



St. John's Wort (*Hypericum perforatum* L.) in Armenia: Bioactive composition, ecological distribution, and cultivation potential for functional food applications

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ABSTRACT

Introduction: *Hypericum perforatum* L. (St. John's wort) is a widely used medicinal and aromatic plant with significant pharmacological and nutraceutical potential. Its bioactive compounds, including hypericin, hyperforin, flavonoids, and phenolic acids, support antidepressant, antiviral, anti-inflammatory, and antioxidant activities. In Armenia, wild populations are distributed across diverse floristic zones and elevations, representing valuable genetic resources with functional food relevance.

Objective: This study aimed to evaluate the ecological, morphological, and phytochemical variation of Armenian *H. perforatum* populations to identify high-value chemotypes suitable for pharmaceutical, ethnobotanical, and functional food applications.

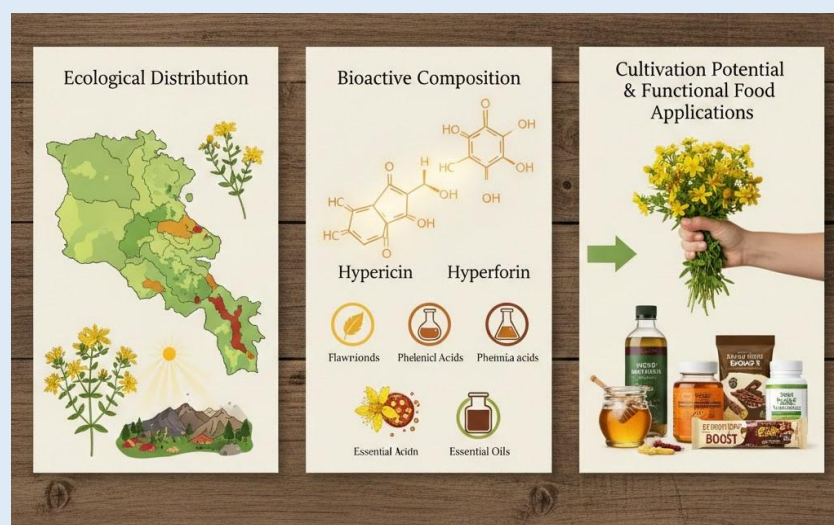
Materials and Methods: Field surveys were conducted between 2023 and 2025 across five Armenian regions (Gegharkunik, Shirak, Vayots Dzor, Lori, and Tavush). Population occurrence records were published by using iNaturalist app and distribution map was generated through QGIS program. Population density, plant height, stem number, and above-ground biomass were recorded using quadrat sampling. In situ phytochemical profiling was performed with TLC

to estimate relative levels of hypericin, hyperforin, and flavonoids. Comparative analysis identified spatial patterns and high-value populations.

Results: Substantial variation was observed across populations. The Jermuk population, located in a cool, moist forest-steppe, exhibited the highest density, biomass, and metabolite levels, making it optimal for pharmaceutical and functional food use. Hermon, located in a semi-arid meadow, showed moderate productivity and resilience, suitable for cultivation in diverse agro-ecological zones. Draghtik, a semi-arid steppe population, produced tall plants with moderate biomass and balanced metabolites, appropriate for general ethnobotanical use. Darpas, at the lowest elevation, displayed low density, height, and metabolite content, likely constrained by shading and vegetation structure. This study represents the first integrated ecological, morphological, and phytochemical assessment of Armenian *Hypericum perforatum* populations, identifying high-value chemotypes and demonstrating the practical utility of rapid field TLC for applied screening.

Conclusion and Future Work: Water availability, more than temperature alone, limits productivity, with optimal moisture and moderate temperatures supporting higher biomass and secondary metabolite accumulation. Rapid field TLC proved effective for identifying high-value populations. These findings provide a scientific foundation for targeted conservation, sustainable harvesting, cultivation, and potential functional food applications. Future research should focus on quantitative phytochemical analysis, genotype–environment interactions, and optimized cultivation trials. Additionally, bioactivity-guided incorporation of *H. perforatum* L. metabolites into functional foods will help ensure standardization, efficacy, and long-term conservation.

Keywords: *Hypericum perforatum* L.; Armenian populations; wild medicinal plants; high-value chemotypes; ecological distribution; bioactive compounds; TLC screening; functional food applications



Graphical abstract: Bioactive Composition, Ecological Distribution, and Functional Food Cultivation Potential of St. John's Wort (*Hypericum perforatum* L.) in Armenia

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INTRODUCTION:

In recent decades, the food industry has expanded beyond traditional goals of ensuring product safety and quality to include the development of functional foods with targeted biological activities [1–2]. This trend is driven by increasing consumer demand for natural, health-promoting ingredients with preventive or therapeutic potential [3–4]. Among such ingredients, medicinal and aromatic plants have gained considerable attention due to their rich phytochemical composition and proven biological activities [5–6].

