EVOLUTION AND LIMITATIONS OF PEDICULARIS RESEARCH: A THREE-DECADE BIBLIOMETRIC AND VISUALIZATION ANALYSIS

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(Received 20th Oct 2025; accepted 22nd Jan 2026)

Abstract. *Pedicularis* serves as an ideal model genus for understanding alpine plant diversification and ecological adaptation. However, a comprehensive global synthesis of its research trajectory remains unavailable. Based on the Web of Science Core Collection (1995–2025), this study conducted a bibliometric and visualization analysis of 492 English-language publications using CiteSpace, VOSviewer, Excel, and Bibliometrix. Results indicate a fluctuating but overall increasing trend, reflecting growing academic influence. Collaboration networks reveal a China-centered structure increasingly integrated into the global research system, with the Chinese Academy of Sciences and Jia Z. J. identified as the most influential institution and author, respectively, and Sino–US collaboration forming the strongest international relationship. The evolution of research themes highlights three major foci: (1) biodiversity formation and biogeographic patterns in the Hengduan–Himalayan region, as bibliometric results indicate that this region represents the global center of species diversity, endemism, and evolutionary radiation of *Pedicularis*; (2) floral trait evolution and pollination adaptation; and (3) ecological responses and ecosystem functions under global change. Future research should integrate phylogenomic, macroecological, and biogeographic modeling approaches to elucidate the coevolutionary mechanisms of morphology, parasitism, and environmental adaptation. Coupling ecological niche modeling with population genomics and physiological ecology could further improve predictions of species' climatic vulnerability, thereby providing theoretical and practical guidance for alpine biodiversity conservation worldwide.
Keywords: *hemiparasitic plants, alpine biodiversity, bibliometric analysis, knowledge mapping, biogeographic patterns, evolutionary radiation*

Introduction

Pedicularis was first described by Linnaeus in 1753 and was originally classified under the family Scrophulariaceae (Editorial Committee of Flora of China, 1968; Zhong, 1963). Later, it was reassigned to the family Orobanchaceae according to the Angiosperm Phylogeny Group (APG) system (Editorial Committee of Flora of China, 1968). *Pedicularis* species are annual or perennial herbaceous plants, typically hemiparasitic, though occasionally facultatively hemiparasitic. The inflorescences are

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2402_26632680

arranged in racemes or spikes (Chen, 2022). The genus displays remarkable morphological diversity and a wide spectrum of floral coloration, conferring considerable ornamental value. In addition, several species possess documented medicinal properties (Li et al., 2014). Globally, *Pedicularis* comprises approximately 600 species and is widely distributed across cold regions of the Northern Hemisphere, including the Arctic, continental Europe, and northwestern North America. Nearly two-thirds of the species occur in China, where they are primarily concentrated in the southwestern and northwestern regions of the country (Zhong, 1963).

In recent decades, research on *Pedicularis* has grown steadily worldwide, expanding from traditional morphological taxonomy to encompass ecology, phylogenetics, and evolutionary biology. However, a systematic and comprehensive synthesis of global research progress is still unavailable. Consequently, the research hotspots, developmental patterns, and emerging trends of this genus remain insufficiently understood, making it difficult to capture its scientific limitations and future directions. Conducting a bibliometric analysis of *Pedicularis* research therefore holds substantial academic value. Bibliometric analysis is an interdisciplinary method that integrates mathematical, statistical, and bibliographic approaches to explore the structure, characteristics, and dynamics of a research field (Zhu and Meng, 2013). Since the early 21st century, bibliometric and visualization tools have been increasingly employed to map scientific knowledge structures, co-occurrence relationships, and thematic evolution, thereby identifying research hotspots and frontiers across diverse disciplines (Aria and Cuccurullo, 2017; Han et al., 2022).

To track and interpret the evolving landscape of *Pedicularis* research, this study draws on data from the Web of Science Core Collection and applies bibliometric and visualization tools including CiteSpace, VOSviewer, Excel, and Bibliometrix. Specifically, this work aims to: (1) analyze publication trends; (2) identify the most influential authors, institutions, and countries; (3) examine collaboration networks and knowledge structures; and (4) reveal major research hotspots and potential future directions. The findings provide an integrated overview of the current status and developmental trajectory of *Pedicularis* studies and offer a valuable foundation for future interdisciplinary research integrating functional traits, macroecology, and species distribution modeling to further elucidate the mechanisms underlying diversification and environmental adaptation in this genus.

Data and methods

Data sources and processing

The literature data were retrieved from the Web of Science (WOS) Core Collection using advanced search strategies. The search query was constructed as TS = (*Pedicularis*), where TS represents the topic field. The publication period was set from January 1, 1995, to October 1, 2025, covering a 30-year span. A total of 524 publications were initially obtained, including journal articles, review articles, early access papers, and data papers. After removing duplicates and screening for relevance, 492 valid records were retained to establish the final research dataset. The detailed literature retrieval and screening process is illustrated in *Figure 1*. To ensure data completeness, “Early Access” publications were included, and bibliographic records up to October 2025 were manually verified and supplemented to minimize the effect of database update lag.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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For data organization, a project directory named "WOS" was created, containing four subfolders: input, output, data, and project. The retrieved records from WOS were exported in plain text format using the option "Full Record and Cited References". These text files were directly imported into CiteSpace and VOSviewer for bibliometric and visualization analyses without additional format conversion.

