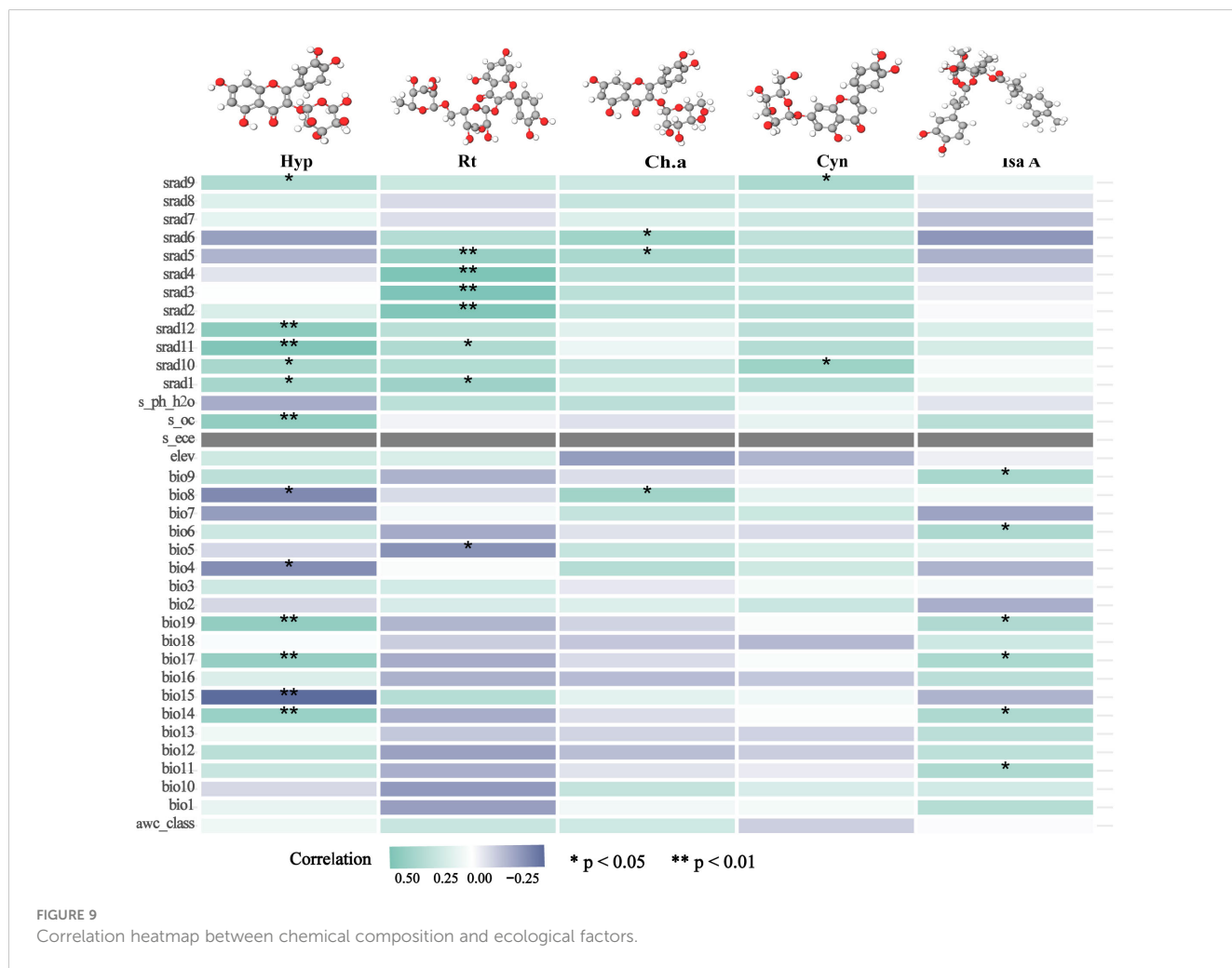


FIGURE 9 Correlation heatmap between chemical composition and ecological factors.

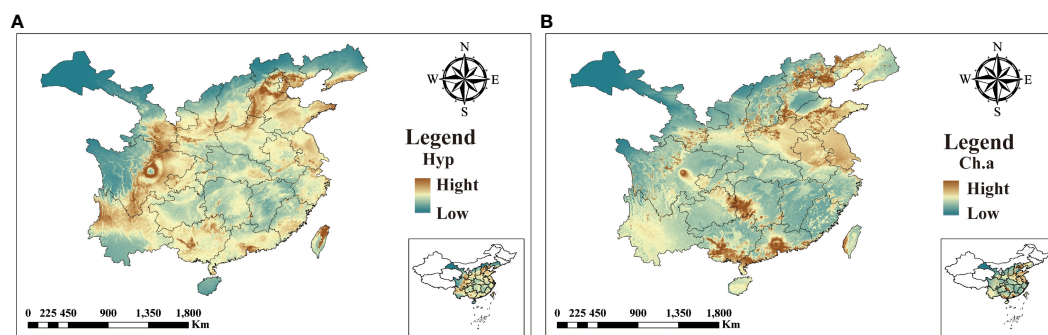


FIGURE 10
The spatial distribution of the content of Hyp (A) and Ch.a (B).

enhance adaptability to adversity and facilitate the formation of authentic medicinal materials (Li et al., 2020).