Within this context, *Hypericum perforatum* L. (St. John's wort) shows significant potential as a functional food ingredient, owing to its diverse pharmacological properties, including antioxidant, anti-inflammatory, antimicrobial, antiviral, and neuroactive (mood-regulating) effects [7–8].

Hypericum perforatum L. (family Hypericaceae) is one of the most widely distributed and well-known medicinal plants worldwide. Its pharmacological activities have underpinned traditional uses for a variety of internal and external ailments. The plant is particularly notable for its rich profile of bioactive

secondary metabolites, including naphthodianthrones (hypericin, pseudohypericin), phloroglucinols (hyperforin, adhyperforin), flavonoids (quercetin, rutin, kaempferol, hyperoside), phenolic acids (chlorogenic and caffeic acids), tannins, and volatile essential oils (monoterpenes, sesquiterpenes) [9–10].

Ecologically, *H. perforatum* is native to Europe, North Africa, and Western Asia, and occurs across temperate European, Mediterranean, Caucasian, and Transcaucasian floristic zones. In Armenia, wild populations are naturally distributed across several floristic regions, including Shirak, Aragats, Lori, Ijevan, Sevan, Darelegis, Zangezur, and Meghri, typically thriving at elevations between 600 and 2200 m [11]. The genus *Hypericum* is represented in Armenia by 39 wild species, among which *H. perforatum* is one of the most commonly sold in Yerevan markets as a medicinal remedy and food plant, mainly used for herbal tea preparation [12]. The ecotypes studied here (2023–2025) represent a valuable genetic reservoir and contribute significantly to the country's medicinal plant biodiversity (Fig. 1).

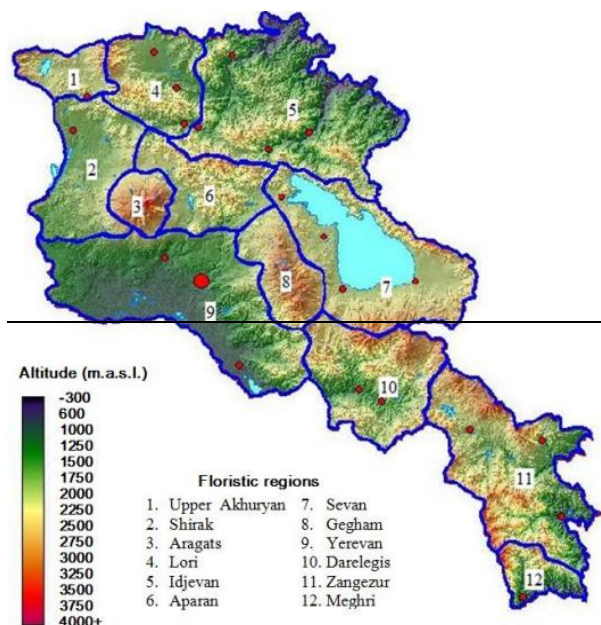


Fig. 1. Floristic regions of Armenia (source: A.L. Takhtajyan, 1954). Topographic and floristic map showing altitude gradients (m.a.s.l.) and delineated floristic regions. Red dots indicate surveyed *Hypericum perforatum* L. locations during field studies (2023–2025) in Gegharkunik, Shirak, Vayots Dzor, Lori, and Tavush.

According to the European Pharmacopoeia, the herbal drug *Hyperici herba* comprises the dried aerial parts and flowering tops harvested during the flowering period. In continental Europe and the Mediterranean, *Hyperici oleum* (oleolite), prepared by macerating flowers in vegetable oil, is widely used for treating minor wounds, burns, sunburn, and other skin conditions [13]. The drug-to-extract ratio (DER) of these traditional preparations typically ranges from 1:4 to 1:20, depending on local practices [13].

Scientific interest in *H. perforatum* increased significantly in the 1980s following the discovery of its antidepressant and anxiolytic effects [14–15]. Initially, hypericin was believed to be the primary active compound, leading to standardization of products based on hypericin content. Subsequent research, however, highlighted the central role of hyperforin [16], along with various phenolic compounds, in mediating the plant's pharmacological effects. Currently, the synergistic action among various secondary metabolites—specifically naphthodianthrones, phloroglucinols, and flavonoids—is widely recognized. This supports the classification of the extract as a phytocomplex with multifaceted therapeutic potential, encompassing antioxidant, anticancer, and neuroprotective properties [17–18].

Despite its commercial value, the availability of *H. perforatum* L. raw material remains limited. In Europe, primary production centers are in Germany, Italy, and Romania, yet much of the global supply still depends on wild harvesting [19].

Cultivation for industrial use offers an opportunity to ensure consistent and elevated levels of bioactive metabolites, but developing optimized field

management practices remains challenging, as many agronomic and environmental factors influence both yield and phytochemical composition [20–21].

Therefore, this study aims to investigate the ecological, geographical, phenological, morphological, and phytochemical characteristics of *H. perforatum* L. populations in Armenia, generating data to support the development of domestication and cultivation technologies for this valuable medicinal plant.

