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Rare mountain plants of Central Asia: biological characteristics, phytochemical profile and biotechnological prospects

Xaydarova Nilufar
Junior scientific Researcher
Institute of Botany Academy of Sciences of the Republic of Uzbekistan
Republic of Uzbekistan, Tashkent
E-mail: nilufarxaydarova1996@gmail.com

Jamalova Dilafruz
Junior scientific Researcher
Institute of Botany Academy of Sciences of the Republic of Uzbekistan
Republic of Uzbekistan, Tashkent
E-mail: dilafruz.bel.91@mail.ru

Kodirov Ulugbek
Senior scientific Researcher
Institute of Botany Academy of Sciences of the Republic of Uzbekistan
Republic of Uzbekistan, Tashkent

Редкие горные растения Центральной Азии: биологические характеристики, фитохимический профиль и биотехнологические перспективы

Хайдарова Нилуфар Нодиржон кизи
мл. науч. сотр Институт ботаники Академия наук Республики Узбекистан
Республика Узбекистан, г. Ташкент

Жамалова Дилафруз
мл. науч. сотр
Институт ботаники
Академия наук Республики Узбекистан
Республика Узбекистан, г. Ташкент

Кодиров Улугбек
ст. науч. сотр Институт ботаники Академия наук Республики Узбекистан
Республика Узбекистан, г. Ташкент

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Abstract

The mountain ecosystems of Central Asia are characterized by high ecological diversity, strong topographic gradients, and a high proportion of geographically restricted plant taxa. Such conditions have led to the formation of local endemics and species with narrow ranges, many of which may be vulnerable to habitat disturbance. In this review, the available information on three rare mountain plants—*Dionysia hissarica* Lipsky (Primulaceae), *Dracocephalum formosum* Gontsch. (Lamiaceae), and *Rhodiola heterodonta* (Hook.f. & Thomson) Boriss. (Crassulaceae)—was summarized within a unified framework. The systematic status, distribution, ecology, conservation significance, level of study, phytochemical composition, biological activity, and in vitro studies of the species were analyzed. *D. hissarica* is a rare endemic species with a narrow range associated with the Hissar Mountains; species-specific phytochemical data are limited, although its essential oil has been characterized using GC-MS. Although floristic and taxonomic information is available for *D. formosum*, species-specific phytochemical and tissue culture studies remain insufficient. *R. heterodonta*, in contrast, has been relatively extensively studied with respect to phenylethanoid glycosides, including heterodontoside and salidroside, as well as antioxidant, antihypoxic, antihyperglycemic, and other biological effects. The possibility of obtaining bioactive metabolites using callus, cell suspension, and organ cultures has also been demonstrated in other representatives of the genus Rhodiola. The results of the analysis indicate a significant gap between conservation needs and biotechnological knowledge, particularly for *D. hissarica* and *D. formosum*.

Аннотация

Горные экосистемы Центральной Азии характеризуются высоким экологическим разнообразием, выраженными топографическими градиентами и высокой долей географически ограниченных таксонов растений. Такие условия способствовали формированию локальных эндемиков и видов с узкими ареалами, многие из которых могут быть уязвимыми к нарушению местообитаний. В настоящем обзоре в единой системе обобщены имеющиеся сведения о трех редких горных растениях — *Dionysia hissarica* Lipsky (Primulaceae), *Dracocephalum formosum* Gontsch. (Lamiaceae) и *Rhodiola heterodonta* (Hook.f. & Thomson) Boriss. (Crassulaceae). Проанализированы систематическое положение, распространение, экология, природоохранное значение, степень изученности, фитохимический состав, биологическая активность и исследования in vitro этих видов. *D. hissarica* является редким эндемичным видом с узким ареалом, связанным с Гиссарскими горами; видоспецифические фитохимические данные ограничены, однако его эфирное масло охарактеризовано с помощью GC-MS. Несмотря на наличие флористических и таксономических данных по *D. formosum*, видоспецифические фитохимические исследования и исследования культуры тканей остаются недостаточными. R. heterodonta, напротив, относительно широко изучена в отношении фенилэтаноидных гликозидов, включая гетеродонтозид и салидрозид, а также антиоксидантного, антигипоксического, антигипергликемического и других видов биологического действия. Для других представителей рода Rhodiola также показана возможность получения биологически активных метаболитов с использованием каллусных, клеточных суспензионных и органных культур. Результаты анализа свидетельствуют о значительном разрыве между потребностями в охране и биотехнологическими знаниями, особенно для *D. hissarica* и *D. formosum*.

