药食同源资源
FOOD & MEDICINE HOMOLOGY RESOURCES
ISSN 3136-103X (online)
https://doi.org/10.26599/FMHR.2026.9740002

Review Article

Food and medicine homology resources on the Qinghai-TibetPlateau: Distribution, development, conservation and future, perspectives

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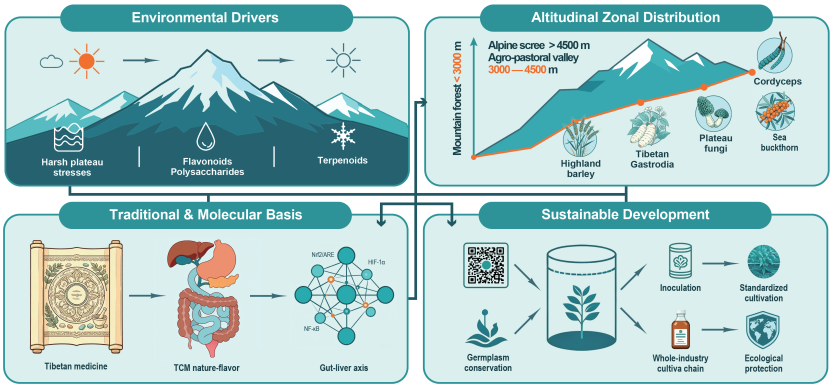
Received: 14 August 2026 / **Revised:** 7 September 2026 / **Accepted:** 7 September 2026

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清華大學出版社 Tsinghua University Press | SciOpen

Abstract: The Qinghai-Tibet Plateau (QTP) is characterized by extreme altitude, hypoxia, intense ultraviolet (UV) radiation, and complex geomorphology. Such extreme environments have fostered a distinctive spectrum of food and medicine homology resources (FMHR). These resources include medicinal and edible plants, animals, fungi, and traditional fermented dairy products, all of which are integrated into Tibetan daily life and ethnopharmacological systems. This review examines the ecological distribution, functional properties, and sustainable utilization of local species, specifically analyzing the impact of severe environmental stress and soil conditions on their adaptation and bioactive accumulation. The resources are then categorized along altitudinal gradients and major ecological zones to analyze their spatial distribution across alpine grasslands, agricultural valleys, and montane forests. By combining traditional Tibetan dietary wisdom and medical theories with modern pharmacological evidence, the review highlights reported biological activities, including antioxidant, antifatigue, immunomodulatory, and metabolic-regulatory activities. Currently, these plateau resources face severe threats from climate change, overexploitation, and inadequate standardization. Based on a comprehensive synthesis of the literature, this review identifies critical evidence gaps including the scarcity of clinical trials, incomplete quality standards, and limited quantitative data on industrial development. To address these challenges and gaps, future strategies focusing on germplasm conservation, scientific validation, industrial upgrading, and sustainable development are proposed. The overarching goal is to provide a systematic reference for the high-value utilization and ecological protection of FMHR on the QTP.



Keywords: Qinghai-Tibet Plateau; food and medicine homology; distribution characteristics; Tibetan medicine and culture; sustainable development

Citation: Li X. Z., Tang C. Y., Li B. L., et al. Food and medicine homology resources on the Qinghai-TibetPlateau: Distribution, development, conservation and future, perspectives. *Food & Medicine Homology Resources*, 2026, 1: 9740002. https://doi.org/10.26599/FMHR.2026.9740002

1 Introduction

The diverse distribution and unique functional properties of food and medicine homology resources (FMHR) on the Qinghai-Tibet Plateau (QTP) are fundamentally shaped by its extreme and highly heterogeneous geographical environment. To establish a comprehensive panorama of these resources, an understanding of the local geomorphic features is essential.

1.1 Unique natural background environment of the QTP

1.1.1 Geomorphic pattern of high-altitude areas

High elevation geomorphic landscapes present a complex spatial mosaic of broad uplands, entrenched gorges, expanding lakes, and permafrost rather than a uniform alpine surface[1]. This spatial contrast is particularly striking in southeastern Tibet where elevated low relief surfaces coexist abruptly with deeply dissected river canyons[2]. Modern fluvial systems also show significant longitudinal heterogeneity by functioning simultaneously as upstream sediment sources and downstream storage corridors through intensified erosion and midstream deposition[3].

Meanwhile rapidly expanding plateau lakes act as key indicators of modern surface water redistribution within interior basins[4]. Such rapid lake growth has reorganized multiple drainage boundaries and fundamentally controls local hydrological connectivity under contemporary climates[5]. Finally cryospheric landforms further shape this dynamic environment as glacier mass loss across High Mountain Asia has persistently increased since the 1960s[6]. Together these actively adjusting components form a highly integrated geomorphic system.

1.1.2 Climatic characteristics

The extreme climate of the QTP is closely linked to its mountainous terrain[7]. Characterized by low temperatures, hypoxia[8], intense solar radiation, distinct wet and dry seasons, and frequent strong winds[9], this environment fosters a unique and fragile ecosystem[10]. Low temperature stands out as the most prominent feature[11]. At an average elevation exceeding 4,000 m, the plateau is significantly colder than plain areas at similar latitudes, with annual mean temperatures ranging from −6 to 8 °C[12-14]. The northern region records summer temperatures below −6 °C[15]. Areas above 4,500 m experience prolonged cold winters and short cool summers with year round frost[14, 16]. A thin atmosphere causes rapid thermal changes[17], resulting in a small annual but large diurnal temperature range[18]. Hypoxia acts as another critical extreme trait[19]. Low atmospheric pressure reduces oxygen partial pressure to roughly half of sea level values[20], while absolute oxygen content drops significantly[19]. This environment strictly limits human activity and governs the metabolism, reproduction, and distribution of local organisms[21-23]. Additionally the plateau receives intense solar radiation[24]. The clear atmosphere with little water vapor and dust weakens atmospheric attenuation of solar radiation. The total annual solar radiation reaches 5,000–8,500 MJ/m^2, and the annual sunshine duration is 2,500–3,400 h[25]. Such strong ultraviolet (UV) exposure causes physiological stress, driving local species to evolve specific antioxidant and photoprotective mechanisms[26, 27].

The southwest monsoon from the Indian Ocean controls the obvious wet and dry seasons[28]. Precipitation shows massive spatial variation, dropping from over 3,000 mm in the southeast to under 200 mm in the northwest[29]. Prevailing strong winds and

low humidity accelerate surface evaporation and exacerbate ecological drought[30, 31]. The combination of multiple extreme climatic factors shapes the distinctive natural background and ecological pattern of the QTP.

1.1.3 Soil and ecological characteristics

Soil and ecological evolution in the northeastern Qinghai Plateau are profoundly shaped by the alpine arid climate and complex geology[32]. Cold conditions favor physical over chemical weathering, resulting in slow soil formation and shallow profiles with early developmental characteristics[33]. Primary zonal soils include alpine meadow soil, alpine steppe soil, and alpine desert soil. These soil types follow a clear vertical distribution pattern[33].

Alpine meadow soil dominates this area, featuring a thick elastic sod layer of roots and minerals[33]. This structure reflects long term vegetation adaptation and protects soil stability[34]. Low temperatures inhibit microbial mineralization, causing massive organic matter accumulation in the topsoil[35, 36]. Consequently these soils possess high organic carbon levels and carbon to nitrogen ratios, making them some of the most organic rich mineral soils globally[37-39]. Surface concentrated root biomass stores major carbon reserves and modulates hydrothermal transport[40-42]. Intense evaporation and limited leaching create alkaline conditions with widespread calcification[43]. The predominantly silt loam soil contains specific clay minerals like mica and kaolinite[33, 44]. However grassland degradation causes significant losses of organic carbon and total nitrogen while increasing soil alkalinity and calcium carbonate content[33, 45]. Ultimately these soils provide a vital foundation for plant growth, carbon sequestration, and ecological security in major river basins.

1.1.4 Mechanisms underlying the accumulation of bioactive compounds in food and medicine homology resources on the QTP

The QTP features a typical alpine ecosystem characterized by high altitude, strong solar radiation, hypobaric hypoxia, drastic diurnal temperature variation, and an arid climate. These environmental constraints profoundly influence the biosynthesis and accumulation of bioactive compounds in native plant and fungal species. Under prolonged exposure to strong UV radiation, low temperatures, and hypoxic conditions, species experience elevated levels of reactive oxygen species. This triggers critical adaptive responses designed to maintain cellular redox homeostasis and minimize oxidative damage. Key metabolic networks, particularly the phenylpropanoid and flavonoid biosynthesis pathways, become highly active and drive the accumulation of phenolic acids, terpenoids, alkaloids, and polysaccharides[46, 47].

Flavonoids and phenolic compounds function as major photoprotective and antioxidant molecules by absorbing UV radiation and scavenging reactive oxygen species, thereby forming an effective biochemical barrier. Concurrently, polysaccharides and soluble sugars facilitate osmotic adjustment to improve tolerance against severe cold and drought. Because short growing seasons and nutrient-limited soils restrict vegetative growth, mountain plants are forced to allocate more carbon toward defensive secondary metabolism. This evolutionary shift yields the distinct low-biomass and high-bioactivity phenotype widely observed in Plateau species[47]. Field studies on Plateau plants offer practical evidence for how extreme environments enhance the accumulation of active compounds. When researchers examine native species along different altitudinal gradients, they often find that higher elevations correspond to increased secondary metabolite production. While absolute concentration values can be difficult to compare directly across studies due to differing analytical methods, the general pattern is highly consistent. Specifically, plant populations growing at higher altitudes tend to accumulate much richer levels of flavonoids, phenolics, and protective glycosides than those growing at lower elevations. These altitudinal differences suggest that long-term exposure to intense UV radiation and cold stress directly triggers the biosynthesis of these valuable components.

The biochemical basis for adaptation to extreme alpine environments is evident across different categories of Plateau resources. For statutory FMHR such as *Hippophae rhamnoides*, high levels of flavonoids, carotenoids, and vitamin C are synthesized to protect against severe oxidative damage caused by intense UV exposure[48-50]. In contrast, traditional ethnic dual-use resources exhibit distinct stress-response metabolite profiles. For instance, the extensive accumulation of salidroside and tyrosol in Rhodiola crenulata supports physiological adaptation to hypoxia and severe oxidative stress. Similarly, specific polysaccharides synthesized by the fungal resource *Ophiocordyceps sinensis* (*O. sinensis*) significantly enhance tolerance to hypoxic conditions while maintaining cellular redox balance[48-50].

Long-term environmental selection pressures promote the enrichment of these bioactive secondary metabolites, providing the biochemical foundation for the unique nutritional and pharmacological benefits associated with both statutory and traditional Plateau resources. These environmentally induced metabolites offer substantial antioxidant, fatigue resistance, and immunomodulatory benefits, confirming a strong mechanistic link between ecological adaptation and functional properties[46, 47]. Given the ongoing trajectory of global climate change, alterations in temperature, precipitation patterns, and radiation levels will inevitably influence the biosynthesis of these compounds. Therefore, elucidating the environmental regulation of secondary metabolism remains essential for the conservation, sustainable utilization, and value-added development of these unique regional biological assets.

1.2 The regional traditional culture and the foundation of FMH in Tibetan medicine

Tibetans have inhabited the QTP for millennia by developing survival strategies grounded in the philosophy of food and medicine homology (FMH). These strategies integrate behavioral customs with specific dietary structures. Traditional practices such as eating until partially full and engaging in regular folk dances provide essential energy homeostasis and vascular protection[51]. Meanwhile intense high altitude UV radiation enhances cutaneous vitamin D synthesis which epidemiological studies link to lower ischemic heart disease rates among locals[52].

Dietary cultural identity also maintains psychological resilience since maladaptation to high calorie Plateau diets often triggers fatigue and depressive symptoms in migrating populations[53, 54]. Consequently indigenous children maintaining traditional lifestyles show superior skeletal adaptation under hypoxic stress without the deformities common in unadapted groups[55].

The highland dietary structure demonstrates distinct altitudinal dependence while consistently relying on highland barley tsampa and butter tea[56].

Cultivation at high elevations increases barley bioactive compounds like β-glucan[57, 58] which exerts immunomodulatory effects and antagonizes metabolic syndrome[59]. Combining roasted barley with butter creates a nutritional synergy where

butter fatty acids promote phytochemical absorption. This diet explains why local pastoralists rarely exhibit hyperlipidemia despite high fat intakes with serum cholesterol displaying an inverted curve against altitude[60]. Such diets promote a metabolically healthy nonobese phenotype[61] by cultivating specific gut microbiota that interact with host hypoxia adaptation pathways to maintain metabolic stability[62,63].

Plateau endemic livestock support this framework. Tibetan pigs offer high proportions of flavor related amino acids and cold tolerant fatty acids[64] while Tibetan sheep adjust their rumen microbiome during harsh winters to process low quality forage efficiently[65] demonstrating physiological advantages over introduced breeds[66]. However modern dietary shifts toward monotonous carbohydrate consumption elevate micronutrient deficiency risks[67] and excessive oil intake drives energy surpluses[68]. Abandoning traditional diets for excessive meat and alcohol increases inflammation and impairs cognitive function highlighting the need for dietary diversification[69]. This dietary lifestyle birthed early medical wisdom. Ancient texts like the *Moon King Medical Classic* recognized the energy storing properties of local ingredients[70]. Tibetan medicine soon formalized geo adaptive nourishment using barley and butter for energy while applying native herbs according to local microclimates[71].

This health framework also requires mental calmness to complement physical nutrition[72] and aligns daily routines with seasonal rhythms to maintain physiological stability[73].

Modern research supports these methods by confirming the synergistic metabolic benefits of Plateau diets and the transdermal efficacy of traditional therapies[74]. Ultimately this wisdom culminated in dietary therapy rules designed to regulate bodily humors[75] by categorizing natural ingredients through specific tastes and post digestive properties[76,77] forming a practical approach that connects human biology with the extreme natural environment[76-78].

1.3 Evolution of FMHR in the context of modern development

In the modern health sector, the FMHR of the QTP serve as more than the foundation of traditional medicine and local diets. They represent a key area combining the health industry, biotechnology, and ecological economy. Their development reflects the relationship between ecological conservation and economic growth, traditional knowledge and modern technology, as well as regional features and global markets.

1.3.1 Unique and irreplaceable nature of native germplasm resources on the Plateau

The value of FMHR on the QTP comes from the unique and irreplaceable nature of their native germplasm, which develops under harsh natural selection. This biological trait explains their distinct position in the modern health industry.