MATERIALS AND METHODS

Field studies: Field investigations were conducted between 2023 and 2025 in the Gegharkunik, Shirak, Vayots Dzor, Lori, and Tavush Regions of Armenia to assess the distribution, ecology, morphology, and phytochemistry of *Hypericum perforatum* L. The objective of these studies was to accumulate ecological, geographical, phenological, morphological, phytochemical, and environmental data to guide the selection of high-quality chemotypes for domestication and functional food applications.

Study Sites: Wild populations of *H. perforatum* L. occur naturally across multiple floristic regions of Armenia, including Shirak, Aragats, Lori, Ijevan, Sevan, Darelegis, Zangezur, and Meghri, typically at elevations between 600 and 2200 m [22]. Four representative sites were selected to reflect ecological, climatic, and vegetation diversity (Table 1; Fig. 1). These sites encompass different ecosystem types, including forest-steppe, steppe, and mountain-steppe meadows, supporting a range of vegetation traits and productivity levels, which are relevant for evaluating adaptability and cultivation potential.

Table 1. Study sites and population characteristics

Population	Region	Floristic Region	Elevation (m)	Ecosystem	Climate	Study Area (m ²)	Quadrats
Jermuk	Vayots Dzor	Darelegis	2080	Forest-steppe (woody species and mixed grass-shrubs, high productivity)	Humid continental, ~14°C summer, 700–800 mm precipitation	2600	78
Dragthik	Gegharkunik	Sevan	1980	Steppe (grassland with drought-	Semi-arid, ~15°C summer,	500	15

Population	Region	Floristic Region	Elevation (m)	Ecosystem	Climate	Study Area (m ²)	Quadrats
				tolerant herbs)	450–550 mm precipitation		
Darpas	Lori	Lori	1400	Forest-steppe (mixed grass-shrubs, moderate productivity)	Humid summers, ~17°C, 600–700 mm precipitation	200	6
Hermon	Vayots Dzor	Darelegis	1750	Mountain-steppe meadow (high biodiversity grassland)	Semi-arid, ~18°C summer, 500–600 mm precipitation	600	18

Sampling and Measurements: Eco-geographical surveys were conducted following standardized wild population sampling protocols [23]. Quadrats of 1 m² were placed randomly (≥5–7 replicates) to cover approximately 3% of each population. Phenological phases, plant density, and morphological traits (height, stem number, flower count, biomass) were recorded using the BBCH scale methodology [24], supplemented with the Hack scale for detailed phenological assessment [20–21].

Biomass Estimation

$$\text{Biomass (g m}^{-2}\text{)} = a \times H^b \times S^c \times D$$

where:

- **a** = model coefficient (from [25])
- **b** = height exponent
- **c** = shoot-related exponent
- **H** = plant height (cm)
- **S** = number of shoots per plant (measured in this study)
- **D** = plant density (plants m⁻²)

For *H. perforatum* L., biomass is positively correlated with both plant height and stem number,

with exponents **b** and **c** usually greater than 1 to reflect exponential growth.

Phytochemical Screening: In situ phytochemical profiling was performed using portable thin-layer chromatography (TLC) kits with silica gel plates, UV detection at 254/366 nm, and standard reagents [26]. Fresh aerial tissue (≈1–2 g) was macerated in methanol, and the resulting extracts were analyzed by TLC. Major classes of compounds were identified using colorimetric reactions:

- Naphthodianthrones (hypericin, pseudohypericin) were detected using NaOH/KOH, producing a red coloration [26].
- Phloroglucinols (hyperforin, adhyperforin) were visualized with vanillin–sulfuric acid, yielding yellow to orange bands [26].
- Flavonoids (quercetin, rutin, kaempferol, hyperoside) were identified using the Shinoda test, which produces red/orange coloration, and an AlCl₃ spray to enhance UV fluorescence [27].

The presence of specific phytochemical classes was inferred from characteristic color changes or precipitate formation, as summarized in Table 2.

Table 2. Colorimetric Tests Used for In Situ Phytochemical Screening

Compound Class	Representative Compounds	Reagents/Test	Expected Reaction	Observation (Positive Test)
Naphthodianthrones	Hypericin, Pseudohypericin	10% KOH or NaOH	Deep red to crimson coloration in alkaline medium	Methanol extract with a few drops of 10% NaOH: red solution confirms presence
Phloroglucinols	Hyperforin, Adhyperforin	Vanillin–sulfuric acid reagent (1% vanillin in conc. H ₂ SO ₄)	Yellow to orange/red-brown on heating	Spray reagent on TLC or filter paper spot: indicates phloroglucinol derivatives
Flavonoids	Quercetin, Rutin, Kaempferol, Hyperoside	Shinoda test (Mg + conc. HCl)	Red to orange coloration	Methanol extract with a few Mg turnings and 1–2 drops HCl: orange/red color