3.7 Correlation analysis between ecological factors and chemical components

The five identified components were correlated with the ecological factors identified by the MaxEnt model (Figure 9), indicating a significant impact of ecological factors on these components. In LJF, Hyp and Isa A show negative correlations with *srad3*, *srad4*, *srad5*, and *srad6*, while *Rt*, *Ch.a*, and *Cyn* exhibit a positive correlation ($p < 0.01$). Additionally, *Rt*, *Ch.a*, and *Cyn* display negative correlations with *bio9*, *bio19*, *bio18*, *bio17*, *bio16*, *bio11*, *bio12*, *bio13*, and *bio14*, whereas they are positively correlated with *bio8*. Furthermore, *bio8* shows a negative correlation with Hyp ($p < 0.05$) and a positive correlation with Ch.a ($p < 0.05$). The correlation between the same ecological factor and different components varies, as does the correlation between different ecological factors and the same component. To address this issue, the spatial analysis function and correlation model of ArcGIS software were employed to create spatial distribution maps for the content of four common peaks (the analysis was not conducted for the correlation between *Cyn* and factors due to its lack of obvious correlation).

Figure 10 illustrates the spatial distribution of the contents of Hyp and Ch.a. Ultimately, the content spatial distribution maps of LJF and the habitat suitability map were superimposed to generate the quality zoning map of LJF in the distribution area, as depicted in Figure 11. In Figure 11, high-quality LJF is predominantly distributed in central and southern Hebei Province, northern Henan Province, central Shandong Province, central Sichuan Province, southern Guangdong Province, and the Taiwan Peninsula. Poor-quality LJF is distributed in northern Gansu, western Sichuan, northeastern Liaoning, and northwestern Shanxi. By comparing the zoning map with the habitat suitability distribution map, it is evident that the low-quality area is not a suitable area. This implies that ecological factors unfavorable to the growth of LJF also hinder the accumulation of LJF pharmacodynamic components. However, suitable areas are not necessarily high-quality areas. Optimal conditions for the growth and development of certain herbs and the accumulation of secondary metabolites do not necessarily align. This discrepancy can be attributed to the complexity involved in the synthesis and accumulation of secondary metabolites in medicinal plants. Research indicates that active ingredients (secondary metabolites) are produced and accumulate under stressful (adverse) conditions. Since the active substances in medicinal plants are predominantly secondary metabolites, this is largely considered a result of plant adaptation to adversity (Al-

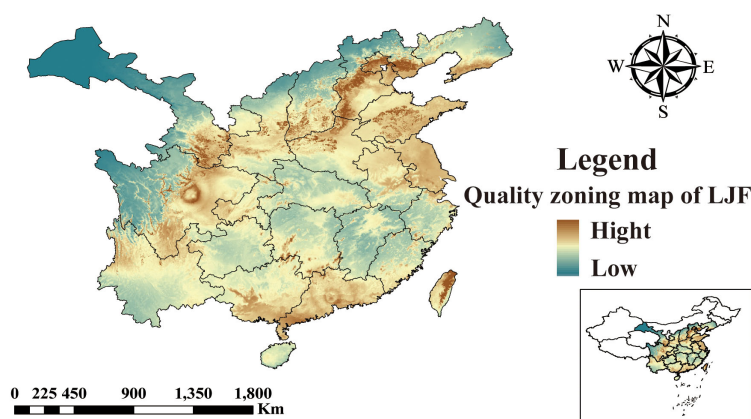


FIGURE 11
The quality zoning map of LJF in Distribution areas.

Khayri et al., 2023). In this study, by considering the spatial correlation between habitat suitability and quality suitability, an LJF quality zoning map was obtained, facilitating LJF production zoning.

4 Conclusion

In this study, we established a new method to evaluate the effects of ecological factors on LJF quality based on HPLC fingerprinting technology, ArcGIS, and MaxEnt models, combined with database data, field sampling, and component analysis. Using the MaxEnt model, the ecological factors affecting the suitable distribution area of LJF were screened as bio4, bio6, bio12, srad2, srad4, s_oc, and elev. The distribution area was divided into highly suitable, medium suitable, low suitable, and unsuitable areas. Under future climate scenarios, the high suitability zone of LJF will expand in southern Gansu, southeastern Tibet, and southern Liaoning. The correlation model between ecological factors and chemical components was established through bivariate correlation analysis. Finally, based on the correlation and ArcGIS spatial distribution model, the LJF quality distribution map is drawn to visually show the distribution area of LJF. The screened ecological factors affecting the distribution of LJF habitat adaptation were compatible with the growth habit of LJF, which verified the reliability of the method. The combination of chromatographic fingerprinting technique and MaxEnt model provides a reference for the conservation of Chinese herbal resources and the selection of cultivation areas, and also provides a new perspective for evaluating the influence of ecological factors on the quality of Chinese herbal medicines.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

JC: Investigation, Methodology, Formal analysis, Conceptualization, Data curation, Writing – original draft. FG: Methodology, Data curation, Writing – review & editing. LW:

Investigation, Writing – review & editing. ZL: Formal analysis, Writing – review & editing. CZ: Formal analysis, Writing – review & editing. HW: Data curation, Writing – review & editing. WL: Investigation, Writing – review & editing. XJ: Supervision, Writing – review & editing. YC: Methodology, Writing – review & editing, Investigation, Supervision. PD: Supervision, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpls.2024.1397939/full#supplementary-material>

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