First, extreme environments have forged unparalleled bioactivity. The QTP features severe environmental conditions including high altitude, UV radiation, low temperatures, hypoxia, and significant daily temperature changes[79-81]. To survive and reproduce in these areas, Plateau plants develop specific physiological and morphological adaptation mechanisms. For example, *Rhodiola rosea* (*R. rosea*) effectively resists hypoxia. Its thick and fleshy stems and leaves store water and nutrients to endure drought and extreme cold[82,83]. The leaf anatomy is also highly specialized, featuring a thicker mesophyll and stomata mostly located on the upper epidermis. This structure maximizes photosynthetic efficiency under severe conditions[84,85]. This survival process stimulates secondary metabolic pathways, causing the plant to accumulate abundant and diverse bioactive compounds like salidroside and tyrosol. This explains why the medical and nutritional value of Plateau plants often surpasses that of plants in low altitude areas or their closely related species. These characteristics are closely associated with the specific environmental conditions of the Plateau.

Second, the complex topography has nurtured extraordinarily rich genetic diversity. The interior of the QTP, crisscrossed by high mountains and deep valleys, has created countless microclimatic and geographically isolated units. This geographical isolation provides ideal conditions for species differentiation and the accumulation of genetic diversity. For instance, studies on *O. sinensis* indicate significant genetic variation among populations across different altitudes and regions on the Plateau[86,87]. The genetic diversity among populations is reflected not only in morphology, but also in their adaptability to different environments and subtle differences in their inherent chemical composition[88]. The extensive genetic variation serves as an important genetic resource for the FMH materials on the Plateau. With current progress in genomics and synthetic biology, these genetic materials provide practical value for breeding new varieties, synthesizing active components, and developing new medical treatments. Therefore, protecting native germplasm resources supports future innovation in the health sector.

However, this uniqueness is accompanied by fragility. In recent years, the impact of global climate change on the Plateau's ecosystems has become increasingly pronounced. Studies predict that continued warming may cause the suitable habitats of many alpine endemic medicinal plants to retreat to higher altitudes, reducing their habitable area and even exposing them to the risk of extinction[89]. Excessive and unscientific harvesting has also placed enormous pressure on wild resources. It is against this backdrop that the protection of native germplasm resources has been elevated to an unprecedented strategic level. The Law of the People's Republic of China on Ecological Protection of the QTP, effective from September 1, 2023, establishes a framework for the systematic protection and sustainable use of these resources. This law strictly prohibits destructive actions like the illegal gathering of protected wild animals and plants[90]. This legislation shifts the approach to Plateau FMHR from simple exploitation to a management system that balances conservation with sustainable application, demonstrating their importance on a national level.

1.3.2 The driving forces of modern dietary upgrading and wellness demands on Plateau FMHR

The natural characteristics of Plateau FMHR provide their biological basis, while the increasing health demands of modern society encourage their application. As the social and economic conditions in China improve, the national consumption pattern is changing from basic food provision to a focus on nutrition and health. This shift in consumption and the rise of health awareness bring new development opportunities for these ancient Plateau resources.

First, the increase in health-related consumption creates significant market demand. During the 2020s, Chinese consumers, particularly the urban middle class and younger populations born after 1990, show a strong willingness to invest in health[91]. The markets for dietary supplements, functional foods and herbal health products have continued to expand at high compound annual growth rates[92]. In this context, FMHR from the QTP gain

popularity due to their pure, natural, and highly effective properties. Consumers widely believe that plants grown in the Plateau's harsh environment embody greater vitality and health benefits, endowing the products with a substantial brand premium. From anti-fatigue *R. rosea* supplements and *Lycium ruthenicum* (*L. ruthenicum*) beverages to *O. sinensis* wellness products, the Plateau's unique geographical indication has become an integral component of core competitiveness, precisely aligning with modern consumers' preference for high-quality, traceable and storied health products.

Second, technological advancement supports industry modernization. Strong market demand encourages the industrial sector to adopt technological innovation and standardization. Modern biotechnology analyzes QTP resources in detail. Advanced techniques such as metabolomic analysis, for instance, are employed to precisely map the chemical composition profiles of wild and cultivated medicinal plants, providing a scientific basis for quality evaluation and authenticity identification and thereby effectively addressing the challenge of counterfeit and substandard products in the market[93]. On the other hand, in order to strike a balance between conserving wild resources and satisfying market demand, unprecedented attention has been devoted to the research and application of artificial cultivation techniques. Through biomimetic cultivation that imitates natural habitats, many rare species are now grown on a large scale. Some studies indicate that under optimized conditions, the concentration of specific active compounds in cultivated plants can equal or exceed that of wild plants[94,95]. At the same time, the progress in extraction, separation, and formulation technologies remains active between 2024 and 2026, aiming to maximize the extraction and application of these bioactive substances[96].

Finally, the dual backing of national strategies and local policies provides robust institutional safeguards for industrial development. At the national level, the implementation plan for the high-quality development of the Chinese medicine industry (2026–2030), issued by eight government departments including the Ministry of Industry and Information Technology, promotes the modernization of ethnic medicine industries. This plan guides the development of distinctive sectors like the traditional Tibetan medicine (TTM) industry[97]. At the local level, provinces and regions including Qinghai and Tibet have also taken active steps. For example, several Tibetan autonomous prefectures in Qinghai introduced and implemented Regulations on Promoting the Development of TTM in 2024, thereby regulating and supporting industrial growth through local legislation. These policies build a comprehensive support system that covers resource conservation, scientific research, standard establishment, and market expansion. The objective is to convert the ecological and resource assets of the QTP into economic benefits for sustainable development.

In conclusion, the FMHR of the QTP are currently at a critical development stage. The conceptual infographic summarizes the environmental characteristics, food–medicine culture, and modern industrial evolution of the QTP (Fig. 1). Their unique nature, resulting from extreme environments, constitutes their primary value. Concurrently, improved health consumption, technological progress, and policy support provide external conditions that integrate these natural resources into modern industrial systems. This transition shifts traditional botanical materials into key components of the modern health industry.

2 Search methodology

A comprehensive literature search was conducted to gather relevant studies on Plateau FMHR. The primary databases utilized included PubMed, Web of Science, Scopus, and the China National Knowledge Infrastructure. The literature search covered publications from January 2000 to the present. The search strategy employed combinations of specific terms such as Tibetan Plateau, FMH, traditional medicine, edible plants, and functional foods. Articles were included if they provided original empirical data regarding the phytochemical composition, pharmacological activities, or historical dietary uses of native Plateau resources. Studies focusing on species outside the Plateau, unreviewed materials, and publications not in English or Chinese were strictly excluded. Two independent researchers screened the literature to ensure academic rigor.

3 Altitudinal zonation and spatial distribution of FMHR

The Tibetan Plateau exhibits a distinct spatial distribution

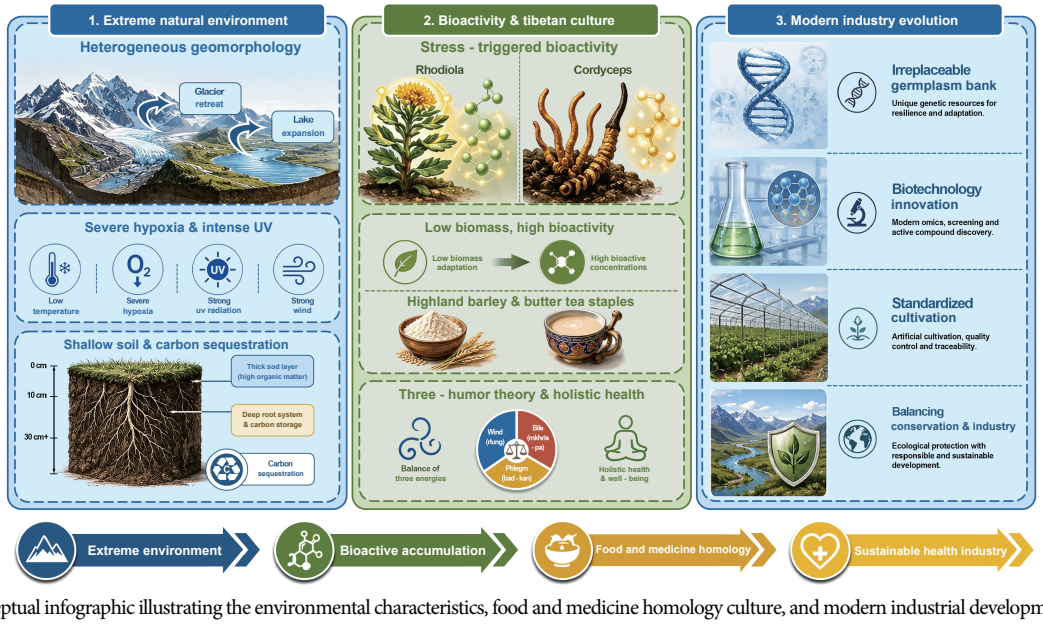


Figure 1 Conceptual infographic illustrating the environmental characteristics, food and medicine homology culture, and modern industrial development of the QTP.

pattern for FMHR characterized by high species diversity in the southeast and low richness in the northwest. Among the more than 12,000 seed plant species on the Plateau, medicinal plants occupy a substantial proportion but are distributed unevenly. The eastern and southeastern regions including the Hengduan Mountains and northwestern Yunnan possess the highest species diversity and endemism. In these core regions, a single grid unit can harbor up to 159 distinct medicinal species. The spatial distribution of representative FMHR and major enrichment zones along altitudinal gradients is schematically illustrated in Fig. 2, providing a macroscopic framework for understanding their distribution across different altitudinal zones and regional enrichment areas.

3.1 High-altitude cold regions (> 4,500 m) and alpine resources

The Tibetan Plateau, being the highest and ecologically geographical unit on Earth, has high-altitude cold regions (above 4,500 m) that are home to a wealth of abundant and unique plants and fungi used for FMHR. These biological resources have evolved special secondary metabolites and physiological adaptation mechanisms under extreme conditions like bitter cold, strong UV radiation, huge day-night temperature differences, poor soil, and drought stress, giving them the dual value of nutritional supplementation and disease treatment.

In the transition zone between the frost weathering belt and alpine meadows at elevations of 4,600–5,000 m, the tender stems and leaves of *Anthriscus sylvestris* Hoffm. are collected as wild edible greens by high-altitude pastoral communities, while its roots are used to replenish *qi* and invigorate the spleen, as well as to promote blood circulation and alleviate pain, thus exhibiting typical FMHR properties. Phytochemical analyses have revealed its antioxidant, immunomodulatory, and antitumor activities[98, 99]. At the edges of alpine rhododendron scrublands, the leaves and flowers of *Rhododendron anthopogon* D. Don are rich in flavonoids and volatile oils. They can be brewed as a herbal tea to relieve altitude sickness and are also used to treat asthma and chronic bronchitis. Essential oil from the plant contains antitumor substances[100, 101].

At elevations of 5,000–5,500 m, in the scree slopes and alpine subnival zone, *Crocus sativus* L. contains major components such as crocin, crocetin, and picrocrocin. It exhibits the effects of promoting meridian circulation and harmonizing *qi* and blood and dispersing stasis and relieving obstructions; and calming the mind and opening the orifices. As a premium spice and natural food colorant, it perfectly embodies the concept of "food and medicine homology"[102, 103]. *O. sinensis* is a fungus-larva complex formed by a parasitic fungus infecting ghost moth larvae, distributed in alpine meadows and at the margins of scree slopes above 4,500 m[104]. It is warm in nature and sweet in taste and is used to replenish the kidney and lung, stop bleeding, and transform phlegm. Modern studies have found that it contains cordycepic acid, cordyceps polysaccharides, and other immunomodulatory and antitumor active substances[98]. *O. sinensis* can be used either as a premium nourishing ingredient in stews or as a medicine to treat various deficiency-related diseases. It is a typical representative of the diversity and uniqueness of food and medicine homology resources on the QTP[105].

3.2 Mid-altitude river valleys (3,000–4,500 m) and the agro-pastoral ecotone

Influenced by the Indian Ocean monsoon and the cold, dry Plateau climate, the mid-altitude river valley belt (3,000–4,500 m) on the southeastern margin of the QTP and in the Hengduan mountains region exhibit microclimatic characteristics of mild winters and springs, humid summers and autumns, and large diurnal temperature variations. This elevation zone coincides with the "core enrichment area" of the agro-pastoral transition zone-where the upper limit of farmland meets the lower limit of pastures-so human activity is frequent. Consequently, the exploration of food and medicine homology resources in these mid-altitude valleys is shifting from a model of "natural supply" toward one of "symbiosis between artificial cultivation and wild resources".

Vicatia thibetica de Boiss. is a perennial herb in the Apiaceae family. In Tibetan medicine, it's called "Jawa", while in Yunnan folk tradition, it's known as "Xigui"[106]. It grows on slopes,

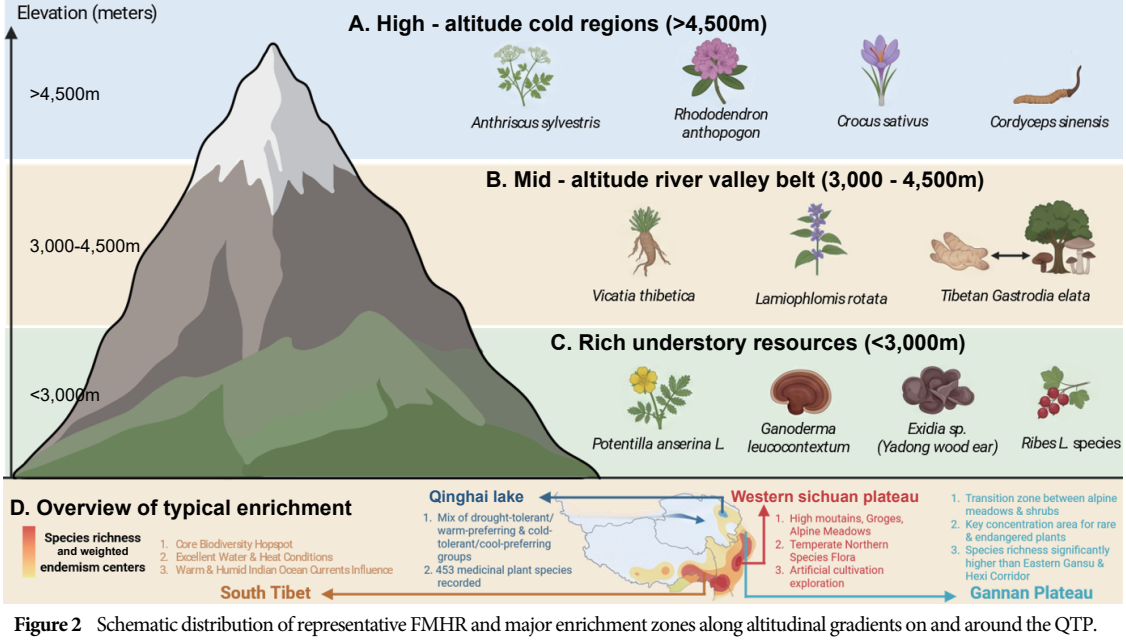


Figure 2 Schematic distribution of representative FMHR and major enrichment zones along altitudinal gradients on and around the QTP.

grasslands, forests, and riverbanks at altitudes of 2,700 to 4,000 m. The root is conical, fleshy, and thick. In Tibetan, "Jawa" means "food", and the rhizome can be used in soups, making it the most distinctive food and medicine homology plant in Tibetan medicine and one of the five major root medicines in the Tibetan pharmacopoeia[107]. According to Tibetan medical theory, it is warm in nature and pungent in taste and used to treat yellow water disease, kidney pain, lower back pain, swelling and pain, and cold-related kidney and lumbar disorders[107]. Modern studies have shown that the root of *Vicatia thibetica* is rich in various active components, including umbelliferone, bergapten, β-sitosterol, daucosterol, flavonoids, polysaccharides, and apigenin. That extracts and polysaccharide components can relieve fatigue, provide antioxidant effects, and slow aging. Its polysaccharides can reduce lactic acid production, enhance the clearance of metabolic byproducts, and effectively scavenge 1,1-diphenyl-2-picrylhydrazyl (DPPH) and 2,2′ -azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) free radicals[106].