These combined approaches enabled rapid, field-level screening of chemical profiles, supporting chemotype differentiation and informed sample selection for laboratory analysis. Hypericin, hyperforin, and flavonoid profiles were key markers for identifying high-quality chemotypes suitable for domestication. Hypericin, in particular, acted as a primary chemotaxonomic marker for *H. perforatum* L., owing to its distinctive red-orange fluorescence under long-wave UV light (366 nm), which facilitated rapid species identification and preliminary chemotype differentiation. Although hyperforin is chemically unstable and light-sensitive, it was effectively detected using TLC followed by vanillin–sulfuric acid staining, appearing as characteristic orange to violet bands upon heating. For reliable field-based chemotype selection, simultaneous visualization of hypericin fluorescence and flavonoid profiles (e.g., via aluminum chloride spray and UV detection) proved valuable for identifying specimens with potentially higher pharmaceutical value. This integrated approach allowed rapid screening of wild populations, guiding the collection of samples for further laboratory-based chemical and pharmacological analyses.

Data Integration: Field occurrence data were digitized

and georeferenced using QGIS [28]. The resulting records were published to the Global Biodiversity Information Facility (GBIF) to ensure open access to biodiversity data [29]. Field observations were recorded by using citizen-science observations app: iNaturalist [30] to cross-validate presence records, highlighting the platform’s utility for global biodiversity research and species distribution modeling [31].

RESULTS

This study identified the ecological (population size, density), morphological, chemical, and growth characteristics of *Hypericum perforatum* L. populations across different ecosystems in Armenia, and produced a current distribution map of the species. These results provide an essential basis for future domestication and functional food applications of this important culinary and medicinal herb in Armenia.

Field observations carried out between 2023 and 2025 recorded nearly 1,500 occurrence data points representing more than 300 species—approximately 10% of Armenia’s plant biodiversity. These records were digitized and published in GBIF (www.gbif.org). Among the 70 medicinal and aromatic plant species observed, *H. perforatum* L. was identified and its distribution mapped by QGIS program (Fig. 2).

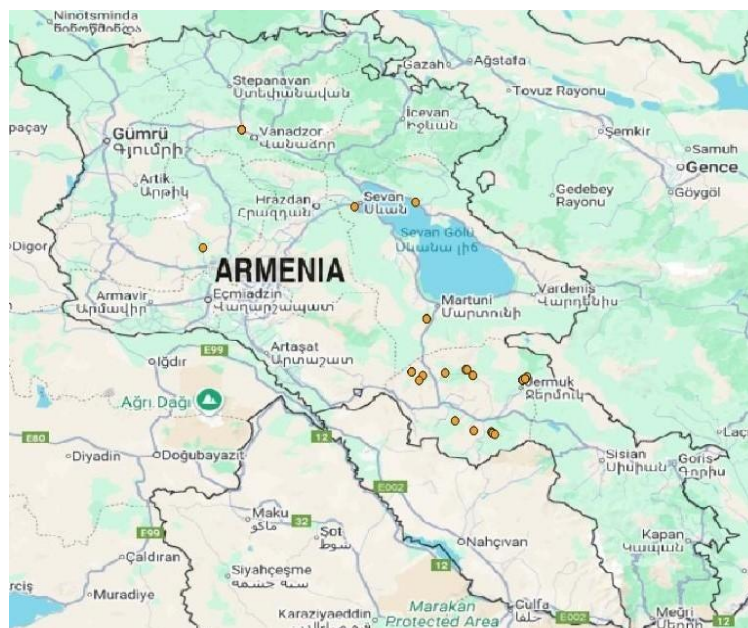


Fig. 2. Distribution of *H. perforatum* L. in Armenia based on 2023–2025 field observations

The map shows populations distributed across southern, central, and northern regions of Armenia, particularly within the *Lori, Sevan, and Darelegis* floristic regions. Field observations revealed ecological, morphological, and chemical characteristics of the populations based on quadrat random sampling and field measurements. Above-ground biomass was estimated from morphological traits and population density, providing a key indicator of yield capacity.

Figures 3–6 illustrate key ecological traits of plant populations across four floristic locations—*Jermuk, Dragthik (Sevan), Darpas, and Hermon*—based on data from 2023 to 2025. These traits include plant height fluctuations, stem number per plant, population density, and biomass (g/m^2), each presented with annual values and average trend lines. Comparative visual analysis supports regional differentiation and temporal dynamics in population structure and productivity.

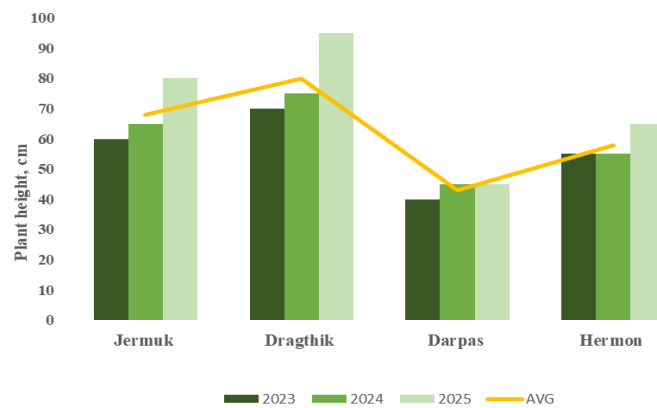


Fig 3: Plant height fluctuations.