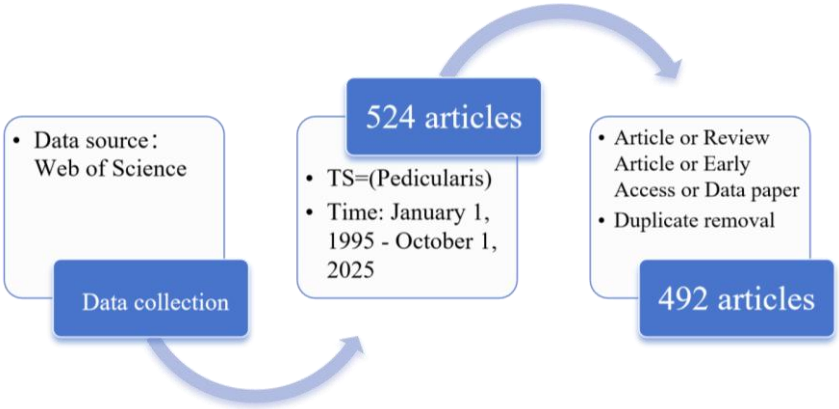

Figure 1. *Schematic diagram of the literature retrieval and screening process*

Research methods

This study combined bibliometric and visualization tools to analyze the *Pedicularis*-related publications retrieved from the Web of Science database. Excel was used for basic statistical analysis and visualization of annual publication trends. CiteSpace 6.4. R1 was employed to perform co-occurrence and network analyses on the processed bibliographic data. The node types were set to Author, Keyword, and other relevant categories, with a time span from 1995 to 2025 and a time slice of one year (Years Per Slice = 1). The pruning and slicing algorithm were applied, and the node selection threshold was set to Top N = 50, meaning that the top 50 nodes from each time slice were retained to generate the final knowledge network. In the resulting knowledge graphs, node size reflects the frequency of occurrence of a term or author—the larger the node, the higher the frequency. Edges between nodes indicate co-occurrence relationships, where the width represents the strength of association, and the color gradient indicates the temporal evolution of the relationship (Zeng et al., 2024). In addition, VOSviewer 1.6.19 was used to construct keyword co-occurrence visualization maps, while the Bibliometrix R package was employed for national and institutional collaboration analyses. These complementary approaches together provided a multidimensional understanding of the overall structure, evolution, and collaboration patterns in *Pedicularis* research.

Results

Analysis of the number of documents published

The annual number of publications reflects research activity and developmental trends within a specific field (Liu et al., 2025). An analysis of publications from 1995 to 2025 reveals a fluctuating yet overall upward trend in *Pedicularis* research (*Fig. 2*). The annual output increased from a minimum of 4 papers in 1995 to a peak of 30 in 2013, highlighting the growing academic influence and productivity within this field. The

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results of a polynomial regression analysis further demonstrate a significant nonlinear growth trend ($R^2 = 0.515$, $p < 0.001$). This moderate explanatory power is consistent with expectations for ecological and bibliometric systems, indicating that *Pedicularis* research development is multifactor-driven, characterized by phased fluctuations and nonlinear evolution rather than a simple linear increase.

Based on internal driving mechanisms, the development trajectory can be divided into three distinct phases:(1) Early exploration (1995-2005) — Annual publications mostly ranged between 5–15 papers, reflecting a preliminary stage with limited research capacity, funding constraints, and an underdeveloped understanding of *Pedicularis* taxonomy and ecology. (2) Growth phase (2006–2015) — Publication output increased markedly, peaking between 2012–2015. This period coincided with the rapid integration of molecular systematics and biogeographical studies, which drove breakthroughs in the field (Yu et al., 2015). The Qinghai–Xizang Plateau ecosystem also became a global focus of ecological research, fostering active international collaborations. (3) Stable and diversified stage (2016–2025) — Annual publications stabilized at a high level (20–30 per year), indicating sustained productivity. Research topics diversified during this period, as national policies emphasizing biodiversity conservation and plateau ecosystem protection promoted extensive studies on alpine plants represented by *Pedicularis* (Dai et al., 2017; Bao et al., 2022). Overall, the fitted curve suggests that despite annual fluctuations, *Pedicularis* research remains in a high-output phase with continued growth potential in the coming years.

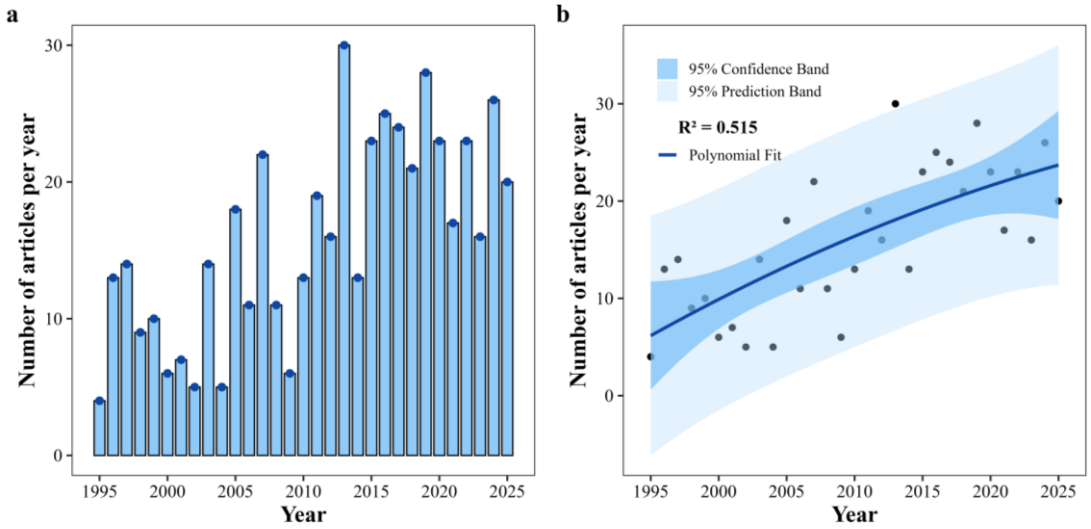

Figure 2. *Annual number of publications on Pedicularis from 1995 to 2025 (a), and the polynomial regression fitting between publication year and number of publications (b)*

Analysis of the main research forces

Author collaboration network analysis

Core authors can be identified based on publication output, which to some extent reflects their academic influence within the field (Chen, 2022). Based on Web of Science data, the CiteSpace visualization reveals a clearly structured author collaboration network in *Pedicularis* research. Statistical results (*Table 1*) show that Jia Z. J. (30 papers), Zheng R. L. (19 papers), and Huang Shuang-Quan (13 papers) are the

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most prolific and influential scholars in this field. The sustained research activity of these core authors since the mid-1990s indicates the formation of a stable and mature research team, which has played a leading role in advancing the field.