Tibetan *Gastrodia elata* (*G. elata*) is a rare food and medicine homology plant of the orchid family, genus *Gastrodia*. Its tuber is used in traditional medicine to extinguish wind and stop convulsions and to calm liver yang[108]. Bomê County in Tibet is the main production area for *G. elata*, where locals have traditionally ground it into powder and taken it with water. This habit of consuming it in powdered form is also maintained by herders in other regions. Wild Tibetan *G.elata*, which has no roots or leaves, completes its life cycle by symbiotically associating with *Armillariella mellea* on fallen logs in mid-altitude valleys at 3,000–4,500 m under fir and spruce forests. Due to its high market price, wild *G. elata* has been overharvested, and traditional pit cultivation consumes a lot of wood and easily causes strain degeneration[109]. In valley regions like Nyingchi in Tibet and Diqing in Yunnan, a "fungus, forest, *Gastrodia*" integrated symbiotic cultivation system has been developed: The layer of fallen branches and leaves under the original forest is kept, selected *Armillaria mellea* (*A. mellea*) is artificially inoculated, and *Gastrodia* tubers are replanted; at the same time, harvesting is limited, with 20% of the tubers left per square meter for natural propagation. This semi-artificial bionic cultivation method keeps the gastrodin content in *Gastrodia* tubers stable at over 0.4% (higher than the pharmacopeia standard), and small populations of wild *Gastrodia* in the forest undergrowth recover to their original density in 3–5 years[110].

Lamiophlomis rotate is a perennial herb in the mint family. Its whole plant is used medicinally for hemostasis, analgesia, and anti-inflammatory effects. Known as "Daba" in Tibetan medicine, it is commonly used to treat traumatic injuries and rheumatic pain[111]. Due to overharvesting, its wild populations have significantly declined in Sichuan, Gansu, Qinghai, Tibet, and other regions, and it is now listed as a Class II nationally protected plant. To alleviate resource pressure, researchers recommend harvesting only the above-ground parts to facilitate plant regeneration, strengthen studies on introduction and cultivation as well as wild tending, and establish a germplasm resource bank. Through models such as imitation-wild cultivation, the genuine nature of the medicinal material can be preserved to a certain extent, enabling sustainable utilization[112].

3.3 Low-altitude mountain forests (< 3,000 m) and understory resources

The low-altitude mountain forest belt of the QTP (below 3,000 m) with its moderate elevation and favorable hydrothermal conditions nurtures an extremely rich array of understory resources with "food and medicine homology". The shady, moist environment and nutrient-rich soil in this area provide perfect conditions for various large fungi, special berries, and roots to thrive.

Potentilla anserina L. (*P. anserina*) belongs to the Rosaceae family. Its tubers are edible and can also be used medicinally. In Tibetan folk medicine, it's called "Zhuolaosazeng" and is commonly used to strengthen the spleen and stomach and to promote fluid production and quench thirst[113]. *P. anserina* is one of the favorite foods among Tibetan people. It's used as one of the ingredients in the Tibetan pastry called "Tai"; its unique aroma and sweetness make it a popular holiday snack. It's also cooked with rice and red dates over low heat to make "Benzhe" porridge[114]. *P. anserina* prefers to grow on riverbanks and meadows, fitting perfectly into transitional habitats in agro-pastoral ecotone. Due to grassland degradation and intensified harvesting, wild *P. anserina* tubers are getting smaller and less dense. This led to the development of a protective cultivation method called "rotational reseeding": After grazing is stopped, *P. anserina* seeds are sown in the grassland, preserving the original vegetation structure, and only the tubers are harvested without damaging the creeping stems, combining wild harvesting with artificial nurturing. Three years after reseeding, the *P. anserina* population shows no significant difference in biomass compared to the original wild population, and the polysaccharide and tannin content in tubers remains stable. This low-intervention, symbiotic approach allows bristlegrass to continue providing both food and medicinal resources while maintaining the productivity of pasturelands[115].

Ganoderma leucocontextum (*G. leucocontextum*) is a new species of Ganoderma unique to the QTP. It was identified and named by Li in 2015, and it got its name because its flesh is white. This fungus can be found on decaying wood and stumps in the understory of low-altitude mountain forests[116,117]. *G. leucocontextum* mainly contains triterpenoids, polysaccharides, proteins, and sterols. Among these, triterpenoids and polysaccharides are the major components and key bioactive substances, exhibiting a wide range of effects including anticancer, antitumor, neuroprotective, immunomodulatory, hypoglycemic, lipid-lowering, and antioxidant activities[118]. As a characteristic edible and medicinal fungus of the Plateau, *G. leucocontextum* can be used either as a medicine for adjunctive disease treatment or processed into health foods and functional products[119].

Exidia sp. is a rare gelatinous edible fungus endemic to the low-altitude forests of the southeastern QTP. It is mainly produced in Yadong County, Tibet, and grows on dead branches of plants in the Rosaceae family. When fresh, it is gelatinous and ear-shaped or disc-shaped and ranges in color from reddish-brown to dark brown[120]. It is rich in proteins and various trace elements, with a crude protein content higher than that of common grains and cash crops such as soybean, millet, wheat, and peanut[121]. In terms of traditional use, local Tibetan people have long gathered Yadong wood ear and presented it as a tonic for patients to help restore health[122].

There are 59 species and 30 varieties of *Ribes* L. plants in China, among which *Ribes himalense*, *Ribes xizangense*, *Ribes menyuanense*, and *Ribes longispinosum* are endemic to the QTP. They belong to the Saxifragaceae family and are commonly found in shrublands at the edges of low-altitude mountain forests and wet areas along streams[123]. Bioactivity analyses indicate that Ribes

fruits are rich in total flavonoids, polyphenols, polysaccharides, anthocyanins, and proanthocyanidins. As a characteristic berry resource in the low-altitude mountain forests of the QTP, Ribes not only holds an important position in TTM but also shows promising potential for development as a food and medicine homology plant[124]. Table 1 presents a systematic summary of major FMHR across different altitudinal zones on the Tibetan Plateau.

3.4 Regional characteristic enrichment zones

The QTP has the richest temperate alpine plant flora in China. Within the main area of the Plateau, there are over 12,000 species of seed plants, and medicinal plants make up a very high proportion. The food and medicine homology resources on the Plateau are distributed very unevenly. The eastern and southeastern regions (the Hengduan Mountains, the western Sichuan Plateau, and northwestern Yunnan) have the highest species diversity and endemism, while the central Plateau and northwest are relatively poor. The area where northwestern Yunnan, western Sichuan, and southeastern Tibet meet is the core region with the most medicinal plants, with a single 0.5 × 0.5 latitude-longitude grid unit recording up to 159 species. Weighted endemism analysis shows that the centers of endemism are concentrated in the Hengduan Mountains, the middle and upper reaches of the Yarlung Tsangpo River, and parts of the Plateau forming isolated patches, reflecting the region's unique role as a refuge during ice ages and a hotspot for rapid species diversification[125, 126].

The Qinghai Lake Basin and its surrounding areas are characterized by a temperate continental semi-arid climate on the QTP. The food and medicine homology resources in this region include both drought-tolerant, warmth-preferring groups and cold-tolerant, cool-preferring groups. A survey recorded 453 species of medicinal plants in this region, notably including Tibetan medicinal specialties such as *O. sinensis*, *Sinopodophyllum hexandrum*, *Dracocephalum tanguticum*, and *P. anserina*. The areas around the lake are also a main production region for major authentic medicinal herbs like *rhubarb*, *Qin Jiao*, *Notopterygium*, and *Rhodiola*[127].

The South Tibet region specifically refers to the central and southern parts of Tibet, as well as areas like Nyingchi, Shannan, and Shigatse. It's a core part of the biodiversity hotspot in the southeastern Plateau. Thanks to the deep influence of the warm and humid currents from the Indian Ocean, the area has great water and heat conditions, and the vegetation vertical zones are well represented-from valley shrubs to alpine scree, medicinal plants are found throughout. Weighted endemism analysis confirms that South Tibet (especially Nyingchi and areas around Lhasa) is a high-value area for endemic medicinal plants[125, 126].

The western Sichuan Plateau is the transitional zone from the QTP to the Sichuan Basin, with landscapes mainly featuring high mountains, gorges, and alpine meadows. The region's Tibetan medicinal plant flora is mainly made up of temperate northern species, and the medicinal plant resources are most abundant in the cold-temperate coniferous forests, subalpine shrubs, and subalpine meadows at elevations of 2,000–3,500 meters. Taking Rangtang County (in the Amdo pastoral area) as an example, there are 215 commonly used native plant species, among which *P. anserina*, *Notopterygium*, and *Nardostachys* are widely used in daily diet and health care. In Danba County (in the Jiarong agricultural area), 90 species from 51 families of commonly used ethnic plants have been recorded, with food and medicine homology plants accounting for 24.4%, demonstrating the diversity of utilization under multi-ethnic integration. The western Sichuan Plateau is also a high-quality production area for medicinal materials such as *Fritillaria cirrhosa*, *O. sinensis*, *Gentiana macrophylla*, and *Rheum officinale*. To alleviate the pressure of wild medicinal plant harvesting, artificial cultivation is being explored in western Sichuan[128].

The Gannan Plateau is located on the northeastern edge of the QTP, at the junction of the Loess Plateau, QTP and Inner Mongolia Plateau. It belongs to a transition zone between alpine meadows and alpine shrubs. Based on data from Gansu Province's fourth survey of traditional Chinese medicine (TCM) resources,

Table 1 Systematic summary of major FMHR across different altitudinal zones on the Tibetan Plateau

Altitudinal zone	Major resources	Ecological distribution	Key constituents	Traditional and modern functions	Evidence type
> 4,500 m (Alpine nival and meadow belt)	*Anthriscus sylvestris*	Transition zones and alpine meadows	Flavonoids, polysaccharides	Improves blood circulation, antioxidant, immunomodulation	**In vitro + in vivo**
	Rhododendron anthopogon	Alpine scrublands	Essential oils, flavonoids	Relieves altitude sickness, asthma relief, antitumor	**In vitro + in vivo**
	Crocus sativus	Scree slopes and subnival zone	Crocin, crocetin	Promotes meridian circulation, natural colorant	**In vivo + clinical**
3,000–4,500 m (Agro-pastoral ecotone)	*O. sinensis*	Alpine meadows	Cordycepic acid, polysaccharides	Replenishes kidney and lung, immunomodulation	**In vivo + clinical**
	Vicia thibetica	River valleys and slopes	Umbelliferone, polysaccharides	Treats cold ailments, antifatigue, antioxidant	**In vitro + in vivo**
	G. elata	Understory of fir/spruce forests	Gastrodin	Calms liver yang, stops convulsions	**In vivo + clinical**
	Lamiophlomis rotata	Valley grasslands	Iridoid glycosides	Hemostasis, analgesia, treats traumatic injuries	**In vivo + clinical**
	P. anserina	Riverbanks and meadows	Polysaccharides, tannins	Strengthens spleen, traditional staple food	**In vitro + in vivo**
< 3,000 m (Montane forest belt)	*G. leucocontextum*	Decaying wood in forests	Triterpenoids, polysaccharides	Immunomodulatory, neuroprotective, antioxidant	**In vitro + in vivo**
	Exidia sp.	Dead branches of Rosaceae	High crude protein, trace elements	Restorative health tonic, nutritional supplement	**In vitro + population-level**
	Ribes sp.	Forest edges and stream banks	Anthocyanins, polyphenols	Functional berry resource, antioxidant	**In vitro + in vivo**

the counties of Gannan Prefecture (Hezuo City, Xiahe County, Luqu County, Diebu County, Zhuoni County, etc.) are key areas with high concentrations of rare and endangered medicinal plants. The species richness here is significantly higher than in eastern Gansu and the Hexi Corridor. Dominant taxa include *Sinopodophyllum hexandrum*, *Fritillaria unibracteata*, *Dactylorhiza hatagirea*, *Nardostachys jatamansi*, *Nardostachys grandiflora*, *Gentiana macrophylla*, *Notopterygium incisum*, etc. Their formation is closely related to relatively high rainfall (> 600 mm), soil mainly consisting of loam, and complex terrain and landforms[129].

4 Geographical distribution and diversity of FMHR on the QTP

The unique alpine environment of the QTP harbors a remarkable diversity of FMHR, encompassing plants, animals, macrofungi, and traditional processed foods. The primary categories of these distinctive resources are illustrated in Fig. 3.

4.1 Plant FMHR

4.1.1 *Cereals*

The QTP preserves a distinctive group of cereal resources closely linked to local ecology and traditional diets. Hull-less barley or qingke serves as the most representative traditional staple[130]. It contains abundant functional components including β-glucan, anthocyanins, and polyphenols[131, 132].

Other vital indigenous grains include Tartary buckwheat and oat which adapt well to cold environments and provide high levels of rutin and protein[133-135]. With a cultivation history exceeding 3,500 years[136], qingke exhibits exceptional health benefits. Its β-glucan and phenolic compounds demonstrate strong antioxidant capacity[137] and potential hypoglycemic functions by improving insulin sensitivity[138]. Dietary fiber in qingke effectively alleviates obesity and dyslipidemia[139, 140]. Research also highlights its anticancer potential through inflammatory pathway regulation[141] and antiatherosclerosis effects[142]. Furthermore, qingke consumption increases muscle glycogen and ATP content to exert vital anti-fatigue and anti-hypoxia benefits for high-altitude survival[143]. Dietary of highland barley enhanced hypoxia survival time by improving ATP content and alleviating oxidative stress damage[144]. Today it is widely utilized in diverse modern food and beverage industries beyond traditional tsamba[145].