Keywords: Dionysia hissarica, Dracocephalum formosum, Rhodiola heterodonta, rare plants, Central Asia, conservation, phytochemistry, secondary metabolites, biological activity, in vitro culture.

Ключевые слова: Dionysia hissarica, Dracocephalum formosum, Rhodiola heterodonta, редкие растения, Центральная Азия, охрана природы, фитохимия, вторичные метаболиты, биологическая активность, культура in vitro.

Introduction

The mountain flora of Central Asia is distinguished by high ecological diversity, complex terrain, and the presence of plant taxa with narrow ranges. The geographical isolation of mountain systems has led to the formation of numerous local endemic and rare species. Because such species may occur as small or fragmented populations, they can be vulnerable to habitat disturbance, erosion, changes in hydrological regimes, tourism, and other anthropogenic factors. Therefore, their conservation requires not only the preservation of natural populations but also the use of ex situ collections, controlled propagation, and, where possible, in vitro culture (Science, 2026) (Abdullaeva NS, 2019). *Dionysia hissarica* Lipsky, *Dracocephalum formosum* Gontsch., and *Rhodiola heterodonta* (Hook.f. & Thomson) Boriss., considered in this review, belong to three different families and differ ecologically and phytochemically. *D. hissarica* is a narrow-range species of the family Primulaceae adapted to rocky biotopes and is recorded in available sources as a rare endemic (Science, 2026) (Book, 2019). *D. formosum* belongs to the family Lamiaceae and is a mountain plant studied within the flora and phytogeography of Uzbekistan (Kew, 2026) (Abdullaeva NS, 2019). *R. heterodonta* belongs to the family Crassulaceae and has a considerably larger body of experimental data on its phytochemistry and biological activity (Zaripova MR, 2024) (Miao Hu, 2024) (Yunuskhodjaev AN, 2014). The phytochemical significance of all three species is relevant from the perspective of conservation biotechnology. A diversity of phenylethanoid glycosides, phenylpropanoids, flavonoids, and other secondary metabolites has been identified in the genus Rhodiola (Yousef GG, 2006) (Jiahui Li, 2026) (Ang LH, 2015). In vitro studies conducted on various representatives of the genus show that the production of salidroside and related metabolites can be regulated through callus, cell suspension, and organ cultures (Grech-Baran M, 2015) (Heliyon., 2026) (Wu S, 2003). The aim of the review is to systematize information on three rare mountain species in terms of systematics, distribution and ecology, conservation significance, phytochemistry, biological activity, and in vitro biotechnology, and to distinguish insufficiently studied areas from the available scientific evidence.

Materials and methods

This work was prepared in the form of a literature review. Data were collected from taxonomic databases, conservation sources, and peer-reviewed scientific publications concerning the three target species. Where species-specific evidence was unavailable, studies on the relevant genera or closely related taxa were considered as methodological and comparative sources. Taxonomic and distribution data were verified using Plants of the World Online and regional botanical literature (Science, 2026) (Kew, 2026). Conservation-related information was based on

the Red Data Book of Uzbekistan and relevant scientific sources (Book, 2019). In the phytochemical and biological sections, priority was given to original studies describing identified compounds, analytical methods used, or experimentally measured biological effects. In the biotechnological section, studies describing callus induction, shoot regeneration, rooting, cell suspension, and other controlled culture systems were analyzed. Because direct in vitro evidence for *D. hissarica* and *D. formosum* is limited, studies on other species of the genus Rhodiola were interpreted as methodological sources rather than direct evidence for these two species (Grech-Baran M, 2015) (Heliyon., 2026) (Wu S, 2003).

Results and discussion

The three species included in the study belong to three different families. *D. hissarica* belongs to the family Primulaceae, *D. formosum* to the family Lamiaceae, and *R. heterodonta* to the family Crassulaceae. Their common feature is their association with specialized mountain or rocky habitats and the need for conservation and propagation under scientific control. However, the level of scientific study differs markedly: *D. hissarica* and *D. formosum* have been studied mainly from floristic and taxonomic perspectives, whereas *R. heterodonta* has been more extensively studied in terms of phytochemistry and biological activity (Science, 2026) (Kew, 2026) (Zaripova MR, 2024).