Table 1. *Top ten productive authors in Pedicularis studies*

Rank	Author	Institution	Publications	First year
1	Jia, ZJ	Lanzhou University	30	1995
2	Zheng, RL	Lanzhou University	19	1996
3	Huang, Shuang-Quan	Central China Normal University	13	2007
4	Guan, Kai-Yun	Kunming Institute of Botany, Chinese Academy of Sciences	11	2007
5	Wang, Hong	Kunming Institute of Botany, Chinese Academy of Sciences	10	2013
6	Li, Ai-Rong	Kunming Institute of Botany, Chinese Academy of Sciences	9	2007
7	Yu, Wen-Bin	Kunming Institute of Botany, Chinese Academy of Sciences	9	2013
8	Wang, WF	Lanzhou University	8	1996
9	Wang, CZ	Lanzhou University	8	1995
10	Li, De-Zhu	Kunming Institute of Botany, Chinese Academy of Sciences	8	2012

The collaboration network also includes representative authors from other countries, reflecting the international context of Pedicularis research

The CiteSpace-generated collaboration network (*Fig. 3*) comprises 684 nodes and 1061 links, with a high modularity (Q = 0.608) and mean silhouette score (S = 0.888), indicating well-defined clusters and strong collaborative connections. The overall structure presents a multi-core collaborative pattern, dominated by three major clusters:(1) The “Classification and Distribution Modeling” cluster, led by Jia Z. J. and Zheng R. L., integrates traditional taxonomy with climate response modeling, bridging classical systematics and ecological modeling.(2) The “Pollination Ecology and Evolutionary Adaptation” cluster, headed by Huang Shuang-Quan and Yu Wen-Bin, represents the ecological and evolutionary research frontier and demonstrates strong Sino–foreign collaboration;(3) The “Morphological and Functional Traits” cluster, centered on Li Ai-Rong and Guan Kai-Yun, provides crucial morphological foundations for subsequent ecological and evolutionary analyses. Overall, the findings indicate that *Pedicularis* research has transitioned from fragmented individual studies to an integrated international collaboration network, reflecting both the specialization and globalization of research within this field.

Institutional collaboration analysis

Analyzing research institutions helps to identify influential research units and understand the distribution of academic productivity across organizations (Yang et al., 2022). Examining institutional collaboration can also reveal the scientific capacity of each organization and promote information exchange and cooperation within the field (Mukherjee et al., 2022). The institutional collaboration network (*Fig. 4*) and institutional productivity ranking (*Table 2*) indicate that research on *Pedicularis* has

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evolved into a highly concentrated, multi-core collaborative system. The network metrics show a high modularity (Q ≈ 0.61) and silhouette coefficient (S ≈ 0.89), reflecting strong collaborative ties and a well-defined structure.

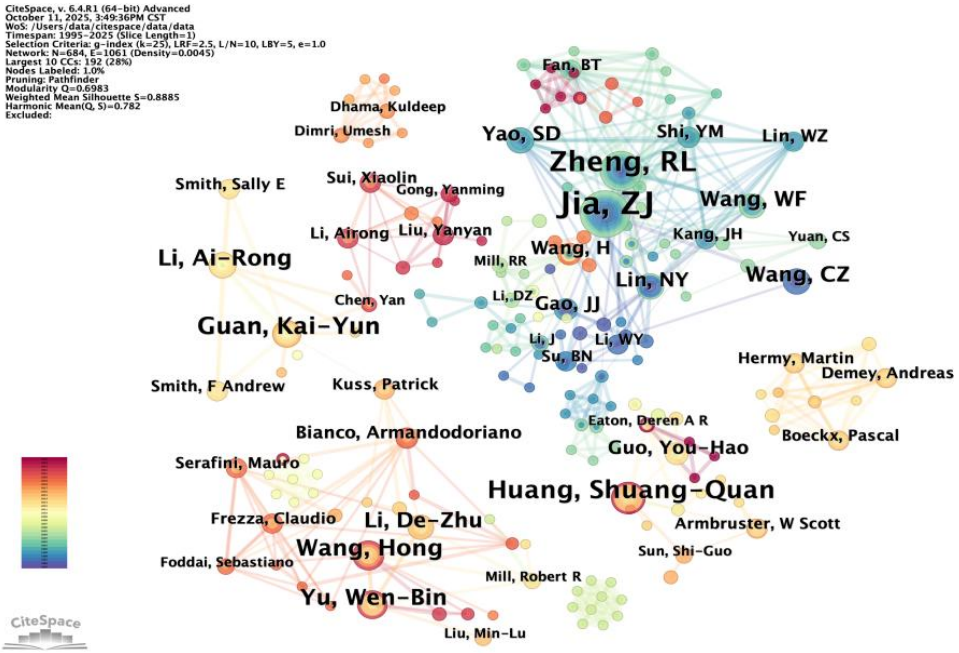

Figure 3. *Author collaboration network of Pedicularis research. Node size represents the number of publications, and edge thickness indicates the strength of co-authorship links*