It is important to clarify the position of quinoa in the Plateau agricultural system. Unlike traditional indigenous resources, quinoa is an introduced exotic crop that achieved large-scale cultivation in Qinghai around 2014[146]. Lacking any historical record in Tibetan medicine, it functions purely as an emerging functional crop adapted to the Plateau rather than a traditional FMHR. Modern evaluations of this introduced crop show that its saponins and peptides possess certain hypoglycemic and antioxidant properties[147].

Studies indicate it can improve lipid profiles[148] and induce apoptosis in specific cancer cell lines[149]. Quinoa protein demonstrated great anti-inflammatory potential by inhibited TNF, MAPK, and NF-κB signaling to reduce the expression of inflammatory factors of TNF-α and IL-6[150]. The bioactive compounds originated from quinoa affect the production of short-chain fatty acids (SCFAs) and the adjustment of intestinal pH to balance the intestinal flora structure, which could improve many diseases related to intestinal flora[151]. Consequently, this non-native grain is increasingly processed into various modern consumer products like yogurt and biscuits to supplement the local food industry[152].

4.1.2 *Fruits*

Berries and succulent fruits native to the QTP constitute a highly diverse group of food and medicine homology resources. Having adapted to the extreme high-altitude environment, which is characterized by UV radiation, large diurnal temperature variations and chronic hypoxia, these plants accumulate exceptionally high levels of bioactive secondary metabolites, including flavonoids, anthocyanins, polyphenols and polysaccharides. These compounds confer multiple health benefits, namely antioxidant activity, cardioprotection, hepatoprotection, immunomodulation and anti-hypoxic effects.

Sea buckthorn (*Hippophae rhamnoides* L.): In Tibetan medicine, sea buckthorn fruits relieve cough, promote digestion, invigorate blood circulation, and alleviate altitude sickness. In TCM, the fruit is sour, astringent, and warm, benefiting the spleen

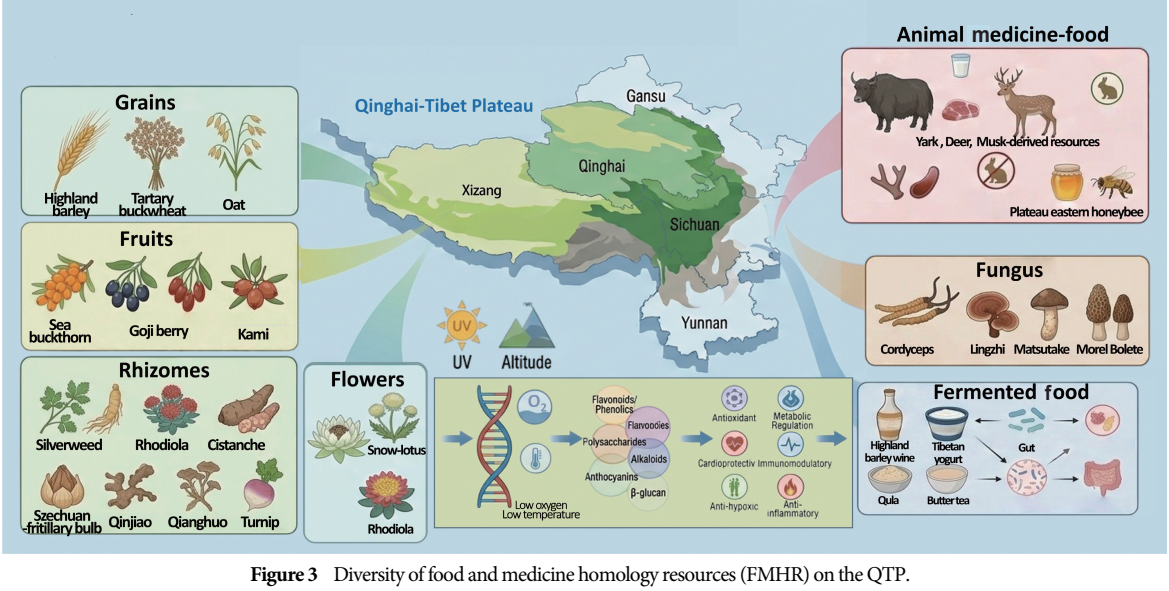


Figure 3 Diversity of food and medicine homology resources (FMHR) on the QTP.

and stomach[153]. Sea buckthorn is exceptionally rich in vitamin C, total flavonoids (isorhamnetin, quercetin, kaempferol glycosides), and polyphenols. A comparative study by Wang *et al.*[154] showed that phenolic extracts of Plateau sea buckthorn berries exhibit strong *in vitro* and cellular antioxidant activity, with *Hippophae rhamnoides* ssp. *sinensis* berries containing the highest levels of total phenolics and flavonoids (rutin and narcissin as major flavonols). Total flavonoids from sea buckthorn also exert significant neuroprotective effects[154]. Pharmacologically, sea buckthorn has demonstrated cardiovascular protection *via* lipid-lowering and anti-atherosclerotic mechanisms, hepatoprotective activity against alcoholic fatty liver disease through regulation of intestinal flora and inhibition of the MAPK/NF-κB pathway, and adaptogenic effects that mitigate hypoxia-induced pulmonary vascular leakage[153]. These findings position sea buckthorn as a promising functional food for cardiovascular health, hepatic protection, and hypoxia tolerance.

Black and red goji berries (*Lycium ruthenicum* Murray and *Lycium barbarum* L.): Black goji berry is traditionally used in Tibetan and Chinese medicine for heart disease, fatigue, and inflammation[155]. It is rich in anthocyanins and polysaccharides, exhibiting antioxidant, anti-inflammatory, immune-enhancing, anti-tumor, and anti-radiation activities[155]. The dark purple-black color of black goji berries results from exceptionally high levels of anthocyanins, which are induced by the intense UV radiation characteristic of the QTP as an adaptive defense mechanism[156]. In contrast, red goji berry contains low levels of anthocyanins, but is abundant in polysaccharides and carotenoids, such as zeaxanthin. Red goji berry polysaccharides (LBPs) exert immunomodulatory effects *via* regulation of macrophages, cytokines, and gut microbiota. Regular goji berry intake (28 g, five times/week for 90 days) significantly increased macular pigment optical density in healthy adults, suggesting protection against age-related macular degeneration[157]. Additional benefits include anti-fatigue, hepatic protection, and anti-aging activities. Both berries hold promise as dietary supplements for chronic disease prevention and healthy aging.

Kami (*Nitraria* spp.) is a shrub belonging to the family Nitrariaceae, with a notably high distribution across the QTP[158]. There are mainly three species including *Nitraria tangutorum* Bobr, *Nitraria sibirica* Pall. and *Nitraria roborowskii* Kom. and primarily distributed in arid environments such as the Gobi Desert[159]. Its mature fruits exhibit a color spectrum ranging from light red to dark red and purple, which was known as "Plateau red pearl". It exhibits strong adaptability to arid and saline environments and serves as an ideal plant for windbreaks, sand fixation, and the maintenance of ecological balance in desert grasslands[159]. Beyond its significant ecological value, the fruit has a long history of consumption and medicinal application. The fruits are harvested upon ripening, dried, and prepared for medicinal use. Its primary functions include strengthening the spleen and stomach, nourishing the body, regulating menstruation, and promoting blood circulation. Consequently, it is indicated for conditions such as physical emaciation, *qi* and blood deficiency, spleen-stomach disharmony, indigestion, menstrual irregularities, and lower back pain caused by deficiency-cold[160]. Modern phytochemical studies have revealed that these fruits are rich in bioactive compounds, including vitamin C, amino acids, fatty acids, flavonoids, anthocyanins, phenolic acids, alkaloids, and polysaccharides[159]. Correspondingly, pharmacological research demonstrates a broad spectrum of bioactivities, encompassing lipid-lowering, hypoglycemic, cardiovascular-protective, neuroprotective, hepatoprotective, and anti-tumor effects[161, 162]. In summary, as a plant with both medicinal and edible value, Nitraria offers substantial nutritional and therapeutic benefits. Given its abundant natural resources in northwestern China, the species presents significant potential for further development and utilization.

Other highland wild berries. Beyond the aforementioned species, a wealth of wild berries with FMH value remains underutilized across the QTP and adjacent Himalayan regions, including wild hawthorn (*Crataegus cuneata*), blue honeysuckle (*Lonicera caerulea*), and barberry (*Berberis* spp.)[163]. These berries are traditionally employed in Tibetan folk medicine for their heat-clearing, detoxicating, fluid-promoting, and dryness-moistening properties[164]. Wild hawthorn fruit also exhibits high antioxidant capacity due to its abundant polyphenols, including phenolic acids and flavonoids, as demonstrated by integrated metabolomic and chemometric analyses[165]. Blue honeysuckle is rich in polyphenols, and a recent study characterized 76 polyphenols across 20 cultivars using HPLC-DAD and HPLC-ESI-QTOF-MS^2, confirming strong antioxidant and α-amylase inhibitory activities[166]. Barberry fruits are also rich in bioactive polyphenols and alkaloids, exhibiting notable antioxidant and anti-hyperglycemic activities, supporting their traditional use for fever, diarrhea, and liver ailments[167]. Collectively, these highland wild berries represent a valuable but underexplored source for functional foods and natural antioxidants.

In summary, the fruit and berry category of QTP FMHR encompass diverse species with well-documented traditional applications and increasingly substantiated pharmacological evidence. The harsh high-altitude environment drives the accumulation of unique bioactive phytochemicals, making these berries promising candidates for functional foods and nutraceuticals targeting oxidative stress, metabolic disorders, and hypoxia-related conditions.

4.1.3 *Rhizomes*

The extreme environmental conditions of the QTP, including frigid alpine climate, intense UV radiation and large diurnal temperature fluctuations, have nurtured a unique group of plants with rhizomes and roots as medicinal and edible parts. During long-term adaptation to the harsh Plateau environment, these plants have accumulated abundant secondary metabolites, forming unique chemical and pharmacological profiles. Compared with leaf, flower, or fruit resources, those from rhizomes and roots often store more concentrated nutrients and bioactive components, endowing them with both high nutritional tonic value and clear medicinal properties. As a result, they occupy an important position in Tibetan medicine and folk dietary therapy.

P. anserina–also known as "Tibetan ginseng" – is the tuberous root of a rosaceous plant and a highly distinctive FMHR on the QTP. It has a long history of both food and medicinal use among Tibetan communities, where it is honoured as "Zhuolao Shaseng" and is a common Tibetan medicine. According to Tibetan medical classics, *P. anserina* is sweet and warm in nature, and possesses functions such as strengthening the spleen and replenishing *qi*, enriching blood and beautifying the face, and promoting fluid production to quench thirst. The root is rich in protein, dietary fibre, and bioactive compounds including tormentic acid, polysaccharides, and flavonoids. Using UPLC-LTQ-Orbitrap high-resolution mass spectrometry, 64 compounds were identified from the ethanol extract of *P. anserina*; the ethanol extract contained

higher total flavonoid and total polysaccharide contents than the water extract and also exhibited better *in vitro* antioxidant activity[168]. Regarding structural characterisation of its polysaccharides, a recent study on Qinghai-grown *P. anserina* reported a homogeneous polysaccharide with a molecular weight of 8.24 × 10^3 Da, a backbone composed of →4)-*α*-*D*-Glcp-(1→, →3)-*β*-*D*-Rhap-(1→ and →4)-*β*-*D*-Glcp-(1→ linkages, and a total sugar content of 90.73 ± 1.94 %. This polysaccharide can modulate the intestinal microbiota and alleviate oxidative stress[169]. Modern pharmacological studies have confirmed that *P. anserina* exhibits antioxidant, hepatoprotective, hypoglycaemic, and immunoenhancing activities, and that its tuberous roots significantly increase the oxygen utilisation capacity of the body[170].

R. rosea is a perennial herb of the Crassulaceae family, mainly growing at altitudes of 2,000–5,000 m in rock crevices and alpine screes characterised by severe cold, hypoxia, strong UV radiation, and large day-night temperature differences. This harsh environment has endowed *R. rosea* with unique genetic traits and specialised metabolites not found in other plants. In the Tibetan medical system, *R. rosea* is primarily used to reinforce healthy energy and consolidate constitution, replenish *qi* and enrich blood, and it is also recorded in the Ming dynasty *Compendium of Materia Medica*. Modern studies have demonstrated its multiple effects, including anti-hypoxia, anti-fatigue, anti-radiation, anti-inflammatory, and antioxidant activities. The major bioactive constituents of *R. rosea* include salidroside, quercetin, rosavin, and polysaccharides. Recent research has innovatively extracted exosome-like nanovesicles from *R. rosea* and elucidated a novel mechanism by which they inhibit vascular endothelial cell pyroptosis and promote angiogenesis in ischaemic tissues through the novel-miRNA-115-5p/TXNIP/NLRP3 signalling axis[171]. In the field of cardioprotection, salidroside suppresses hypoxia-induced apoptosis of cardiomyocytes and improves mitochondrial energy metabolism *via* the EGLN1/HIF-1α pathway; it also activates the AMPK pathway to promote mitochondrial biogenesis and enhance exercise endurance[172]. As an internationally recognised plant adaptogen, *R. rosea* holds great promise in functional foods and sports nutrition. However, with continuously increasing market demand, wild *Rhodiola* resources are facing varying degrees of over-harvesting pressure, and there is an urgent need to strengthen research on artificial cultivation and resource conservation.

Cynomori Herba (*Cynomorium songaricum*, *C. songaricum*) and Cistanche (*Cistanche deserticola*, *C. deserticola*) are two representative tonic rhizome/root species in the QTP and its surrounding arid regions. Both are parasitic plants-*C. songaricum* parasitises the roots of *Nitraria* spp. and *C. deserticola* parasitises the roots of *Haloxylon ammodendron*-and both exhibit the traditional effects of tonifying kidney *yang*, enriching essence and blood, moistening dryness, and nourishing the sinews. *C. songaricum* contains polysaccharides, flavonoids, triterpenoids, and other components, and possesses antidepressant, antioxidant, anticancer, and immunomodulatory activities. Using UPLC-Q-Orbitrap high-resolution mass spectrometry, 1,100 chemical constituents have been identified from *C. songaricum*[173]. In mechanistic studies, a homogeneous polysaccharide from *C. songaricum* (CSP1) was shown to ameliorate high-fat-diet-induced testicular dysfunction by remodelling the gut microbiota, repairing the intestinal barrier, and regulating the "gut-testis axis", thereby inhibiting activation of the TLR4/NF-κB inflammatory pathway[174]. To address the poor water solubility and stability of luteolin, a flavonoid present in *C. songaricum*, Guan *et al.* constructed a nanocomplex using succinylated lactoferrin and pH-driven self-assembly, systematically elucidated the self-assembly mechanism, and successfully applied the complex to the development of 3D-printed dysphagia diets[175,176]. Regarding *C. deserticola*, its phenylethanoid glycosides (CPhGs, mainly composed of oleuropein-like compounds and acetyl oleuropein-like compounds) exert renoprotective anti-ageing effects by regulating the STAT1, P53 and cGAS-STING signalling pathways. Furthermore, the phenylethanoid glycosides and polysaccharides from *C. deserticola* can activate the AMPK/PGC-1α pathway, promote mitochondrial biogenesis, enhance ATP production, and exhibit pronounced anti-fatigue activity[177].