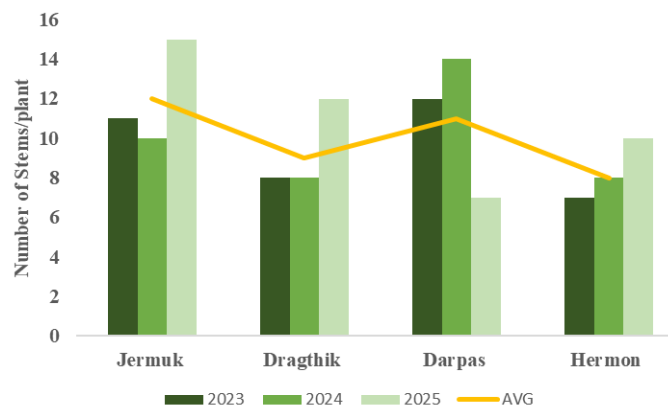


Fig 4: Plant’s stem numbers.

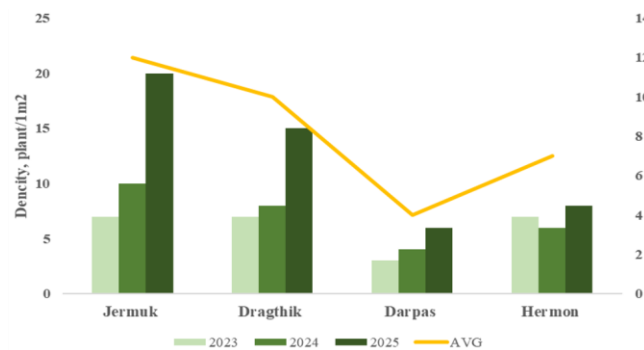


Fig 5: Population’s Density (ecological trait).

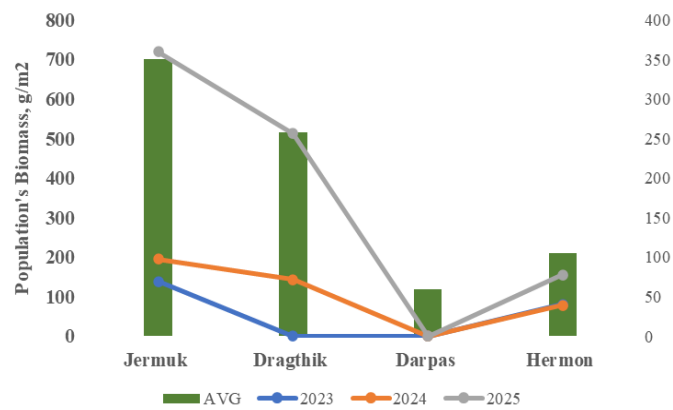


Fig 6: Population's Biomass, g/m²

Ecological and Morphological Traits: Jermuk population demonstrated the strongest ecological and morphological performance. Density and plant height increased markedly, reaching approximately 20 plants/m² and 80 cm, respectively (Figs. 3, 5). The number of stems showed a slight decrease in 2024 (Fig. 4). Biomass rose sharply to around 700 g/m² (Fig. 6), indicating positive correlations among ecological and morphological traits. This pattern is characteristic of competitive populations developing under stable climatic conditions.

Hermon population, although located within the same floristic region as Jermuk, exhibited substantially lower values. Its density was about half that of Jermuk (Fig. 5), and both plant height and stem number were lower, though each showed slight increases during the study period (Figs. 3, 4). Biomass approximately doubled over the years but remained around six times lower than Jermuk, averaging about 156 g/m².

Dragthik population (Sevan floristic region) showed notable upward trends in all measured parameters. Density doubled over the course of the study, and plant height reached the highest value among all populations, attaining approximately 95 cm in 2025 (Fig. 3). Biomass accumulation increased to around 500 g/m² (Fig. 6), making Dragthik the second most productive site after Jermuk.

In contrast, Darpas population exhibited the lowest ecological and morphological indicators. Both density and biomass were significantly lower than those observed in high-altitude populations. Biomass averaged approximately 59 g/m² despite moderate stem numbers (Figs. 4, 6). Plant height remained relatively stable at about 45 cm (Fig. 3), while stem number decreased by nearly half over the study period. Biomass fluctuated, peaking around 76 g/m² in 2024, but overall productivity remained 2–12 times lower than Hermon and Jermuk populations.