Dionysia hissarica Lipsky is a species of the genus Dionysia in the family Primulaceae and is recorded as an accepted name in current taxonomic data (Science, 2026). The species is described as a small, cushion-forming plant associated with rocky habitats. In the conservation literature of Uzbekistan, it is recorded as a rare endemic growing on rocky substrates, including sandstone crevices and moist microhabitats near waterfalls. The distribution of the species is associated with the Hissar mountain system of Uzbekistan, and available data indicate the middle course of the Sangardak River in Surkhandarya Region and adjacent rocky biotopes (Book, 2019). The availability of moisture and dependence on specialized microhabitats indicate ecological specialization of the species. Such conditions may increase the vulnerability of small populations to changes in habitat. The main body of scientific literature on *D. hissarica* concerns distribution, habitat, and conservation issues. In 2018, the chemical composition of essential oil obtained from the aerial parts of the species was studied using GC-MS (Mamadalieva NZ, 2018). Apart from this study, direct information on the species' non-volatile secondary metabolites, biological activity, and tissue culture is limited. Therefore, *D. hissarica* is considered an important promising object for ex situ conservation and species-specific phytochemical studies.

Dracocephalum formosum Gontsch. belongs to the family Lamiaceae and is indicated as an accepted species of the genus Dracocephalum in current taxonomic resources (Kew, 2026). Floristic studies conducted in Uzbekistan provide information on the distribution and phytogeographic characteristics of the species (Abdullaeva NS, 2019). The species is regarded as a perennial herb adapted to mountain environments. *D. formosum* is associated with the mountainous regions of Central Asia, and regional data record its occurrence in the Hissar and adjacent mountain systems. Detailed experimental data concerning soil chemistry, water availability, light regime, and microclimate of the species are insufficient. These factors may affect not only population persistence but also the accumulation of secondary metabolites. Existing studies on *D. formosum* have mainly focused on floristics, taxonomy, phytogeography, and conservation (Book, 2019) (Abdullaeva NS, 2019). Although various phenolic acids, flavonoids, phenylpropanoids, lignans,

terpenoids, and volatile compounds have been identified in other representatives of the genus Dracocephalum, these data cannot be accepted as direct evidence for *D. formosum*. Species-specific studies of the metabolite profile, biological activity, and in vitro propagation of the species remain an important scientific gap.

Rhodiola heterodonta (Hook.f. & Thomson) Boriss. is a perennial mountain plant of the family Crassulaceae belonging to the medicinally important genus Rhodiola. In historical taxonomic literature, it may also occur under the name Sedum heterodontum. *R. heterodonta* has a broader experimental base in phytochemistry and biological activity compared with *D. hissarica* and *D. formosum* (Zaripova MR, 2024) (Miao Hu, 2024) (Yunuskhodjaev AN, 2014). The species is associated with Central Asia and adjacent mountainous regions. Studies based on material collected in Uzbekistan have investigated populations in the Angren and Burchmulla areas, located at approximately 1200–1800 m above sea level (Zaripova MR, 2024). The species' association with mountain environments and medicinal properties makes sustainable collection and propagation important issues.

The most clearly documented chemical study of *D. hissarica* is devoted to its essential oil. Mamadalieva and co-authors analyzed the essential oil obtained from the aerial parts using GC-MS and identified a complex profile of volatile compounds (Mamadalieva NZ, 2018). This result indicates that the species has a characteristic volatile chemical composition, but it does not define the complete spectrum of secondary metabolites. Data on non-volatile metabolites are insufficient. In the future, it would be appropriate to analyze extracts of different polarities using HPLC-DAD and LC-MS/MS, as well as to determine total phenolics and flavonoids. The species-specific phytochemical profile of *D. formosum* has not yet been sufficiently developed. Phenolic acids, flavonoids, phenylpropanoids, lignans, terpenoids, and volatile compounds have been identified in the genus Dracocephalum, but genus-level data do not directly confirm the composition of *D. formosum*. Therefore, a comprehensive metabolomic study based on sequential extraction, GC-MS, and HPLC/LC-MS/MS is necessary for this species. *R. heterodonta* has the most phytochemical evidence among the three species. Grace and co-authors identified heterodontoside, tyrosol methyl ether, salidroside, viridoside, mongroside, tyrosol, and other related compounds, as well as proanthocyanidins, in an 80 % ethanol extract (Grace MH, 2009). Comparative analysis of three Rhodiola species confirmed the presence of characteristic phenylethanoid and related glycosides in *R. heterodonta* CITATION Gra09 \l 1033 (Grace MH, 2009). A 2024 study of material obtained from Uzbekistan identified flavonoids, saponins, phenolic compounds, tannins, terpenoids, and reducing sugars (Zaripova MR, 2024). A 2026 systematic review summarized that more than 500 chemical compounds have been reported in the genus Rhodiola (Jiahui Li, 2026). Direct experimental evidence concerning the biological activity of *D. hissarica* is currently limited. The main available chemical study focused on characterization of the essential oil and did not include comprehensive pharmacological evaluation (Mamadalieva NZ, 2018). Therefore, activities reported for other Dionysia species cannot be automatically transferred to this species. Antibacterial, antioxidant, anti-inflammatory, and other tests should be conducted using authenticated extracts. Species-specific biological activity data for *D. formosum* are also limited. Although numerous biological effects, such as antioxidant and antimicrobial properties, have been studied in Dracocephalum representatives, genus-level evidence does not constitute direct evidence for *D. formosum*. In the future, it would be appropriate to combine the chemical profile with standardized