Szechuan-fritillary Bulb (*Fritillaria* spp.) is a rare medicinal plant of the Liliaceae family, valued for its antitussive, expectorant, lung-clearing and moistening effects. Its chemical composition is dominated by alkaloids, and there are significant differences in both chemical profiles and pharmacological activities among different *Fritillaria* species. Owing to a sharp decline in wild population density compared with the 1980s and a long growth cycle of 5–7 years, *Fritillaria* has been listed as a national second-grade protected wild plant in China.

Qinjiao (*Gentiana* spp.) belongs to the Gentianaceae family and is used by Mongolian, Tibetan and Yi ethnic groups for dispelling wind-dampness, clearing damp-heat, alleviating joint pain, and relieving asthenic fever. The active component gentiopicroside from *Gentiana* targets the CXCL12/CXCR4 signalling axis, inhibits the expression of HIF-1α, VEGF-A and Ang-2, and thereby blocks pathological angiogenesis in rheumatoid arthritis[178].

Qianghuo (*Notopterygium incisum*) is an Apiaceae plant that contains volatile oils, coumarins, phenolic acids, and many other constituents. In 2024, two new linear furanocoumarins were isolated from *Notopterygium incisum*; they exert anti-inflammatory effects by suppressing COX-2 and iNOS expression, and one of them was shown to inhibit the PI3K/AKT pathway by down-regulating p-PI3K and p-AKT. *Notopterygium incisum* exhibits outstanding activities in anti-inflammation, analgesia, inhibition of synovial hyperplasia, and bone destruction prevention, but its wild resources are also facing the challenge of over-exploitation[179].

Yuan Gen (*Brassica rapa* L., *B. rapa*, Tibetan name "Nyuma") is the fleshy root of a Brassicaceae plant and a traditional FHMR endemic to the QTP. It has been cultivated and consumed for more than a thousand years in high-altitude regions. Tibetan medicine holds that *B. rapa* is warm and pungent in nature, and possesses functions such as clearing heat, relieving summer-heat, nourishing the body and increasing oxygen supply, as well as dispelling wind-cold and resolving phlegm. The root is rich in protein, dietary fibre, vitamin C, and minerals including calcium, iron, zinc and selenium. Notably, its glucosinolate content is significantly higher than that of ordinary vegetables, and hydrolysis generates bioactive isothiocyanates. Modern pharmacological studies have shown that *B. rapa* extracts exhibit significant antioxidant capacity, with total phenolic and flavonoid contents positively correlated with free-radical-scavenging activity; the polysaccharides from *B. rapa* can enhance macrophage phagocytosis and lymphocyte proliferation, indicating good immunomodulatory activity; moreover, *B. rapa* has unique efficacy against high-altitude hypoxia, improving blood oxygen-carrying capacity and protecting mitochondrial function[180].

In summary, the QTP harbours rich and distinctive

rhizome/root plant resources that are both edible and medicinal. These include *P. anserina*, a "Plateau ginseng" with high nutritional value and comprehensive tonic effects; *R. rosea*, an adaptogenic plant with core anti-hypoxia and anti-fatigue functions; the tonic roots *C. songaricum* and *C. deserticola* that warm kidney *yang*, enrich essence and moisten dryness; the medicinal herbaceous roots *Fritillaria*, *Gentiana* and *Notopterygium* with additional dietary therapy value; and *B. rapa*, an indispensable traditional food-medicine vegetable in the daily life of Plateau communities. Through long-term adaptation to the Plateau environment, these plants have formed unique chemical and pharmacological profiles and serve as important carriers of Tibetan medical wisdom and folk dietary therapy.

4.1.4 Flowers

The flowering medicinal and edible plants of the QTP occur under extreme high-altitude conditions characterized by low temperature, hypoxia, and strong UV radiation, and these stresses have promoted the evolution of morphologically specialized alpine taxa with distinctive secondary-metabolite profiles[181]. Many such resources are distributed in alpine meadow scree slopes, rocky habitats, and other high-mountain ecotones, and they constitute an important component of the biological and medicinal culture of TTM on the Plateau[182]. Although the growing and flowering seasons are short, alpine plants frequently accumulate flavonoids, phenolics, terpenoids, and other stress-related metabolites under high-altitude conditions[181]. Notably, despite its prominent floral appearance, *Rhodiola* is utilized primarily for its roots and rhizomes.

Snow-lotus taxa within *Saussurea* are among the best-known alpine medicinal plants associated with the QTP and adjacent high mountains[183]. Representative taxa include *Saussurea tridactyla* in Xizang, *Saussurea laniceps*, (*S. laniceps*) in Sichuan, Xizang, and Yunnan, and *Saussurea medusa* (*S. medusa*) in Gansu, Qinghai, western Sichuan, Xizang, and northwestern Yunnan, generally occurring on alpine scree slopes or rocky slopes at roughly 3,000–5,600 m[184]. These plants commonly bear densely woolly or pubescent bracts, which are widely interpreted as adaptations to cold, desiccation, and strong UV radiation in alpine habitats[184]. In Tibetan and other Asian medical traditions, snow-lotus plants have been used for rheumatic disorders, traumatic injury, menstrual disorders, and related cold-associated syndromes[184]. Phytochemical studies show that snow-lotus taxa contain terpenoids, flavonoids, lignans, coumarins, alkaloids, and polysaccharides, supporting both medicinal and functional-food interest[184]. However, many snow-lotus populations are threatened by over-collection, habitat disturbance, slow life history, and low regeneration capacity[185].

4.1.5 Whole herbs and other characteristic Tibetan botanical resources

The extreme environments of the QTP and TTM have nurtured unique botanical resources, prominently represented by *Corydalis* and *Anisodus* species. Distinct from conventional resources classified by standard plant organs such as grains, fruits, roots, or flowers, these endemic plants are characterized by whole-plant utilization and dual dietary-medicinal values. They serve as fundamental raw materials for both classical Tibetan prescriptions and daily healthcare, featuring exceptional high-altitude adaptability and unique biological activities.

Corydalis, the largest genus of the Papaveraceae family, has around 428 species across the globe. There are 298 species in China, including 219 endemic species[186]. Over 120 species are found on the QTP, and 94 species are distributed in Xizang, making this Plateau the global differentiation center of *Corydalis*[186]. These plants primarily inhabit alpine screes, grassy slopes and forest gaps at altitudes of 3,000–5,000 m, with the Hengduan Mountains and northern Xizang Plateau as the distribution hotspots. More than ten species are commonly used in Tibetan areas, such as *Corydalis scaberula*, *Corydalis polyphylla* and *Corydalis filicina*. Their whole plants and tubers are used medicinally, serving as the original plants of Tibetan medicines "Zijin" and "Regong", and nearly 60% of them are endemic species. Tibetan medicine holds that these plants exhibit the efficacies of clearing heat and detoxifying, relieving pain and anti-inflammation, as well as protecting the liver and gallbladder[187]. Local residents often decoct the whole plants or grind them into powder for dietary therapies to exert anti-inflammatory and analgesic effects, and these species are also important ingredients of classic Tibetan medicines such as Renqing Mangjue. Phytochemical studies reveal that *Corydalis* is dominated by isoquinoline alkaloids (protopine, tetrahydropalmatine), flavonoids and coumarins[170]. Alkaloids are the core active components, possessing analgesic, sedative, hypotensive, hepatoprotective and antibacterial activities[188].

Solanaceous tropane alkaloid plants are among the most distinctive food and medicine homology resources in Tibetan regions. Species of the genus *Anisodus* (Solanaceae), represented by *Anisodus tanguticus* and *Anisodus luridus*, are rich in tropane alkaloids (TAs), including hyoscyamine and scopolamine[189]. Tibetan herders have long used these plants as veterinary medicine to treat yak abdominal distension, inflammation, and anorexia. During periods of medical scarcity, the crude extract, coded as "654" (yielding the clinical drugs anisodamine and anisodine), made significant contributions to Plateau frontier construction and healthcare. Quantitative analysis has revealed exceptionally high hyoscyamine content in *Anisodus luridus*, with levels reaching 18.93 mg/g dry weight (DW) in the ovary, significantly higher than those found in the traditional medicinal plant *Atropa belladonna*[189]. From the perspective of the three humors theory of Tibetan medicine, these tropane alkaloid plants possess pungent and bitter tastes with warm properties, acting on *rLung* (wind, རླུང) and *mKhris pa* (bile, མཁྲིས་པ). Their functions include dispelling wind, relieving spasm, analgesia, anesthesia, and anti-motion sickness effects. The principle of combating toxicity with toxicity employing proper processing and pattern differentiation exemplifies Tibetan medicine's sophisticated approach to poisonous plants[190].

4.2 Animal-derived nutritional and traditional medicinal resources

Animal-derived resources on the QTP are closely tied to alpine pastoral livelihoods and ethnic medical practices. These resources must be strictly categorized according to modern regulatory frameworks. Yak products and bee products represent compliant nutritional resources suitable for food development. Traditional medicinal materials derived from wildlife such as deer and musk are excluded from the FMH system due to their protected status and are discussed here solely as a cultural supplement to ethnic medicine. The development of these distinct categories requires separate pathways of evidence and legal compliance.

4.2.1 Yak resources

Yak (*Bos grunniens*) is the most representative domestic animal of the QTP and a core compliant food resource. Yak milk is

nutritionally dense with abundant proteins, lipids, and characteristic fatty acids[191]. Yak meat features high protein and low fat content alongside favorable profiles of essential amino acids, making it ideal for sports-nutrition and low-fat meat products[192]. The intensive utilization of slaughter by-products further improves resource value. Yak bone provides collagen and peptides generated by enzymatic hydrolysis. Studies on yak-bone collagen hydrolysates reveal multiple peptide fragments released under simulated gastrointestinal conditions[193]. Cartilage-derived chondroitin sulfate serves as a common ingredient in joint-health products, and its quality depends heavily on molecular weight and purification processes[194]. Future yak resource development should focus on the coordinated production of collagen peptides, calcium-phosphorus complexes, and high-value functional ingredients rather than generic traditional claims.

4.2.2 *Traditional medicinal animal resources*

Certain animal-derived materials hold a prominent position in TTM systems but lack the legal basis for use as ordinary food. Velvet antler, deer blood, and natural musk are derived from national key protected wild animals. Consequently, they are strictly classified as medicinal resources and are entirely excluded from the FMH framework. Modern pharmacological studies indicate that velvet antler contains peptides, amino acids, and glycosaminoglycans related to tissue repair and immune modulation[195]. Deer antler base also possesses a long history of medicinal use supported by chemical evidence[196]. Natural musk is a glandular secretion historically used in traditional prescriptions, and contemporary research focuses on muscone and related compounds alongside their pharmacological actions[197]. Because wild musk deer and other Plateau deer species face severe ecological threats, the absolute priority for these species is wildlife conservation. These traditional medicinal resources are presented here purely to reflect the historical context of ethnic medicine. Any utilization must rely on legal farming, artificial substitutes, and strict compliance with endangered species regulations rather than commercial food development.

4.2.3 *Honeybees and insect resources*

Honeybees and other resource insects constitute an important compliant category of Plateau food resources. Apis cerana populations on the Plateau demonstrate strong adaptation to high altitude, cold, and strong radiation. Plateau-valley landforms significantly influence their population differentiation and genetic conservation[198, 199]. The value of bee products lies in their potential contributions to nutrient supply, antioxidant activity, and immune regulation. A comprehensive review outlined the biological actions of honey, propolis, and royal jelly while highlighting the need for clearer clinical evidence[200]. For QTP bee products, research should focus on the relationships between specific nectar sources, altitude gradients, and bioactive components. Quality evaluation requires monitoring phenolic compounds in propolis and characteristic fatty acids in royal jelly. This development model can effectively connect ecological protection with sustainable agricultural practices.

Overall, animal-derived resources on the QTP must be developed with clear regulatory boundaries. Compliant food resources such as yak and bee products offer substantial potential for nutritional upgrading and high-value ingredient extraction. Conversely, protected traditional medicinal resources require strict conservation and legal substitution. Future progress depends on establishing sustainable use assessments, connecting traditional efficacy with modern multi-omics evidence, and improving quality traceability to ensure both safety and ecological balance.

4.3 Fungi

Macrofungi represent a vital ecological and economic component, serving as critical drivers of nutrient cycling and acting as a vast repository of bioactive compounds[201]. The geographical distribution of macrofungal resources across the QTP is highly heterogeneous, governed by complex intersections of elevation, localized microclimates, host plant biogeography, and topographical variables[202]. Macrofungi inhabit diverse ecological niches ranging from the high-altitude alpine meadows to the dense, mixed coniferous and broadleaf forests of the Plateau's southeastern peripheries. Generally, macrofungal species richness is negatively correlated with elevation, with forest ecosystems exhibiting higher diversity than grasslands. Moreover, owing to the unique environmental conditions of the QTP, numerous novel species remain undiscovered and await future characterization[201]. For instance, regions such as the Niyang River Basin and the broader Xizang (Tibet) region exhibit exponentially higher fungal density and diversity, with 1,056 macrofungal species identified in a diversity survey[203].

The QTP harbors an abundance of macrofungi with significant edible and medicinal value. Representative taxa include *O. sinensis*, *G. leucocontextum*, *Tricholoma matsutake*, *Morchella* (morels), and various members of the *Boletaceae* family. Notably, the QTP serves as a center of evolutionary radiation for two functional macrofungal groups, morels and boletes[204, 205]. Among them, *G. leucocontextum*, a unique high-altitude species of the *Glucidum* complex, has shown therapeutic potential for repairing pulmonary injury and nephropathy[206, 207]. The main bioactive components of *O. sinensis*, such as cordycepic acid, and cordyceps polysaccharides, protect lung function mainly by inhibiting airway inflammation[208, 209]. These components effectively alleviate chronic cough, asthma, and emphysema, while also serving as an adjuvant therapy for respiratory failure secondary to cor pulmonale[210]. In addition, various proteins abundant in *O. sinensis* have been reported to exert multiple biological effects including anti-fungal infection, anti-virus and immune regulation[211]. The cordyceps polysaccharides and diverse active proteins it contains can activate immune cells to regulate immunity bidirectionally[212, 213]. They are also capable of scavenging oxygen free radicals and alleviating cellular oxidative damage, so as to deliver anti-aging and body-strengthening effects[211, 214]. Additionally, *Tricholoma matsutake*, known locally as "Songrong", is a world-renowned edible fungus that is abundantly found in the mixed pine and oak forests of the southeastern QTP[215].