Phytochemical Traits: In situ phytochemical screening (TLC field method) revealed clear chemotype variations among the studied populations. The results were qualitative, based on the intensity of coloration. A summary of these chemotype differences is presented in Table 3. Specifically:

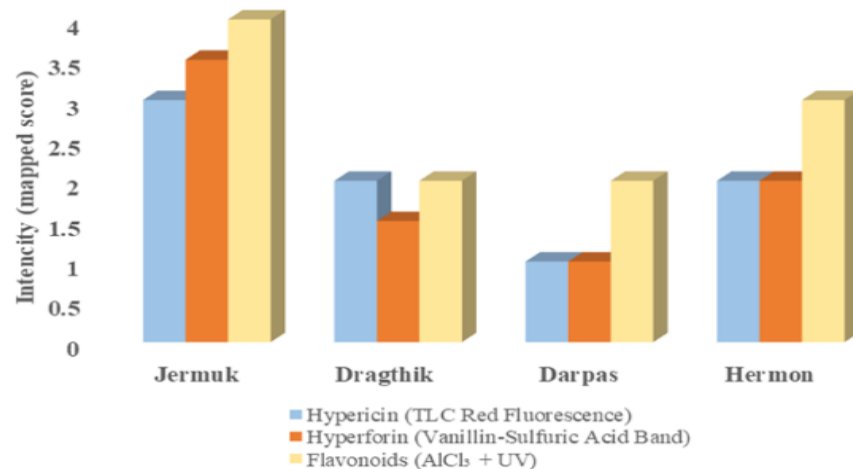
- **Hypericin:** Strong red-orange fluorescence under UV indicated higher concentrations (e.g., Jermuk), while weak bands (e.g., Darpas) suggested low levels. Literature reports quantitative ranges of 0.003–3% dry weight.
- **Hyperforin:** Detected via vanillin–sulfuric acid spray. Strong bands (~2–4.5%) were observed in robust chemotypes.
- **Flavonoids:** Fluorescent bands under UV after AlCl₃ spray correlated with estimated flavonoid content (2–12%).

Table 3. In situ phytochemical screening of *H. perforatum* populations.

Location	Hypericin (TLC Red Fluorescence)	Hyperforin (Vanillin–Sulfuric Acid Band)	Flavonoids (AlCl ₃ + UV)
Jermuk	++ (Strong)	++ (Moderate–Strong)	+++ (Very Strong)
Dragthik	+ (Moderate)	± (Weak–Moderate)	+ (Moderate)
Darpas	± (Weak)	± (Weak)	+ (Moderate)
Hermon	+ (Moderate)	+ (Moderate)	++ (Strong)

The comparative intensity of these compounds across populations is illustrated in Fig. 7, which

visualizes estimated relative levels of hypericin, hyperforin, and flavonoids based on TLC signal strength.

**Fig. 7.** Estimated compound levels across populations

- Jermuk – Displayed the strongest TLC signals, particularly for flavonoids, followed by hypericin and hyperforin. This suggests that the Jermuk population has high concentrations of bioactive compounds, making it a promising source for developing standardized functional food ingredients.

- Hermon – Showed consistently strong signals, slightly lower than Jermuk. Its stable compound profile indicates suitability for cultivation and scalable raw-material production.

- Dragthik – Exhibited moderate but well-balanced signals for all three compound groups, representing a population with a diverse bioactive profile that may be suitable for broader functional applications.

- Darpas – Demonstrated weak hypericin and hyperforin bands and moderate flavonoids. This suggests lower suitability for high-value functional food formulations compared to the other populations.

DISCUSSION

The present field investigation, conducted across five Armenian regions (Gegharkunik, Shirak, Vayots Dzor, Lori, and Tavush) between 2023–2025, provides new insights into the ecological, morphological, and phytochemical variability of *Hypericum perforatum* L. under diverse environmental conditions. The wide geographic distribution observed aligns with the species' well-documented ecological flexibility and its ability to adapt to contrasting climatic and edaphic conditions, consistent with global findings [32]. Ecological and morphological differences recorded among populations reflect strong influences of local microclimates, altitude, precipitation, and vegetation structure, all of which are known to modulate growth traits and secondary metabolite accumulation in *H. perforatum* L. [33]. Some patterns observed in this study also mirror classic altitudinal effects: cooler temperatures, reduced evapotranspiration, and improved soil moisture

retention at higher elevations support higher plant density and biomass.

This helps explain why the Jermuk and Dragthik populations, both located above 1900 m, exhibited greater density, taller plants, and higher biomass. Similar correlations between elevation, moisture availability, and population performance have been widely reported in mountain ecosystems [33].

The Jermuk population, located in a cool, moist forest–steppe environment, produced the highest biomass and density among the studied populations. Moderate temperatures and relatively high precipitation favor vigorous vegetative growth and competitive population structure. Conversely, the Hermon population, despite belonging to the same floristic region, grows under semi-arid mountain-steppe conditions. Its moderate biomass suggests adaptation to periodic drought and higher solar radiation, an ecological pattern also described in stress-tolerant meadow communities. These traits may indicate valuable resilience for future cultivation programs across diverse agro-ecological zones of Armenia.