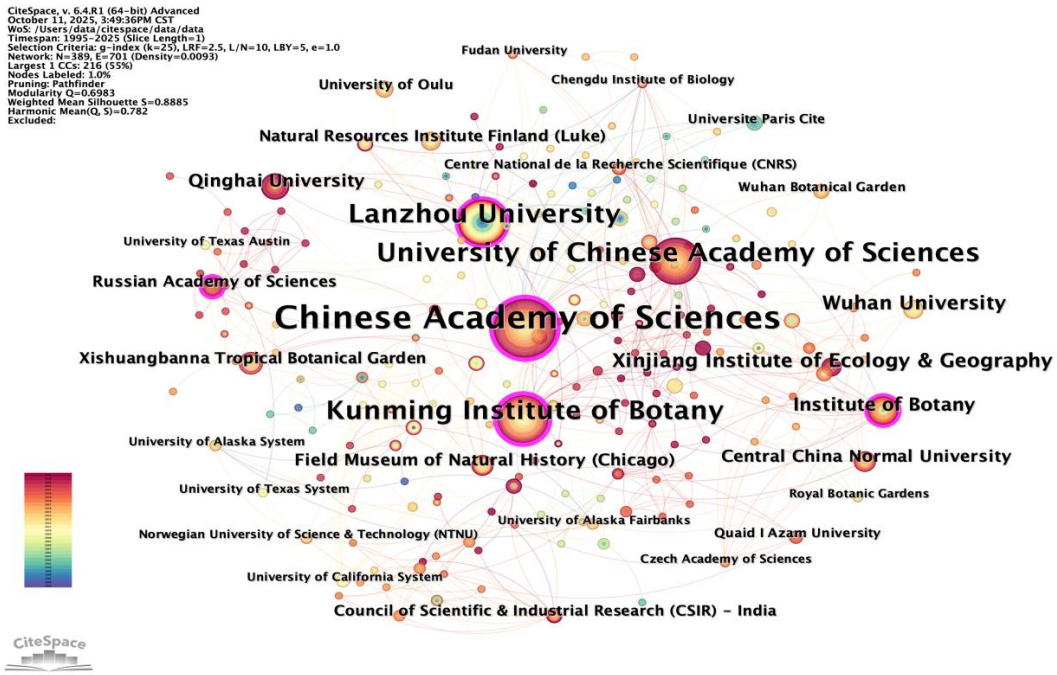

Figure 4. *Institutional collaboration network in Pedicularis research*

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Table 2. *Top ten institutions contributing to Pedicularis research*

Rank	Institution	Country	Publications	Centrality	First year
1	Chinese Academy of Sciences	China	149	0.20	1996
2	Kunming Institute of Botany	China	64	0.21	1998
3	Lanzhou University	China	63	0.12	1995
4	University of Chinese Academy of Sciences	China	63	0.09	2006
5	Xinjiang Institute of Ecology and Geography	China	18	0.02	2011
6	Wuhan University	China	17	0.02	2002
7	Institute of Botany	China	15	0.13	2003
8	Qinghai University	China	14	0.01	2013
9	Central China Normal University	China	11	0.04	2014
10	Field Museum of Natural History (Chicago)	United States of America	11	0.06	2011

The Chinese Academy of Sciences (CAS) ranks first with 149 publications, far exceeding other institutions, underscoring its leading influence in *Pedicularis* research. The Kunming Institute of Botany ranks second in output (64 papers) but exhibits the highest centrality (0.21), making it the key collaboration hub in the network. Lanzhou University follows closely (63 papers), reflecting the growing engagement of domestic universities in *Pedicularis* studies. Peripheral institutions such as the Xinjiang Institute of Ecology and Geography and Qinghai University are also increasingly active, representing a regional expansion of research focus toward the Qinghai–Xizang Plateau, which aligns spatially with the core diversity areas of *Pedicularis*. International collaboration, though relatively limited in quantity, plays an essential role in expanding the global reach of this field. The participation of institutions such as the Field Museum of Natural History (USA) has enhanced cross-regional cooperation and facilitated the internationalization of *Pedicularis* research. Overall, the field is transitioning from fragmented institutional efforts toward a multi-centered, globally connected research network, highlighting both national specialization and international collaboration.

Analysis of national cooperation

International collaboration plays a vital role in fostering scientific development and innovation (Gazni et al., 2012). The global collaboration network of *Pedicularis* research (*Fig. 5*) reveals a distinct China-centered and cross-continental integrated structure. Each node (circle) represents a country where larger nodes indicate higher publication output. Thicker connecting lines reflect stronger collaboration intensity, i.e., a greater number of jointly published papers. China and the United States serve as the two major collaboration hubs, underscoring their central positions in both research productivity and international influence. European countries such as the United Kingdom, Finland, Poland, and Italy form a closely connected regional cluster, primarily engaged in joint research through collaborations with China and the United States. Meanwhile, Asian countries including India, Pakistan, and Saudi Arabia have established regional linkages within the China-led collaboration framework, reflecting the growing integration of regional scientific efforts into the global research network.

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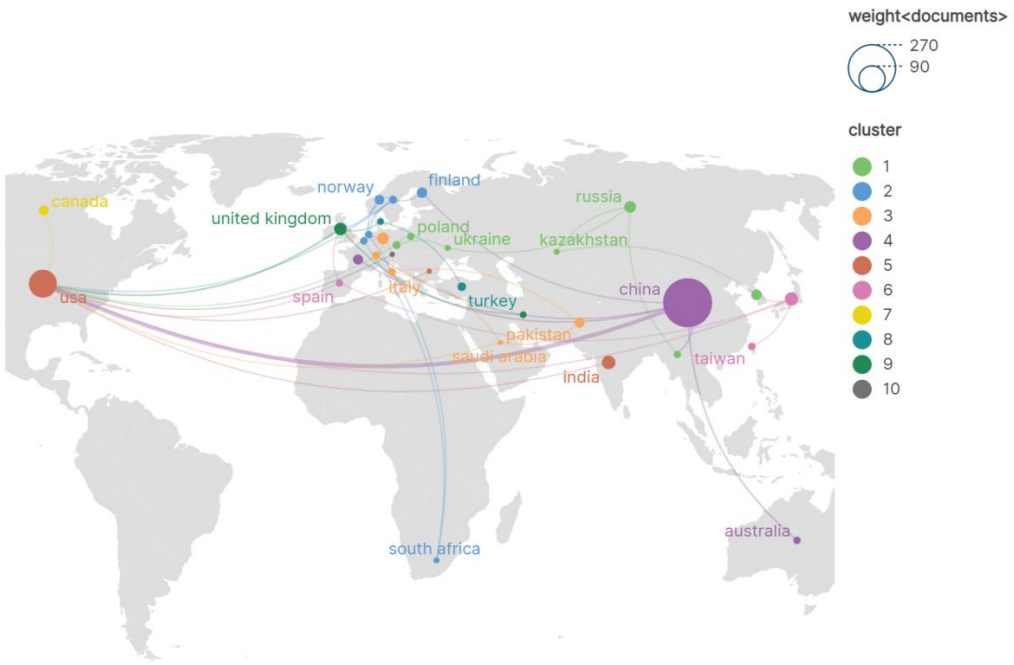

Figure 5. *International cooperation network of Pedicularis*

Analysis of research hotspots and development trends

Analysis of co-occurrence of keyword hotspots

Keywords represent the intellectual core of an academic paper and encapsulate the essence of research topics. They provide a concise overview of frontier hotspots within a field and serve as indicators of emerging research directions (Yang et al., 2022). The frequency of keyword occurrences reflects the intensity of scholarly attention within a given period, while the centrality of a keyword measures its structural importance in the co-occurrence network—defined as the proportion of the shortest paths between other nodes that pass through a given node (Liao et al., 2020). A higher frequency indicates a more intensively studied topic, whereas greater centrality suggests a key connecting role in the research landscape.