4.4 Fermented food resources

Fermented foods represent a crucial biological adaptation to the extreme Plateau environment characterized by severe cold and hypoxia. Traditional dietary wisdom translates into modern functional food evidence[216] and serves as a key lens for interpreting regional ecological adaptation[217]. Epidemiological evidence highlights the systemic health impact of this integrated dietary pattern. Recent population studies link habitual consumption of Tibetan staples to specific metabolic syndrome indicators[218]. Furthermore, distinctive Plateau diets show significant relevance in high-altitude polycythemia research[219], proving that traditional claims of cold adaptation have tangible metabolic bases.

Highland barley wine serves as a primary fermented cereal resource. Microbiome investigations reveal that co-fermentation utilizing specific lactobacilli and yeasts improves the nutritional profile and lipid-lowering activity[220]. The dynamic succession of the microbial community directly dictates flavor formation[221] and yields complex aroma compounds characteristic of authentic Plateau liquor[222].

Tibetan yogurt and fermented yak milk act as remarkable natural probiotic reservoirs. Metagenomic profiling identifies rich populations of indigenous lactic acid bacteria and yeasts varying significantly across altitudes[223]. Products like naturally fermented kurut harbor a chemically and microbiologically complex ecosystem[224]. Yak milk fermentation effectively merges animal-derived nutrients with Plateau-adapted microorganisms[191]. Similarly, the dried cheese Qula functions as a vital carrier of resilient microbial strains capable of surviving severe gastrointestinal stress[225]. Related microbiome studies on Tibetan kefir demonstrate that these communities protect intestinal barrier function and modulate gut flora to prevent environmental liver injury[226].

Butter tea is different from the other products because the final beverage is not a fully fermented food. It is usually prepared from tea infusion, yak butter or dairy fat, salt, and sometimes milk. Nevertheless, it belongs to a broader fermented dairy and tea dietary complex. Its functional interpretation should therefore be cautious: The warming effect traditionally attributed to butter tea may be explained by hot fluid intake, fat-derived energy, salt replacement, and improved palatability in cold environments rather than by a single active ingredient.

The tea fraction is still relevant to gut regulation. Wang *et al.*[227] summarized that tea polyphenols interact with gut microbiota and are transformed into metabolites with biological activity. Sima *et al.*[228] further discussed two-way interactions between tea polyphenols and gut microbiota in the context of atherosclerosis. He *et al.*[229] found that Tibetan tea reduced high-fat-diet-induced obesity and modulated gut flora in mice. Zhu *et al.*[230] showed that *Bacillus licheniformis*-based intensive fermentation of Tibetan tea increased bioactive compounds, improved antioxidant capacity, and reinforced the intestinal barrier in mice. Cheng *et al.*[231] demonstrated that gut bacteria such as *Bacteroides* utilize dietary polysaccharides and produce short-chain fatty acids beneficial to gut health. These mechanisms help explain how tea-related components in butter tea may participate in intestinal microbial metabolism.

Across these foods, probiotic and prebiotic mechanisms are interconnected. Gao *et al.*[232] emphasized that probiotic effector molecules, including metabolites, cell-wall structures, and exopolysaccharides, are central to gut-health modulation. Li *et al.*[233] further showed that capsular polysaccharides of probiotics contribute to immunomodulatory functions. In Tibetan foods, these mechanisms may be supplied by live lactic acid bacteria and yeasts in fermented dairy, β-glucan and phenolics from Qingke, and tea polyphenols from butter tea. Together, they may support intestinal barrier integrity, beneficial microbial enrichment, short-chain fatty acid production, energy metabolism, and inflammation regulation.

In conclusion, Tibetan traditional fermented foods form a food-microbe-host-environment system adapted to high-altitude life. Highland barley wine contributes fermented cereal metabolites; Tibetan yogurt and Qula provide dairy proteins, minerals, and microbial resources; and butter tea offers heat, energy, salt, and tea-derived polyphenols. Future research should avoid general claims and instead focus on strain-level identification, safety assessment, standardized processing, metabolomics, metagenomics, and controlled human intervention trials. Only through this evidence chain can traditional concepts such as gut regulation, warming the middle, and Plateau adaptation be translated into modern functional food science.

5 Functional efficacy and evidence hierarchies

TTM systems and regional Plateau dietary cultures have long utilized specific biological resources to counteract extreme environmental constraints. The figure provides a comprehensive overview of the functional efficacy and underlying mechanisms of core food and medicine homology resources from the QTP (Fig. 4). Modern pharmacological research seeks to validate these traditional applications by exploring shared molecular targets. However, current functional claims must be strictly evaluated according to established evidence hierarchies. Most mechanistic

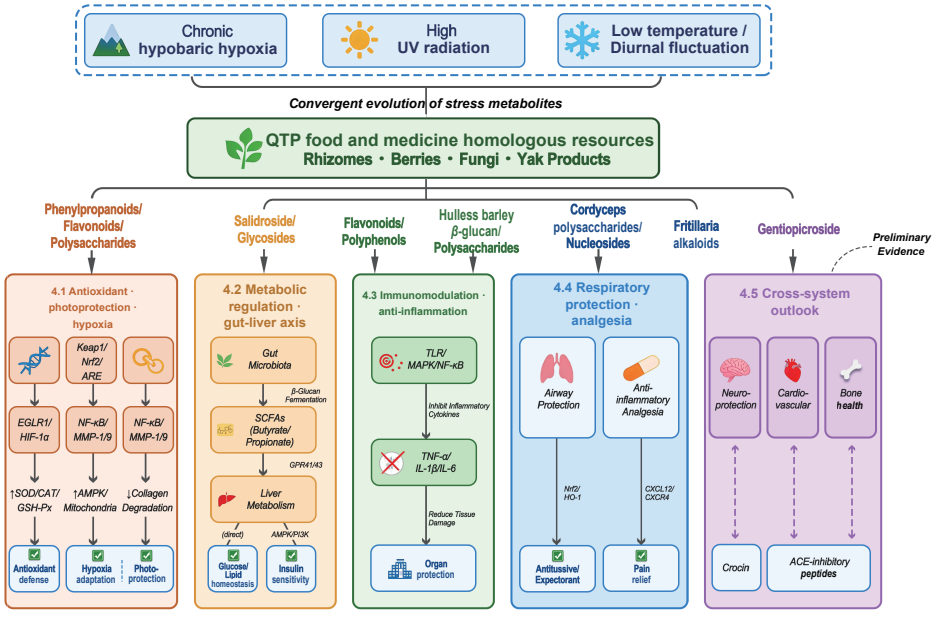


Figure 4 Comprehensive overview of the functional efficacy and underlying mechanisms of core food and medicine homology resources from the QTP.

insights discussed below originate from lower-tier evidence involving *in vitro* assays and animal models, whereas high-quality human clinical and epidemiological evidence remains critically scarce.

5.1 Oxidative stress resistance, photoprotection, and hypoxia adaptation

High-altitude survival necessitates robust cellular redox homeostasis. Pre-clinical studies predominantly utilizing murine models and cultured cells demonstrate that phenylpropanoids, flavonoids, and polysaccharides from alpine resources activate the nuclear factor erythroid 2-related factor 2 (Nrf2)/heme oxygenase-1 (HO-1) antioxidant axis. These metabolites up-regulate endogenous antioxidant enzymes and suppress lipid peroxidation[49, 50, 234-236]. Specifically, *in vitro* cardiomyocyte and neuronal models show that salidroside and tyrosol enhance cellular antioxidant capacity *via* the Kelch-like ECH-associated protein 1 (Keap1)/Nrf2 cascade[234, 237]. Similarly, sea-buckthorn derivatives trigger Nrf2-mediated HO-1 expression to mitigate oxidative injury in isolated vascular and dermal tissues[238, 239].

Regarding hypoxia adaptation, cell-based and rodent experiments indicate that bioactive compounds stabilize the hypoxia-inducible factor-1α (HIF-1α) signaling pathway. Salidroside modulates the egl-9 family hypoxia inducible factor 1 (EGLN1)/HIF-1α axis to rescue cultured cardiomyocytes from hypoxia-induced apoptosis[175]. Animal studies further reveal that *Cordyceps*-derived polysaccharides induce HIF-1α targets to improve pulmonary vascular remodeling and skeletal muscle endurance[240-242].

Photoprotective effects are largely supported by *in vitro* assays using keratinocytes and fibroblasts, where flavonoid extracts suppress matrix metalloproteinases and inflammatory signaling[243]. While these preclinical findings provide a mechanistic rationale for traditional uses, robust clinical validation for acute mountain sickness prophylaxis or human skin protection remains restricted to a few small-scale trials[234].

5.2 Metabolic regulation and the gut-liver axis

Plateau dietary staples modulate systemic metabolism primarily through enterohepatic circulation and gut microbiota interactions. Animal experiments confirm that soluble dietary fibers such as hulless barley *β*-glucan delay gastric emptying and modulate short-chain fatty acid production, which subsequently regulates hepatic gluconeogenesis in murine models[244, 245]. Colored barley polyphenols also enhance insulin sensitivity *via* the AMP-activated protein kinase (AMPK) pathway in laboratory rodents[246].

Pre-clinical *in vivo* studies demonstrate that Plateau root and berry polysaccharides undergo selective colonic fermentation to enrich beneficial microbiota[247]. Furthermore, rodent models fed fermented yak-milk products exhibit reinforced intestinal barriers and reduced systemic inflammation[248-250].

Despite these promising animal data, high-quality human epidemiological and clinical intervention studies are lacking. It remains unverified whether the metabolic benefits observed in lowland rodent models translate effectively to chronically hypoxic human populations.

5.3 Immunomodulation, anti-inflammatory activity, and organ protection

Evidence for immunoregulatory and organ-protective activities relies heavily on macrophage cell lines and induced animal models. In lipopolysaccharide-stimulated macrophages, high-altitude fungal polysaccharides inhibit the nuclear translocation of nuclear factor kappa B (NF-κB) and reduce inflammatory cytokine secretion[250, 251]. Rodent models of inflammation demonstrate that glycosides from Plateau herbs suppress cyclooxygenase-2 expression and alleviate pain *via* specific kinase pathways[252].

Gut-liver axis protection is similarly supported by pre-clinical *in vivo* research. Fungal and fern-root polysaccharides attenuate hepatic steatosis and oxidative stress in mice[251, 253-255]. Yak-milk peptides also protect murine livers by enhancing mucosal barriers and restoring protein-energy status[250, 256, 257].

A major limitation in this domain is the lack of chemical standardization. Without rigorous chemotaxonomic characterization for varying species, extrapolating these pre-clinical results to clinical efficacy is highly unreliable[258, 259].

5.4 Respiratory protection and analgesic applications

Target-specific pharmacological studies in animals support the traditional empirical use of certain botanicals for respiratory and musculoskeletal conditions. Murine models of ammonia-induced cough reveal that isosteroidal alkaloids reduce cough frequency while protecting airway macrophages against oxidative stress *in vitro*[260]. Animal models of arthritis show that specific glycosides and coumarin derivatives block pathological angiogenesis and down-regulate inflammatory pathways[178, 252]. Although these pre-clinical studies align with traditional wind-dampness remedies, human clinical pharmacokinetic and efficacy data remain completely absent.

5.5 Emerging cross-system bioactivities and evidence limitations

Preliminary pre-clinical investigations suggest additional cross-system biological activities. Rodent and cell-based assays indicate that specific Plateau compounds modulate neurotransmitter systems for potential neuropsychological benefits[261, 262]. *In vitro* biochemical assays demonstrate that yak casein peptides exhibit angiotensin-converting enzyme (ACE)-inhibitory properties, while bone-derived peptides stimulate osteoblast proliferation[263-266]. Dermal barrier maintenance by Plateau flavonoids is similarly supported exclusively by cell culture models[267].

Overall, an analysis of the evidence hierarchy reveals a critical shortfall in current research. The overwhelming majority of efficacy claims stem from lower-tier evidence including *in vitro* assays and acute rodent studies. Higher-tier evidence derived from well-designed human clinical trials and large-scale epidemiological cohorts is fundamentally missing. Future research must prioritize authenticated materials, clarify dose-response relationships, and execute controlled human trials to properly translate these traditional cultural resources into evidence-based functional interventions.

6 Theoretical implications and cultural heritage of QTP FMHR

6.1 The core theoretical system of FHM in Tibetan medicine

Tibetan medicine is a traditional medical system shaped by the unique natural and cultural environment of the QTP. It merges

indigenous Tibetan healing experience with elements drawn from Chinese, Indian, and Arabic medicine, forming a comprehensive theoretical framework and a distinctive ethnomedical heritage. Central to this framework is the principle of FMH, which holds that diet and medicine share a common origin and nature. Dietary therapy constitutes a core component of Tibetan medical theory and stands as an essential treatment modality among the four classical therapeutic principles, including "diet, lifestyle, medication, and external therapies". This foundational concept underpins the Tibetan medical understanding of life processes, disease pathogenesis, and strategies for prevention and treatment[268].

The philosophy of "the five elements" and "the three humors" provide the theoretical and pathological basis for FMH[269]. According to the five-element doctrine, all phenomena, including food and medicine, arise from "earth, water, fire, wind, and space", and thus lack an absolute boundary, establishing the elemental unity. The three-humor theory attributes health to the dynamic equilibrium of "Long, Chiba, and Peigen"; disease results from their imbalance. Consequently, the primary function of both food and medicine is therefore to correct humoral disturbances, restore balance, and preserve health, offering a precise pathological rationale for dietary intervention.

The systematic codification of this knowledge appears in the "Four Tantras", which documents over 200 dietary items, prioritizes diet as the foremost treatment principle, and articulates the key theoretical categories of "six tastes, eight properties, and seventeen effects", standardizing the classification and indication-based application of food and medicinal substances[270]. Subsequent scholarship, enriched by texts such as the *Eight Branches and the Crystal Mirror of Materia Medica*, further refined the framework of Tibetan dietary medicine. Grounded in these classics, Tibetan physicians developed a detailed system for applying foods, precisely categorizing grains, oils, vegetables, fruits, and spices according to their properties and therapeutic indications. The system also recognizes the nutritive essence extracted from food as the core substance of human metabolism, underpinning growth, development, and the generation of vital constituents, a concept strikingly congruent with the principles of modern nutritional principles[268, 271]. In practice, the theory prioritizes prevention and emphasizes constitution-, age-, and disease-specific dietary prescriptions, anticipating key tenets of contemporary precision nutrition.

Taken together, this theoretical framework encapsulates the millennia-old wisdom of Tibetan medical culture and provides distinctive intellectual resources and profound cultural depth for functional food development[272], dietary management of chronic diseases, and the advancement of precision nutrition.