Dragthik, a steppe habitat with semi-arid conditions, displayed the tallest plants among all populations. This pattern, also reported in steppe vegetation, likely reflects structural adaptation to high light exposure and intense competition for sunlight, rather than solely climatic factors. Despite relatively dry conditions, the combination of moderate temperature, air humidity from Lake Sevan, and open vegetation structure supports vertical growth.

Darpas, the lowest-elevation site within a humid forest–steppe system, unexpectedly showed the weakest ecological and morphological performance. Shading from woody vegetation, altered herbaceous composition, and potential interspecific competition likely contribute to low density, height, and biomass. Habitat structure, particularly canopy cover, can suppress photosynthesis and secondary metabolism in

light-demanding species such as *H. perforatum* L. The composition of herbaceous species in this habitat also differed from other sites. Notably, *Origanum vulgare* L., which was consistently observed as a companion species across the other populations, was absent in Darpas. This observation suggests that *Origanum vulgare* L. may play a symbiotic role in the growth of *H. perforatum* L., and its absence from this habitat might cause the growing decline of *H. perforatum* L. population. These observations highlight that favorable climatic conditions do not always translate to optimal growth if vegetation structure imposes competitive constraints.

Phytochemical variation among the studied populations was substantial and is linked to environmental stressors such as temperature fluctuation, solar radiation, and water availability, all known to influence biosynthetic pathways for hypericin, hyperforin, and flavonoids. Our results align with previous research showing that environmental heterogeneity and genotype–environment interactions strongly shape the biochemical composition and pharmacological potential of *H. perforatum* L. [34].

Phytochemical screening revealed clear chemotype differentiation. The Jermuk population exhibited the strongest TLC signals for all tested compounds, likely influenced by its cool, moist climate, which enhances phenolic and naphthodianthrone biosynthesis [35–36].

The Hermon population also showed strong metabolite expression, slightly lower than Jermuk, consistent with drought- and UV-induced stimulation of flavonoid pathways [36–37]. Dragthik exhibited moderate but balanced metabolite levels typical of semi-arid steppe systems [35]. By contrast, Darpas displayed the weakest hypericin and hyperforin intensities, possibly due to reduced UV exposure and shading in its forest–steppe environment [38]. These findings align with recent discussions on the bioactive

potential of wild plant populations and their translation into functional foods [38–39].

The biochemical richness of Armenian *H. perforatum* positions it as a promising source of health-promoting compounds. Strong population-level variability underscores the importance of selecting appropriate chemotypes for standardization and industrial applications. Recent reviews emphasize that transitioning from identifying wild bioactive sources to developing standardized functional food products requires a rigorous interdisciplinary approach [40]. The present study addresses challenges in sourcing stable plant-based functional ingredients for human health management [39].

The present work provides a novel contribution to the understanding of *H. perforatum* in Armenia by combining ecological, morphological, and phytochemical analyses in a single integrated study. We identified high-value chemotypes with elevated levels of hypericin, hyperforin, and flavonoids, which are promising for functional food and nutraceutical applications. Additionally, the application of rapid field TLC demonstrates a practical, cost-effective tool for preliminary screening of bioactive-rich populations, facilitating future conservation, cultivation, and functional product development efforts.

Identification of high-value chemotypes, such as the Jermuk population, represents an essential first step toward functional food fortification and the production of standardized bioactive ingredients [39]. The bioactive compounds of *H. perforatum*, including hypericin, hyperforin, and flavonoids, have demonstrated antioxidant, anti-inflammatory, and neuroprotective effects, bridging the ecological and phytochemical findings of this study to potential human health applications [38].

Implications for Conservation, Cultivation, and Nutraceutical Use: The identification of chemically stable and bioactive-rich populations of *H. perforatum*

aligns closely with the principles of functional food science, in which standardization, precise definition, and strict quality control are essential for developing scientifically validated functional ingredients. Establishing rigorous quality-control procedures and a unified standardization framework is considered a fundamental requirement in the field [41].

In the context of increasing global demand for natural bioactive ingredients in functional food development, the biochemical richness of Armenian *H. perforatum* positions it as a promising source of health-promoting compounds. The present study contributes to the early phases of functional food development as outlined in the Functional Food Center’s 17-Step Model [2]. Specifically, it aligns with Step 1 (basic research) by investigating ecological, morphological, and phytochemical characteristics of wild *H. perforatum* populations, Step 2 (identification and examination of bioactive compounds) through TLC-based screening of hypericin, hyperforin, and flavonoids, and provides preliminary groundwork for the standardization and cultivation of high-value chemotypes. This alignment underscores the translational potential of our findings toward functional food applications.