According to WOS statistics (*Table 3*), the most frequent keywords were *Pedicularis* (67 occurrences), Evolution (60), and Phenylpropanoid glycosides (47). The highest betweenness centrality values were observed for *Pedicularis* (0.53) and Evolution (0.31), indicating that research over the past three decades has primarily focused on taxonomic evolution and phytochemical composition. As illustrated in *Figure 6*, the co-occurrence network can be broadly divided into three interconnected thematic clusters. The blue cluster centers on "phenylpropanoid glycosides," "iridoids," and "verbascoside," representing studies in phytochemistry and pharmacology. These terms are frequently associated with "antioxidants," "oxidation," and "radical scavenging," suggesting that research on secondary metabolites and their physiological activities has become a key hotspot. The red and green clusters revolve around "evolution," "diversity," "floral traits," and "Hengduan Mountains," highlighting the integration of ecological adaptation and speciation mechanisms, with emphasis on evolutionary–environmental interactions. Meanwhile, the purple cluster is characterized by keywords such as "parasitic plants," "Orobanchaceae," and "semi-natural grassland," reflecting

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research into the ecological interactions between parasitic species and grassland ecosystems. Together, these clusters form a continuous research gradient from phytochemistry to evolution and ecology, suggesting that *Pedicularis* studies have gradually evolved from descriptive taxonomy and distributional assessments toward a multidisciplinary synthesis integrating chemical, evolutionary, and ecological perspectives.

Table 3. *Top ten keywords ranked by frequency and centrality*

Rank	Keyword	Occurrences	Centrality	First year
1	Pedicularis	67	0.53	1996
2	Evolution	60	0.31	1995
3	Phenylpropanoid glycosides	47	0.19	1996
4	Scrophulariaceae	32	0.08	2005
5	Diversity	28	0.11	1996
6	Competition	17	0.08	1996
7	Parasitic plants	15	0.04	2012
8	Orobanchaceae	14	0.02	2007
9	Phylogeny	12	0.05	2001
10	Climate change	12	0.06	2006

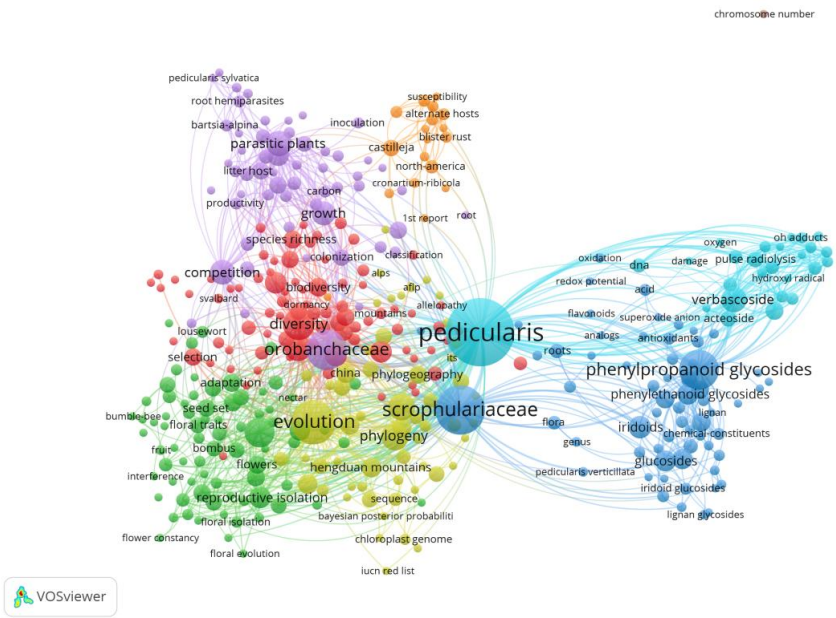

Figure 6. *Co-occurrence graph of keywords*

Keyword cluster analysis

This study employed the clustering function in CiteSpace and extracted cluster labels using the default Log-Likelihood Ratio (LLR) algorithm. The software calculates two key parameters—modularity (Q) and mean silhouette (S)—to evaluate the quality and clarity of the clustering structure. Generally, a Q value between 0.4 and 0.8 indicates a reliable network structure, while the silhouette coefficient (ranging from 0 to 1)

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measures intra-cluster consistency, with higher values reflecting greater homogeneity (Zhu et al., 2018).

After importing data from the Web of Science Core Collection, the network achieved a modularity (Q) of 0.6912 and a mean silhouette (S) of 0.8885, indicating a well-structured and robust clustering result. A total of ten major thematic clusters were identified (*Fig. 7*). The largest cluster, #0 "Hengduan Mountains", represents the geographical and phylogenetic core of *Pedicularis* diversity, where the cluster size corresponds to the number of publications supporting that theme (Wu et al., 2020). Clusters #1 "phytochemistry" and #8 "iridoid glucosides" constitute a module on chemical ecology and secondary metabolites;#2 "diversity" and #9 "geographic variation" reflect studies on diversity patterns and biogeographical differentiation, emphasizing conservation and spatial evolution;#3 "semi-natural grassland" and #7 "plant density" are linked to community processes and management ecology in grassland systems;#6 "buzz pollination" highlights research on pollination mechanisms and floral trait evolution. Relatively peripheral clusters, such as #4 "pulse radiolysis" and #5 "Cronartium ribicola", point to methodological and pathogen-interaction topics, illustrating the growing interdisciplinarity of *Pedicularis* research. Although *Cronartium ribicola* is a fungal pathogen rather than a plant taxon, its occurrence as a separate keyword cluster reflects a subset of studies on plant–pathogen interactions and disease ecology in alpine and subalpine ecosystems, where *Pedicularis* species are included as components of the plant community or as potential hosts.