6.2 Interpretation of Tibetan Plateau FMHR from the perspective of TCM theory

TCM provides a systematic theoretical framework for interpreting the functional value of FMHR on the QTP. While Tibetan medicine has developed its own sophisticated understanding of Plateau health preservation, TCM explains these resources mainly through the concepts of nature and flavor, meridian tropism, tonification and dispersion, adaptation to regional constitution, and correspondence between environment and therapeutic properties. In this framework, the extreme Plateau environment, characterized by cold climate, hypoxia, intense UV radiation, large diurnal temperature variation, and relatively dry air, is not merely a geographical background, but a key ecological force shaping both the material composition and traditional efficacy of local FMHR.

Both traditional systems acknowledge that prolonged exposure to severe cold and hypoxia depletes vital energy and impairs internal organ functions. Through a supplementary TCM lens, local ecological adaptations are frequently interpreted as warming and tonifying actions that complement Tibetan elemental theories. For example, yak derived products are traditionally valued for supporting the constitution of high-altitude populations by providing high-quality proteins and lipids. Similarly, widespread alpine botanicals such as Rhodiola species demonstrate robust anti fatigue and stress adaptive activities[273]. Sea buckthorn provides well documented antioxidant and tissue protective properties[274]. While Tibetan medicine categorizes these resources based on elemental qualities to pacify specific humors, a supplementary TCM perspective aligns these effects with supplementing vital energy and resolving environmental stressors, reflecting a shared empirical understanding of physiological adaptation.

Fungal resources also illustrate how TCM translates ecological uniqueness into therapeutic meaning. *O. sinensis*, formed through the interaction between fungus and insect larvae in alpine meadow ecosystems, is traditionally described as nourishing both lung and kidney, relieving cough and dyspnea, replenishing essence, and strengthening the body. These functions correspond to its modern reported immunomodulatory, anti-inflammatory, anti-fatigue, respiratory protective, and endocrine-regulating effects[275]. From the TCM perspective this dual lung-kidney attribution is particularly meaningful for Plateau populations, because respiration, oxygen utilization, essence storage, and physical endurance are closely interrelated in traditional theory.

Grain and fermented resources can be interpreted through the TCM concept of spleen–stomach regulation as the foundation of acquired constitution. Highland barley, a staple crop of the Plateau, is rich in β-glucan, dietary fiber, polyphenols, and resistant starch. Traditionally, cereal foods strengthen the spleen, harmonize the stomach, and sustain *qi* production. Modern studies on cereal β-glucans and dietary fibers demonstrate their roles in improving glycemic control, lipid metabolism, gut microbiota composition, and short-chain fatty acid production[276]. Tibetan yogurt, milk residue, butter tea, and barley wine further embody the transformation of food properties through fermentation. In TCM terms, fermentation can "mature" or "harmonize" raw materials, improving digestibility and moderating cold or difficult-to-digest properties; in modern terms, fermentation introduces probiotics, bioactive peptides, organic acids, and microbiota-modulating metabolites.

TCM also emphasizes regional adaptation, often summarized as the principle that local resources are suited to local people and local climates. This idea offers a valuable interpretive lens for Plateau FMHR: Plants and animals that survive high cold, hypoxia, and UV stress often accumulate protective secondary metabolites, dense nutrients, or specialized structural components. These ecological adaptations may partly explain why Plateau resources are frequently associated with anti-fatigue, antioxidative, warming, nourishing, lung-protective, and immune-supporting functions. Contemporary systems biology and network pharmacology further support the TCM view that multi-component natural products may act through multi-target, multi-pathway regulation rather than single-compound pharmacology[277, 278].

Overall, TCM theory enriches the interpretation of QTP FMHR

by linking ecological environment, material composition, human constitution, and functional application into an integrated explanatory system. This theoretical perspective does not replace modern phytochemistry, nutrition, or pharmacology; rather, it provides a culturally rooted and clinically oriented framework for resource classification, functional positioning, product development, and personalized dietary-health applications.

6.3 Medicinal wisdom in folk customs and daily diet

The theory of FMH in Tibetan medicine centers on the balance of the "three humors"[78]. The *Four Medical Classics* systematically categorizes ingredients based on their six flavors, eight properties, and seventeen effects. TCM theory elucidates the efficacy and positioning of food and medicine resources in high-altitude regions from the perspectives of the four properties, five flavors, and the ascending and descending actions along meridians[279, 280]. The principles of these theoretical frameworks find concrete and vivid manifestations in the daily dietary practices of the Tibetan people. The dietary customs of Tibetan residents seamlessly integrate "food and medicine" forming a pragmatic health preserving system characterized by the four-dimensional synergy of "taste, efficacy, physique, and environment"[281, 282]. Based on food preferences and functional orientations, this system can be classified into five core types: A preference for drinking butter tea, consuming fermented dairy products, drinking Tibetan barley wine, using spicy and warm condiments, and having highland barley *tsampa* as the staple food.

The custom of consuming butter tea embodies medicinal wisdom in warming and invigorating gas to protect against cold and hypoxia. Butter tea is an emulsion of brick tea (bitter-sweet, cold), yak butter (sweet, warm), and salt (salty, cold). Their combination achieves salty flavor guiding to the kidneys, warm nature dispelling external cold, and bitter cold clearing internal heat, collectively contributing to cold resistance, hypoxia tolerance, and alertness[283]. Repeated whisking ensures thorough emulsification, which delays tea polyphenol oxidation and enhances the bio-availability of fat-soluble components[284, 285]. Some research has confirmed the significant functional activity of yak butter and its by-products[286]. In addition, compound drinks based on Tibetan tea have been proven to prevent high-fat diet-induced obesity and improve blood lipids and oxidative stress levels by regulating gut microbiota[287].

The tradition of consuming fermented dairy products embodies medicinal wisdom in using sour and warm properties to invigorate the spleen and regulate intestinal function[288]. Fermented products such as Tibetan yogurt and milk residue, often consumed with honey or *P. anserina*, are used to alleviate pediatric dyspepsia, constipation in the elderly, and common bloating among high-altitude populations. Dong *et al.*[289] performed whole-genome sequencing of *Lactobacillus plantarum* CGMCC 8198, isolated from traditional yak yogurt in Naqu, Tibet, and revealed multiple functional gene clusters associated with antioxidant activity, stress response, and intestinal adhesion, thereby offering a molecular basis for the probiotic properties of this strain. Additionally, the *Lactiplantibacillus plantarum* EA3 strain, isolated from traditional fermented yak yogurt, exhibits excellent antioxidant activity and can withstand 4 mmol/L H_2O_2 oxidative stress. Notably, no virulence factors or hemolytic activity were detected in its genome[290]. Furthermore, functional peptides generated through the degradation of yak casein demonstrate multiple bio-activities, including ACE inhibition, antibacterial, and anti-inflammatory effects[291]. Collectively, these findings suggest that probiotics and their metabolites in traditional fermented dairy products underpin the scientific rationale behind the concept of "sour, warm, and spleen-strengthening".

The custom of consuming Qingke liquor embodies medicinal wisdom in using its pungent and warm properties to promote blood circulation, unblock meridians, and refresh the mind[292, 293]. Qingke liquor is fermented from hulless barley, producing low alcohol and small-molecule active substances[294]. From the perspective of flavor and nature, it is pungent (dispersing and moving) and warm (promoting warmth and unobstruction), thus facilitating *qi* and blood flow, warming the stomach, dispelling cold, and invigorating blood circulation[295]. Highland barley is rich in β-glucan, and *in vitro* fermentation studies have confirmed its prebiotic potential by enhancing gut microbiota diversity, increasing short-chain fatty acids, and lowering pH[294]. However, the complex interplay between ethanol's vasodilatory effects and barley polyphenols' antioxidant activities should be noted. Current evidence cannot solely attribute Qingke liquor's health benefits to β-glucan, and future research should distinguish between the independent effects of alcohol consumption and barley intake.

The custom of favoring spicy and warm seasonings embodies medicinal wisdom in using pungent warmth to dispel cold and dampness. Given the cold and humid Plateau climate, spicy and warm foods are widely used as meal accompaniments or in stewed meat. The pungent flavor promotes *qi* flow and induces slight perspiration to expel external cold-damp pathogens[296]. This prevention through diet aligns with the TCM theories that "pungent and sweet flavors disperse to generate yang" and "pungent dispersion dispels dampness." Ethnobotanical surveys in Tibetan communities have documented approximately 50 wild edible plants used as seasonings or health-promoting foods, among which Sichuan peppercorns and various wild *Allium* species serve dual functions of seasoning and warming the interior to dispel cold.

The custom of consuming highland barley *tsampa* as a staple food embodies medicinal wisdom in nourishing the stomach, alleviating hunger, and fortifying the body. *Tsampa* is made from highland barley (sweet flavor, neutral nature), making it suitable for prolonged consumption to sustain health. It is often blended with butter, milk dregs, and *P. anserina* powder to form a "strength-enhancing meal" used for postpartum or post-illness recovery. *P. anserina* (Tibetan "Chuoma") plays a key pharmacological role in this blend. A systematic review identified 154 compounds in *P. anserina*, with polysaccharides and triterpenes as the primary active constituents, exhibiting antioxidant, immunomodulatory, hematinic, and hepatoprotective effects[170]. Finally blending tsampa with *P. anserina* forms a staple meal designed to nourish the stomach and fortify the body where the abundant polysaccharides provide immune support[170]. Together these dietary preferences form an integrated knowledge system rooted in alpine ecology offering an irreplaceable cultural reference for resource development. Fig. 5 illustrates the multiple theoretical foundations of the QTP and Chinese FMHR.

7 Development, conservation and sustainable utilization of FMHR on the QTP

7.1 Current development status: From traditional use to evidence-based industrialization

The FMHR of the QTP have long been embedded in local dietary culture, ethnic medical systems, and environmental

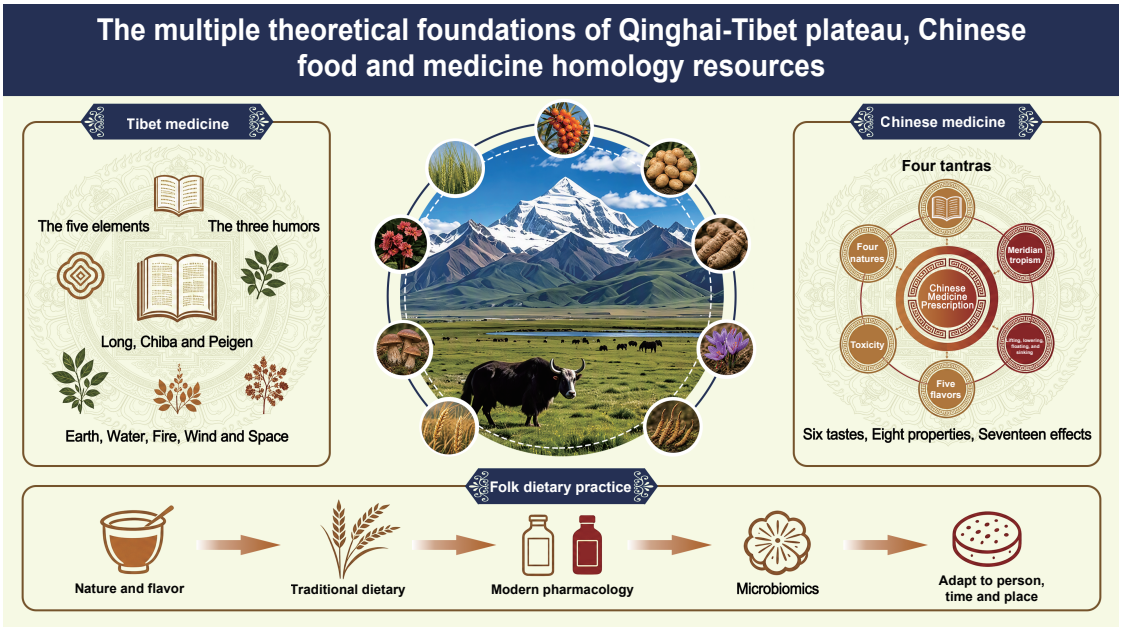


Figure 5 Multiple theoretical foundations underlying food and medicine homology resources on the QTP.

adaptation strategies. In Tibetan and other highland communities, many Plateau plants have traditionally been consumed both as foods and as medicinal materials, especially for alleviating fatigue, improving hypoxia tolerance, supporting digestion, and maintaining general health under high-altitude conditions[182]. Fig. 6 further summarizes the practical application and sustainable development mode of QTP FMHR. This long-standing pattern of "daily nourishment combined with preventive therapy" provides the cultural and practical foundation for the modern development of FMHR on the Plateau[182].

At present, the development of these resources has entered a transitional stage from empirical use to evidence-based utilization. Ethnobotanical investigations from Tibetan areas have documented extensive local knowledge concerning wild food and medicine homology plants, indicating that the Plateau still preserves abundant traditional experience in the collection, processing, seasonal use, and health functions of native species[297]. Such surveys are important because they not only identify candidate species for further development, but also reveal that many food and medicinal uses are deeply linked to ecological seasonality, local health needs, and high-altitude living conditions[297].