Functional foods are defined as products that provide health benefits beyond basic nutrition, often containing bioactive compounds that promote physiological well-being or reduce the risk of chronic disease [1–2]. The diverse phytochemical profile of *H. perforatum*—specifically hypericin, hyperforin, and various flavonoids—presents significant potential for integration into functional beverages, nutraceutical supplements, or as standardized additives in fortified food matrices. Transitioning from raw extracts to viable commercial products requires several critical milestones: the precise quantification of bioactives via advanced analytical platforms (e.g., HPLC-MS/MS), the identification of elite chemotypes through genotype–environment interaction studies, and the optimization

of cultivation protocols. Ultimately, bioactivity-guided formulation and clinical validation are essential to ensure the delivery of standardized, safe, and efficacious functional food products.

Recent studies further emphasize the importance of bioactive-rich botanical sources in the development of functional foods with health-promoting properties. Functional foods enriched with phytochemicals have demonstrated considerable therapeutic potential, highlighting the value of populations such as Jermuk and Hermon, which exhibited strong bioactive profiles in the present study [42–45]. Collectively, these findings support the potential use of *H. perforatum* as a promising raw material for functional food formulations.

Additionally, functional food development, from raw material selection to scientific validation and regulatory approval, requires a systematic, stepwise approach. This development cycle depends on well-characterized biological materials and standardized analytical methodologies [38]. In this context, the biochemical and ecological variability documented in the present work provides essential groundwork for identifying optimal populations for future functional food development.

Future Directions: Building on the findings of this study, future research should prioritize several key areas. First, quantitative phytochemical analysis is essential. Advanced analytical techniques, such as HPLC, LC–MS/MS, and NMR, should be used to precisely quantify major bioactive compounds, generating data required for functional food and pharmaceutical standardization.

Second, investigations into genotype–environment interactions are needed to clarify the genetic basis of metabolite variability among Armenian populations. Integrating molecular markers with detailed environmental parameters will help identify traits linked to enhanced bioactive compound production.

For potential commercial applications, optimized cultivation trials should be conducted under controlled

and semi-controlled conditions. These should evaluate the effects of altitude, soil composition, irrigation regimes, and light exposure on both biomass yield and secondary metabolite accumulation.

Next, functional food applications should be explored through bioactivity-guided extraction and incorporation of *H. perforatum* metabolites into food matrices. This includes assessing compound stability, bioavailability, sensory compatibility, and potential health-promoting effects.

Finally, robust conservation strategies are required to protect unique chemotypes and prevent overharvesting. Long-term preservation of Armenia's natural populations and their genetic diversity is essential for sustainable utilization and future functional food development.

CONCLUSION

Hypericum perforatum L. populations in Armenia exhibit substantial ecological, morphological, and phytochemical variation, strongly influenced by elevation, moisture, and habitat structure. Among the studied populations, Jermuk (2080 m, cool, moist forest-steppe) showed the highest plant density (~20 plants/m²), biomass (~700 g/m²), and secondary metabolite levels, making it the most promising source for pharmaceutical, ethnobotanical, and functional food applications. Hermon (1750 m, semi-arid meadow) demonstrated moderate productivity and resilience, suggesting potential for cultivation across diverse agro-ecological zones. Dragthik (1980 m, semi-arid steppe) produced tall plants (~95 cm) with moderate biomass (~500 g/m²) and balanced metabolite profiles, suitable for general ethnobotanical and functional food use. Darpas (1400 m, lowest-elevation site) exhibited low density, height (~45 cm), and metabolite content, likely constrained by shading and vegetation structure.

Water availability, rather than temperature alone, emerged as the primary factor limiting productivity. Optimal moisture and moderate temperatures

supported both high biomass and elevated levels of bioactive compounds. Rapid field TLC proved effective for identifying populations with high functional value, providing a practical tool for selecting plant material for functional food development.

The documented phytochemical richness of Armenian *H. perforatum* L. populations underscores their significance for functional food science, where standardized, bioactive-rich plant materials are essential for developing scientifically validated, health-promoting products. These results provide a scientific foundation for the conservation, domestication, and functional food utilization of Armenian *H. perforatum* L., supporting sustainable harvesting and optimized cultivation strategies. Further ecological, quantitative, and genetic studies are needed to elucidate the mechanisms driving spatial variation and to ensure consistent sourcing of bioactive compounds for the functional food industry.

Abbreviations

- *H. perforatum* – *Hypericum perforatum* L.
- L. – Linnaeus (taxonomic author)
- m.a.s.l. – meters above sea level
- TLC – Thin Layer Chromatography
- UV – Ultraviolet
- DER – Drug to Extract Ratio
- BBCH – Growth stages scale for plants
- GBIF – Global Biodiversity Information Facility
- QGIS – Quantum Geographic Information

System

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editing; AS – experimental setup, data collection, writing–review and editing; AA- experimental setup, data collection, writing–review and editing; LM – experimental setup, data collection, writing–review and editing; AS – data curation, resources, writing–review and editing. All authors read and approved the final manuscript.

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