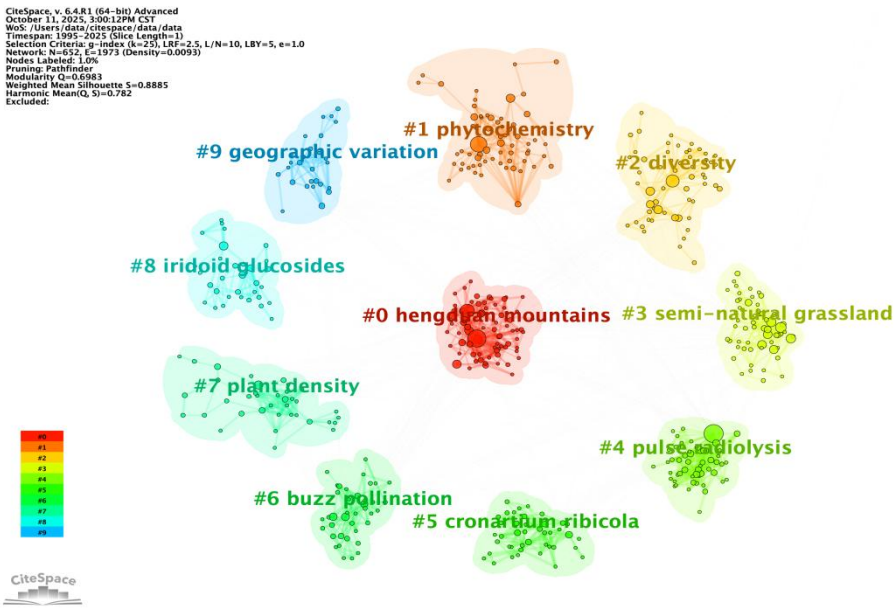

Figure 7. *Keyword clustering graph*

Keyword clustering timeline graph analysis

The keyword clustering timeline reflects the evolutionary trajectory and interconnections among different research themes (Li et al., 2017). The timeline visualization in CiteSpace displays the chronological development of each major topic and its relevance within the field (Pan et al., 2022). In this study, the downloaded literature dataset was imported into CiteSpace for timeline analysis to visualize the

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temporal span and thematic linkage of clusters. The resulting timeline of the top ten keyword clusters is shown in *Figure 8*. Clusters #1 "Phytochemistry" and #8 "Iridoid glucosides" have remained active since the 1990s, forming the foundational axis of geographical and chemical ecology research. Between 2005 and 2015, the research focus expanded toward ecological processes and community-level interactions: cluster #6 "Buzz pollination" was frequently associated with floral-trait-related terms such as floral traits and reproductive isolation; clusters #2 "Diversity" and #7 "Plant density" captured the deepening investigations into community structure and biodiversity dimensions; while #3 "Semi-natural grassland" extended discussions to grassland management and anthropogenic disturbances. After 2015, the timeline thickened markedly in themes related to geographical differentiation and conservation. Cluster #0 "Hengduan Mountains" persisted throughout the timeline and developed new branches in recent years, echoing the late-stage intensification of #9 "Geographic variation", thereby reaffirming the Hengduan Mountains as a core region for diversity maintenance and lineage diversification in *Pedicularis*.

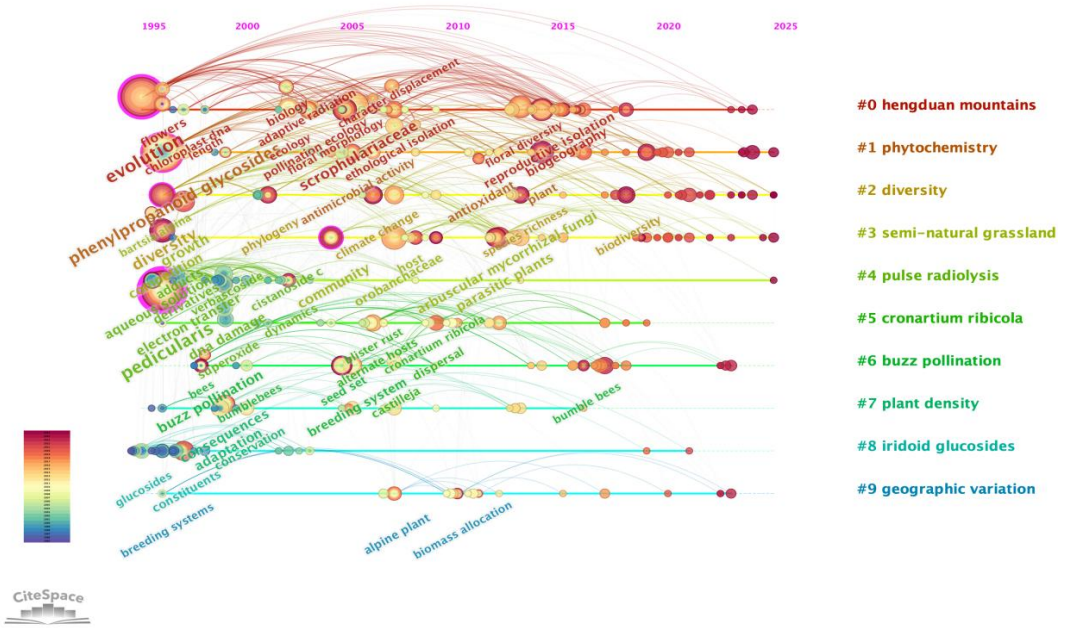

Figure 8. *Timeline visualization of the top ten keyword clusters*

Keyword emergent analysis

Keyword bursts refer to a sharp increase in the frequency of a keyword within a short period, reflecting the research topics that have drawn collective attention from scholars during that time (Yang et al., 2022). The "Begin" and "End" values indicate the start and end of each burst period, while "Strength" represents the intensity of the burst, with higher values signifying greater influence (Wu et al., 2020; Li and Li, 2024).

To capture the dynamic evolution and persistence of research focus in *Pedicularis* studies, the burstness detection function in CiteSpace was applied to identify the top 25 keywords with the strongest citation bursts (*Fig. 9*). Each bar corresponds to a fixed time interval, with red segments representing the duration of keyword bursts, and burst

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strength values indicating the relative intensity of research activity during that period (Li and Cheng, 2016; Tuerdi et al., 2024).