In recent years, some representative Plateau resources have begun to accumulate modern pharmacological, nutritional, and even preliminary clinical evidence, thereby accelerating their transformation into functional foods, nutraceuticals, and value-added health products[297]. A typical example is Tibetan turnip (*Brassica rapa L.*), a traditional edible crop widely used on the Plateau. Human research has shown that short-term consumption of Tibetan turnip products improved indices related to hypoxia tolerance, oxygen utilization, antioxidant capacity, and cardiopulmonary adaptation in healthy participants, suggesting

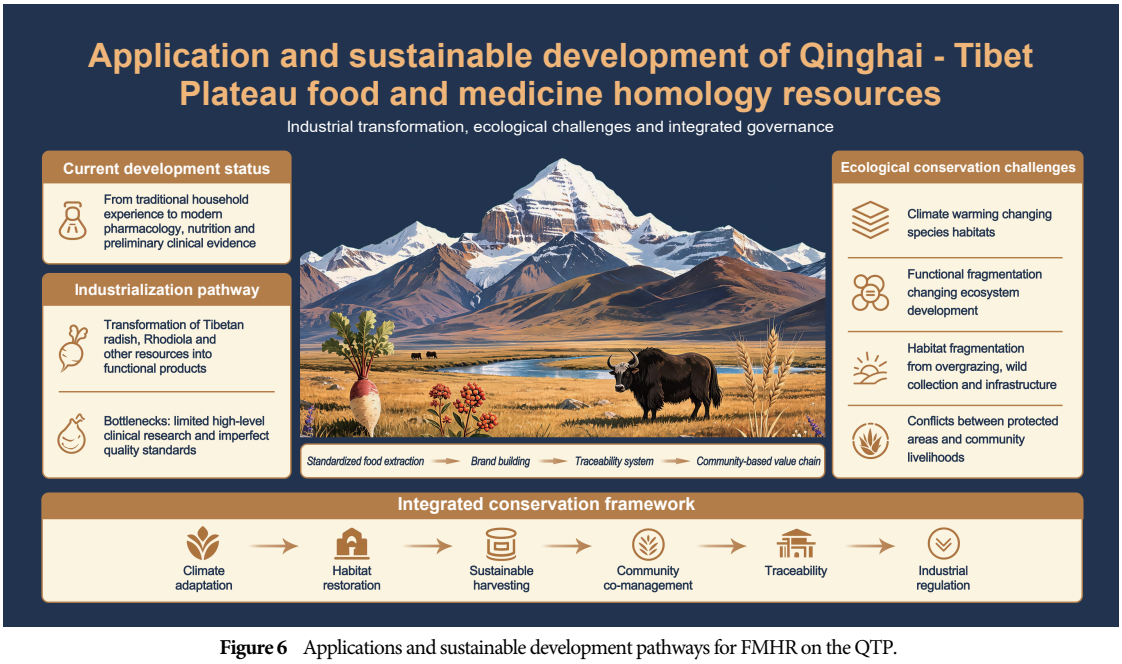


Figure 6 Applications and sustainable development pathways for FMHR on the QTP.

that certain traditional highland foods may have measurable physiological benefits beyond basic nutrition[298]. Further mechanistic studies and reviews have also linked Tibetan turnip to anti-hypoxia, anti-fatigue, immunomodulatory, and neuroprotective activities, which has strengthened its potential for functional food development[299].

Another important development direction concerns *Rhodiola* species, especially *Rhodiola crenulata*, which occupy a significant position in Tibetan medicine and high-altitude health products[182]. Modern studies have reported anti-fatigue, anti-hypoxia, and mitochondrial protective effects for *Rhodiola crenulata*, while recent evidence syntheses further support its relevance for high-altitude disease intervention and adaptation-related products[79]. However, unlike Tibetan turnip, the commercialization of Rhodiola has also exposed major sustainability problems. Trade studies have shown that rising market demand, species substitution, adulteration, and continued dependence on wild collection have created pressures on resource authenticity, quality control, and long-term conservation[300]. Therefore, *Rhodiola* represents both the opportunity and the challenge of industrializing Plateau FMHR.

More broadly, current research increasingly frames QTP resources within the concept of geo-authentic Tibetan medicine and highland functional foods. Recent reviews emphasize that many Plateau plants derive their distinctive value from the combined effects of altitude, low-oxygen environments, strong UV radiation, and local ecological conditions, which may shape their metabolite accumulation and bioactivity profiles[182]. From an industrial perspective, this means that the development of FMHR is no longer limited to crude raw material trade; it is increasingly associated with origin-based branding, quality evaluation, bioactive component identification, and the development of standardized extracts, capsules, beverages, and health-oriented food products[301].

At the same time, the evidence base supporting industrialization is still uneven. On the one hand, review articles have highlighted the rapid expansion of pharmacological studies on Tibetan materia medica and high-altitude plants, especially in areas such as anti-inflammatory activity, antioxidant action, anti-fatigue effects, metabolic regulation, and hypoxia adaptation[297]. On the other hand, much of the existing evidence remains concentrated in *in vitro* assays, animal experiments, or general pharmacological screening, while robust clinical trials, dose-response studies, processing standardization, and long-term safety evaluation are still limited for most species[297]. Thus, the current industrialization pathway is better described as evidence-informed rather than fully evidence-validated.

From an industrial perspective, the development model on the QTP is shifting from raw material export to deep processing, although macroscopic statistical data for the "FMH" sector remains embedded within broader agricultural and Tibetan medicine statistics. Recent regional data from the past five years illustrates this transition. For example, Qinghai Province, a core region of the QTP, has vigorously developed characteristic biological industries. The cultivation area for key Plateau FMHR, such as *Hippophae rhamnoides* (seabuckthorn) and *L. ruthenicum* (black goji berry), has expanded significantly, with ecological planting areas exceeding hundreds of thousands of hectares to alleviate the pressure on wild reserves. Correspondingly, product types have diversified. Major local and national enterprises have moved beyond traditional dried herbs to develop over a hundred product categories, including standardized flavonoid extracts, supercritical CO2 extracted seed oils, freeze-dried powders, and functional beverages.

Despite these advances, the current development status of FMHR on the QTP can be summarized as a progression from traditional household use toward early-stage industrialization. Although iconic resources have shown promising market value, the sector faces distinct bottlenecks. Quantitative data on wild reserves for alpine species (e.g., wild Rhodiola and Fritillaria) show declining trends in easily accessible areas due to overharvesting, prompting governments to restrict wild collection. Future industrial upgrading depends on balancing scientific validation with sustainable agricultural practices. Enterprises must establish traceable supply chains based on artificial cultivation rather than wild foraging, ensuring that traditional Plateau knowledge is transformed into credible, safe, and ecologically responsible products.

7.2 Conservation challenges: Climate sensitivity, human disturbance and ecological governance

Although FMHR on the QTP have considerable ecological, cultural, and industrial value, their conservation faces increasing pressure from climate change, intensified human disturbance, and the complexity of ecological governance. Compared with lowland ecosystems, alpine ecosystems on the Plateau are characterized by low temperature, short growing seasons, shallow soils, slow community recovery, and high environmental sensitivity. These features make many food and medicine homology resources highly vulnerable once their habitats are disturbed or their population regeneration is disrupted[302].

Climate sensitivity is one of the most fundamental challenges. Experimental warming studies on the Tibetan Plateau have shown that rising temperature can rapidly reduce alpine plant species richness and alter plant community composition, indicating that Plateau vegetation is highly responsive to even short-term warming[303]. Follow-up field research further suggested that warming, rather than grazing alone, can reduce rangeland quality by changing forage composition and ecosystem function[303]. For FMHR, this implies that climate change may not only affect species distribution, but also change the ecological conditions that support the accumulation of bioactive compounds. Many Plateau food and medicine homology plants are adapted to cold, hypoxic, high-radiation environments; therefore, warming, altered precipitation, permafrost thaw, and soil moisture decline may shift suitable habitats upward or fragment them across narrow alpine zones[303].

The impacts of climate change are also closely linked with grassland productivity and ecosystem stability. Remote-sensing and ecological studies have shown that alpine grassland productivity on the QTP is shaped by nonlinear interactions between climatic factors and human activities, rather than by a single driver[304]. This complexity is especially important for resource conservation because some areas may experience vegetation greening, while others suffer degradation, desertification, or community simplification. Such spatial heterogeneity makes it difficult to apply uniform conservation measures across the Plateau. For species with narrow ecological niches, limited dispersal ability, or slow regeneration, even localized habitat degradation may lead to long-term population decline.

Human disturbance constitutes the second major conservation challenge. The QTP is both an ecological security barrier and a

living landscape for pastoralism, agriculture, medicinal plant collection, tourism, transportation, and resource extraction. A major review of rangeland degradation on the Plateau emphasized that degradation is driven by multiple interacting factors, including grazing pressure, climate variability, land-use change, policy transitions, and local socioeconomic conditions[302]. Overgrazing can reduce vegetation cover, weaken root systems, compact soils, and accelerate erosion, thereby damaging habitats where many food and medicine homology plants occur. In alpine meadows, overgrazing has been shown to trigger soil cracking, which can further accelerate severe meadow degradation and reduce the resilience of plant communities[305].

Wild harvesting creates a more direct pressure on high-value FMHR. Driven by market demand, collectors often target roots, bulbs, rhizomes, whole plants, or fungal complexes, many of which are slow-growing and difficult to regenerate after destructive harvesting. Trade-related research on Himalayan medicinal plants such as *Fritillaria cirrhosa* and *Nardostachys jatamansi* shows that market demand, household livelihood strategies, accessibility, and trade networks strongly shape harvesting behavior, meaning that conservation cannot be separated from local economic incentives[306]. Similar problems have been reported in the trade of Chinese *Rhodiola* species, where increasing commercial demand, species substitution, and dependence on wild collection raise concerns about authenticity, resource depletion, and long-term sustainability[300]. These cases are highly relevant to the QTP because many representative food medicine resources, including *Rhodiola*, *Fritillaria*, *Cordyceps*, and other alpine medicinal plants, are located in fragile habitats and are economically attractive.

Another important issue is that human disturbance often produces cumulative ecological effects. Grazing, road construction, mining, tourism, settlement expansion, and seasonal harvesting may individually appear limited, but together they fragment habitats and increase access to previously remote resource areas. Once roads and market channels expand, the cost of collecting wild resources declines, which may intensify harvesting pressure. At the same time, trampling, digging, waste disposal, and disturbance to soil crusts can damage alpine vegetation and delay natural recovery. Because many Plateau ecosystems have slow nutrient cycling and low productivity, their restoration after disturbance is often much slower than in low-altitude ecosystems[302].

Ecological governance and spatial conservation strategies have therefore become central to sustainable utilization. In response to declining wild reserves, the Chinese government has implemented large-scale conservation programs over the past decade. The QTP now features an extensive network of protected areas. According to recent assessments, by the end of 2020, there were 330 natural protected areas on the QTP, covering 88.34 million hectares and accounting for 34.20% of the Plateau's total landmass[307]. Furthermore, the establishment of the Sanjiangyuan National Park (covering over 190,000 square kilometers) and the Qilian Mountain National Park has strictly zoned core conservation areas where commercial harvesting of wild food and medicine homology plants is entirely prohibited.

These spatial protection measures have yielded measurable ecological benefits. Remote sensing and field monitoring confirm that vegetation coverage in core protected areas has steadily recovered and provided stable refuges for wild populations of threatened FMH species. At the same time, formal protected-area coverage cannot completely safeguard resources located in peripheral or multi-use zones. Various human pressure factors including grazing intensity, road density, and local economic dependence indicate that conservation effectiveness varies significantly across different regions and relies heavily on local management capacity[308]. This situation is especially critical for high-value species like *Cordyceps sinensis* and *Rhodiola* because they primarily grow in alpine meadows under the joint management of local pastoral communities.

Effective ecological governance should also recognize the role of local communities and customary institutions. Research on rangeland management on the QTP shows that market-based grazing land transfers interact with customary institutions, suggesting that local rules, household decisions, and community-level arrangements can significantly influence resource management outcomes[309]. For FMHR, community participation is especially important because local residents often possess detailed knowledge of species distribution, harvest timing, processing methods, and regeneration patterns. Excluding communities from conservation may weaken compliance, whereas participatory management can align biodiversity protection with livelihood security.

In this context, conservation of food and medicine homology resources should follow an integrated strategy. First, climate-sensitive species and habitats should be identified through long-term monitoring, species distribution modeling, and field surveys. Second, destructive harvesting should be replaced by rotational collection, quota management, non-destructive harvesting techniques, and artificial or semi-wild cultivation where feasible. Third, protected-area management should be linked with ecological compensation, community co-management, traceability systems, and market regulation. Finally, industrial development should be conditioned on resource sustainability: Products derived from wild resources must have clear origin, harvest standards, population monitoring, and quality-control systems. Without these safeguards, industrialization may intensify ecological pressure rather than promote sustainable development[306].

Overall, the conservation challenges facing FMHR on the QTP are not limited to biological vulnerability. They arise from the interaction of climate warming, fragile alpine habitats, livelihood dependence, market demand, and governance capacity. Therefore, future conservation should shift from passive protection of individual species toward an integrated framework that combines climate adaptation, habitat restoration, sustainable harvesting, community participation, protected-area effectiveness assessment, and evidence-based industrial regulation. Only under such a framework can the Plateau's FMHR be conserved as both biological heritage and sustainable foundations for future health-oriented industries.

8 Conclusions and perspectives

The QTP alpine ecosystem harbors a unique repertoire of food and medicine homology resources shaped by extreme environmental conditions such as high altitude, intense UV radiation, and hypobaric hypoxia. Long-term adaptive evolution under these stresses promotes the accumulation of diverse secondary metabolites including flavonoids, polyphenols, and terpenoids. While these compounds constitute the material basis for their remarkable antioxidant, anti-hypoxia, and anti-fatigue activities, current pharmacological research heavily relies on preliminary *in vitro* and animal models. The precise molecular mechanisms mediating these health benefits remain insufficiently

elucidated, particularly regarding their multi-target synergistic effects, *in vivo* metabolic trajectories, and interactions with human gut microbiota.

Despite their expanding applications, the industrialization of these Plateau resources faces systemic bottlenecks across the entire value chain. Ecologically, changing climate conditions coupled with prolonged unsustainable harvesting practices severely threaten wild populations and germplasm diversity. Agronomically, the absence of standardized processing practices and immature artificial cultivation techniques lead to significant fluctuations in raw material quality. Furthermore, a critical gap exists in clinical translation. The current literature lacks well-designed, large-scale human clinical trials to validate the safety and efficacy of these resources, which restricts the transition from traditional empirical knowledge to modern evidence-based medical and nutritional applications. These limitations collectively constrain the development of high-value products and the sustainable utilization of Plateau resources.

To overcome these challenges and elevate the research impact, future development must adopt a multidimensional framework integrating ecological conservation with clinical translation. First, establishing rigorous raw material quality standards and advancing biomimetic cultivation technologies are fundamental to ensuring a consistent resource supply while preventing the depletion of wild populations. Second, research priorities must shift toward conducting robust clinical trials to provide solid scientific evidence for health claims. Guided by TTM knowledge, the integration of multi-omics and artificial intelligence will accelerate the discovery of bioactive compounds and the mapping of precise pharmacological pathways. This evidence-based approach will lay the groundwork for developing high-value functional foods, targeted nutritional interventions, and foods for special medical purposes. By focusing on altitude-related physiological challenges, metabolic disorders, and chronic diseases, the future utilization of these unique FMHR can achieve a dynamic balance between sustainable ecological preservation and high-impact biomedical innovation.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Conflicts of interest

The authors declare that there are no conflicts of interest in this work.

Acknowledgments

None.

Funding

This research was funded by the rapid identification technology between wild *Cordyceps sinensis* and artificial *Cordyceps sinensis* and its application (ZNT-2026-03), the Chinese Academy of Sciences-People's Government of Qinghai Province on Sanjiangyuan National Park (LHZX-2022-01) and the Wild *Cordyceps sinensis* Identification and Application Project (QHRD-2025-004). Lhasa Major Science and Technology Program Project (Grant No.: LSKJ202533).

Author contribution statement

Five co-first authors jointly organized, drafted, and revised the manuscript. Two corresponding authors developed the conceptual framework and revised the manuscript. The remaining authors provided intellectual input and assisted with drafting sections of the manuscript.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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