antioxidant, antimicrobial, and enzyme inhibition tests. The biological activity of *R. heterodonta* has been documented in relatively greater detail. Grace and co-authors reported adaptogenic and antihypoxic effects associated with an 80 % ethanol extract (Grace MH, 2009). The choleretic effects of root and rhizome extracts have also been studied (Kurmukov AG, 2011), while another study evaluated adaptogenic properties and chronic toxicity (Yunuskhodjaev AN, 2014). A 2024 study identified antioxidant activity in several in vitro free-radical-scavenging systems, as well as effects related to glucose binding, glucose transport, and inhibition of α-amylase and α-glucosidase (Zaripova MR, 2024). In a separate network pharmacology study, components were identified using LC-MS/MS, and mechanisms associated with PI3K/AKT and Nrf2-Gpx4 were proposed for the antihyperglycemic effect; such mechanistic predictions require additional experimental validation (Miao Hu, 2024).

The literature shows a significant difference in research intensity among the three species. Although *D. hissarica* is documented in terms of distribution, habitat, and conservation significance, species-specific phytochemistry, biological activity, and biotechnological studies are scarce. Floristic and taxonomic data are available for *D. formosum*, but direct experimental evidence concerning its metabolite profile, biological activity, and tissue culture is insufficient. *R. heterodonta*, in contrast, has substantially more direct evidence concerning phytochemistry and biological activity, as well as an established and advanced methodological biotechnology base within the genus Rhodiola (Zaripova MR, 2024) (Ang LH, 2015). In future studies, especially for narrow-range mountain species, taxonomic authentication and documentation of voucher specimens are important. Seed biology, establishment of aseptic culture, sterilization, and germination protocols should be optimized separately. Combinations of plant growth regulators should be tested separately for each species rather than being transferred unchanged from closely related taxa. For *D. hissarica*, supplementation of the essential oil profile with non-volatile metabolites; for *D. formosum*, development of a broad metabolomic profile based on LC-MS/MS and GC-MS; and for *R. heterodonta*, linking marker compounds such as salidroside and heterodontoside with culture conditions are important directions (Mamadalieva NZ, 2018) (Grace MH, 2009) (Jiahui Li, 2026). Conservation and biotechnology can be integrated into a single workflow: collection of authenticated material and preparation of a voucher → assessment of seed viability and sterilization → aseptic germination → shoot multiplication → rooting → acclimatization → establishment of an ex situ collection → callus or suspension culture when necessary → determination of the target metabolite profile → assessment of biological activity. Such an approach may reduce destructive sampling from natural populations and create reproducible material for subsequent biochemical and pharmacological studies.

Conclusion

Dionysia hissarica, *Dracocephalum formosum*, and *Rhodiola heterodonta* are three ecologically distinct but important representatives of the mountain flora of Central Asia from the perspectives of conservation and scientific research. Despite their restricted ranges and conservation significance, *D. hissarica* and *D. formosum* remain insufficiently studied in terms of phytochemistry, biological activity, and in vitro propagation. *R. heterodonta*, in contrast, has a broader experimental basis owing to phenylethanoid glycosides, documented antioxidant and antihypoxic effects, and the developed biotechnological base of the genus Rhodiola (Zaripova MR,

2024) (Ang LH, 2015). For all three species, the development of species-specific in vitro protocols is important for ex situ conservation and obtaining plant material under scientific control. For *D. hissarica* and *D. formosum*, the priority should be to establish reproducible aseptic regeneration systems and initial metabolite profiles, whereas for *R. heterodonta* it is appropriate to optimize regeneration and metabolite production based on existing phytochemical markers. An approach integrating conservation, phytochemistry, and biotechnology provides a practical scientific platform for further research on these rare mountain plants.

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