The analysis reveals three distinct developmental stages in this field:(1) Early stage (1995–2004): Research mainly focused on chemical constituents and radical processes, as indicated by burst keywords such as glucosides, lignan glycosides, electron transfer, superoxide, verbascoside, and pulse radiolysis, reflecting a focus on secondary metabolites, antioxidant mechanisms, and radiation chemistry approaches.(2) Middle stage (2005–2014): The research emphasis shifted toward ecological and evolutionary processes, with frequent bursts in breeding system, adaptation, ecology, and reproductive isolation. The strongest bursts in reproductive isolation and evolution highlight an intensified interest in pollination biology, floral trait evolution, and speciation mechanisms. (3) Recent stage (2015–2025): Emerging keywords such as floral traits, dispersal, growth, biodiversity, impacts, and competition indicate a growing integration of climatic, environmental, and functional factors in understanding diversity patterns and interspecific interactions within ecosystems. The transient burst of Orobanchaceae suggests taxonomic updates in parasitic lineages, while the recent rise of *Pedicularis kansuensis* (2022–2025; strength = 3.93) signals a new frontier focusing on species-level ecological adaptation and potential range expansion risks.

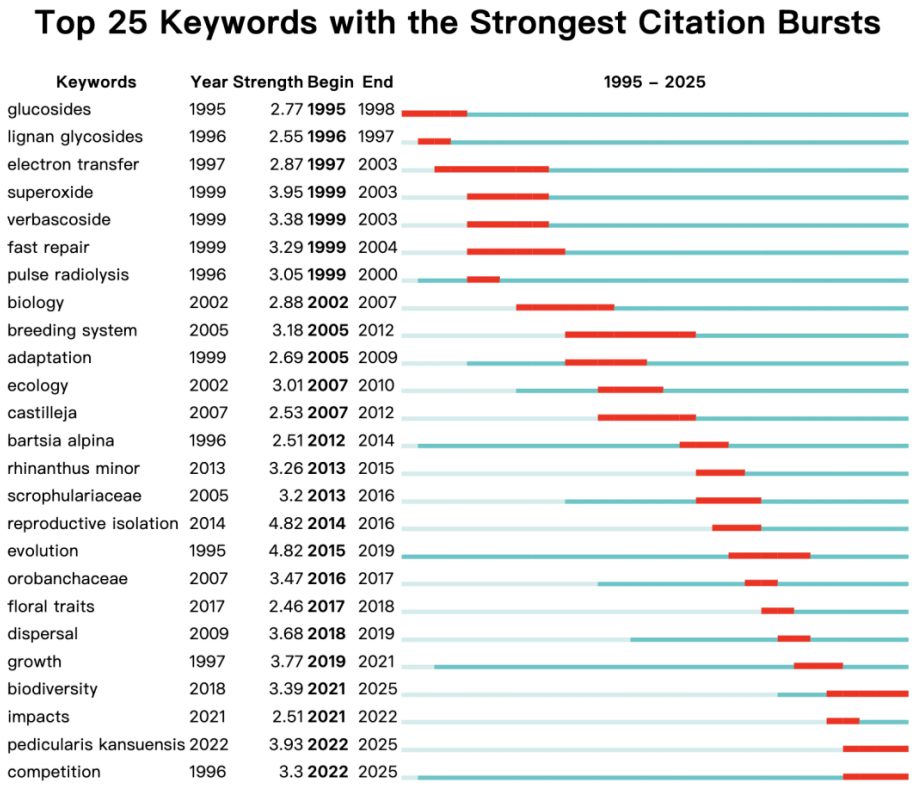

Figure 9. *Keyword burst detection map of Pedicularis research*

Discussion

Pedicularis is a highly diversified and globally distributed genus that plays an important role in alpine ecosystems. Owing to its remarkable richness and color variation, the genus not only possesses high ornamental value but also holds medicinal

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potential (Tang et al., 2017). To date, no comprehensive bibliometric analysis of *Pedicularis* research has been reported. In recent years, with the growing emphasis on biodiversity conservation and ecological protection of the Qinghai–Tibet Plateau in China, studies on *Pedicularis*—a representative alpine genus with significant ecological and evolutionary importance—have shown an increasing trend, gradually becoming a prominent focus of botanical research. The visualization of author, institution, and country collaboration networks revealed a structured research landscape dominated by Chinese scientific strength, which has progressively integrated into the global research system. A core group of influential scholars, including Jia Z. J., Zheng R. L., and Huang S.-Q., has formed a leading research community through long-term collaboration. The Chinese Academy of Sciences (CAS), encompassing institutes such as the Kunming Institute of Botany, the Institute of Botany, and affiliated universities, has established itself as a central research hub. This dominance is closely linked to the CAS's long-term strategic investment in biodiversity research and China's unique geographical advantages (Li and Pritchard, 2009). China and the United States show the highest publication outputs and the most frequent international collaborations. China's pivotal position is largely attributed to the overlap between the center of species distribution and the center of research resources. The hotspots of *Pedicularis* diversity are concentrated in the Qinghai–Tibet Plateau and the Hengduan Mountains. As noted by Sun et al. (2017), the Hengduan region, one of the world's 34 recognized biodiversity hotspots, provides an ideal setting for alpine plant diversification due to its complex geology, topography, and climatic heterogeneity. Similarly, Liu et al. (2024) demonstrated that approximately 270 *Pedicularis* species in the Hengduan–Himalayan region exhibit exceptionally high spatial and morphological diversity. Looking ahead, further academic exchange and collaborative, cross-regional, and multi-perspective studies are needed to advance understanding of this ecologically significant genus.

An examination of the development trajectory of *Pedicularis* research over the past three decades clearly illustrates the evolution of research focus in this field. The studies can be divided into three major stages.

(1) Early exploratory stage (1995–2005): During this period, the number of publications on *Pedicularis* remained relatively low, and research mainly concentrated on elucidating the chemical diversity of the genus and its taxonomic implications. For instance, Su et al. (1998) simultaneously reported iridoid and phenylethanoid glycosides in *Pedicularis artselaeri*, while Yuan et al. (2003) identified new iridoid glycosides from *Pedicularis kansuensis formal albiflora*. Meanwhile, Olmstead et al. (2001) proposed a systematic taxonomic revision that split the former family Scrophulariaceae and reclassified parts of it into Orobanchaceae, providing a new phylogenetic framework. These works underscored the importance of chemical and systematic studies that dominated the late 1990s.

(2) Mid-term growth stage (2006–2015): This period was marked by a significant increase in publication output, accompanied by a conceptual shift from "what" to "why." Research focus expanded from descriptive taxonomy toward understanding evolutionary and ecological mechanisms. Huang and Shi (2013) demonstrated that even when sharing the same bumblebee pollinators, different *Pedicularis* species can achieve floral isolation by depositing pollen on different body parts of the pollinators, thereby reducing interspecific interference—a classic example of prezygotic isolation. Similarly, Corbet et al. (2014) analyzed the mechanics and pollen-release dynamics of buzz pollination across eight bumblebee-pollinated *Pedicularis* species, emphasizing

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DOI: http://dx.doi.org/10.15666/aeer/2402_26632680

the morphological and physical coordination between floral structures and pollinator behavior.

(3) Recent stabilization stage (2016–2025): In the most recent decade, the research scale has expanded from the species level to ecosystem and regional biogeographic patterns. Xing and Ree (2017) quantitatively tested the "uplift-driven diversification" hypothesis in the Hengduan Mountains, highlighting the critical role of topographic complexity and climatic gradients in promoting in situ diversification and diversity accumulation. At the same time, research topics have become increasingly diversified. As an indicator genus in alpine ecosystems, *Pedicularis* has attracted growing attention for its ecological niche dynamics, interspecific interactions, and responses to environmental stress. Zhang et al. (2024) employed the MaxEnt model to predict future distribution patterns of three *Pedicularis* species in the Qinling Mountains and adjacent regions, revealing dual influences of climate and geological evolution. Bao et al. (2022) further optimized the prediction accuracy of *Pedicularis longiflora* and its varieties by incorporating topographic and climatic variables. Li et al. (2023) conducted nutrient addition experiments and found that *P. kansuensis* exhibited significant growth and competitive advantages under nitrogen deposition, suggesting that global change factors may enhance the ecological role of the genus within alpine meadow ecosystems.

Based on keyword co-occurrence, clustering, and burst analyses, three major research hotspots were identified in studies of *Pedicularis*:(1) Diversity formation and biogeographic patterns. This research theme focuses on the mechanisms of species formation and geographical differentiation of *Pedicularis* in the Qinghai–Tibet Plateau and the Hengduan Mountains, emphasizing how complex topography and climatic gradients shape diversity patterns. Previous studies have demonstrated that the Hengduan and Himalayan regions represent the core centers of diversification for *Pedicularis*, where unique geomorphology, climatic heterogeneity, and glacial history have jointly promoted rapid radiation and in situ speciation (Xing and Ree, 2017). Yu et al. (2015) reconstructed a comprehensive phylogenetic framework of the genus and revealed pronounced patterns of geographic isolation and lineage divergence that closely correspond to the geomorphological evolution of the Qinghai–Tibet Plateau. (2) Trait evolution and adaptive mechanisms. Keywords such as "evolution," "reproductive isolation," "floral traits," and "buzz pollination" highlight growing interest in the evolutionary and adaptive significance of reproductive morphology. Recent studies have explored the roles of floral evolution, pollination adaptation, and reproductive isolation in driving species divergence. Xu et al. (2025) applied biomechanical analysis and pollination network approaches, demonstrating that morphological coordination between floral structures and bumblebee body size enhances pre-mating isolation within *Pedicularis*. Similarly, Yang et al. (2002) provided evidence supporting the hypothesis of coordinated evolution between the stigma and corolla, offering new insights into the evolutionary mechanisms underlying floral adaptation and diversification in this genus. (3) Responses to global change and ecosystem functioning. The third hotspot, characterized by keywords such as "climate change," "competition," and "growth," focuses on the impacts of environmental changes—particularly climate warming and nitrogen deposition—on ecological niches, community competitiveness, and alpine ecosystem structure. Field studies have shown that *Pedicularis* plays a vital functional role in alpine meadows; for example, *P. kansuensis* can significantly alter community composition and soil nutrient dynamics (Qin et al., 2022). However, its ecological niche

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conservatism may constrain its adaptive potential under climate warming (Tkach et al., 2014). These findings collectively provide valuable directions for future research, emphasizing the importance of integrating evolutionary, ecological, and environmental perspectives to understand *Pedicularis* responses to global change.

Conclusion

This study represents the first comprehensive bibliometric analysis of *Pedicularis* research over the past three decades (1995–2025) by integrating VOSviewer, CiteSpace, Excel, and Bibliometrix. It systematically depicts the knowledge structure, collaboration networks, and thematic evolution within the field. The global research output shows a generally upward yet fluctuating trend, with China occupying a central role and forming a multi-tiered collaborative network led by the Chinese Academy of Sciences. The evolution of research can be divided into three distinct phases: an early exploratory stage (1995–2005), a rapid growth stage (2006–2015), and a recent stabilization stage (2016–2025). Research topics have progressively shifted from chemical taxonomy to pollination evolution and ecosystem functioning, reflecting an increasing trend toward interdisciplinary integration. Looking forward, *Pedicularis* research can be further advanced in several directions:(1) The Hengduan–Himalayan region, recognized as one of the centers of diversity and endemism for *Pedicularis* (Yu et al., 2008; Wang et al., 2009), should be emphasized as a key area by integrating molecular systematics, macroecology, and biogeographical modeling to elucidate lineage divergence and mechanisms shaping species diversity; (2) More attention should be given to multidimensional interactions among *Pedicularis*, host plants, pollinators, and microbial communities, combined with functional trait and ecological strategy frameworks, to uncover coordinated mechanisms of morphological and ecological adaptation.(3) The integration of ecological niche modeling, population genomics, and physiological ecology experiments is encouraged to evaluate species' survival risks under climate change, providing essential insights for the conservation and ecological restoration of *Pedicularis* and other alpine plants worldwide.

Acknowledgements. This research was supported by the Special Foundation for the National Science and Technology Basic Research Program of China (Grant No. 2021FY100201), the Key Research and Development Program of the Xizang Autonomous Region, China (Grant No. XZ202501ZY0151), and the Graduate Innovation Program of Xizang Agricultural and Animal Husbandry University (Grant No. YJS2024-41).

Conflict of interests. The authors declare that they have no conflict of interests.

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