



RESEARCH ARTICLE

Organ-specific phytochemical composition and elemental distribution in *Myosotis alpestris* F.W.Schmidt

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Received: 19 March 2026; Accepted: 12 June 2026; Available online: Version 1.0: 20 September 2026

Cite this article: Mamadaminova DM, Ochilov UA, Perdebaeva GD, Toshov HM, Kurbanliyazova GT, Khaydarov KQ. Organ-specific phytochemical composition and elemental distribution in *Myosotis alpestris* F.W.Schmidt. Plant Science Today (Early Access). <https://doi.org/10.14719/pst.14601>

Abstract

This study examines the organ-specific metabolic profiles of *Myosotis alpestris* F.W. Schmidt, focusing on soluble carbohydrates, free amino acids, water-soluble vitamins, flavonoids and mineral elements. Samples of roots, leaves and stem-flower tissues were collected from natural populations and analysed using high-performance liquid chromatography (HPLC) and multi-element analysis. The results showed that soluble carbohydrates, including glucose, fructose, sucrose and maltose, were unevenly distributed among plant organs, with the highest total carbohydrate content observed in stem-flower tissues. A total of 20 free amino acids were identified, with glutamine and cysteine representing dominant components in aerial organs. Water-soluble vitamins (B1, B2, B3, B6, B9 and vitamin C) exhibited organ-specific accumulation patterns, with folic acid (B9) concentrated in roots and ascorbic acid in reproductive tissues. Flavonoid analysis revealed a more complex phenolic profile in aerial organs compared with roots. Elemental analysis demonstrated significant variation in macro-, micro- and trace element accumulation among plant organs, with calcium (Ca) and iron (Fe) predominantly enriched in stem-flower tissues. Overall, the findings indicate pronounced metabolic compartmentalisation in *M. alpestris* and demonstrate its potential as a valuable source of biologically active compounds. These results provide a foundation for future studies on the pharmacological, nutritional and ecological significance of this species.

Keywords: free amino acids; high-performance liquid chromatography–diode array detector; metabolic profiling; mineral elements; organ-specific metabolism; phytochemistry; soluble carbohydrates; vitamins

Introduction

The *Myosotis* genus comprises herbaceous plants that are found in temperate areas of Eurasia and North America. These plants can be found in different types of environments, from high mountain meadows to areas that have been disturbed. The evolutionary history and biogeographic patterns of Boraginaceae have been investigated in recent phylogenetic and macroecological studies (1) and the regional floristic diversity of the family in Central Asia has been summarised in comprehensive treatments (2). Despite extensive morphological, taxonomic and biogeographical investigations of *Myosotis* species, limited information is available regarding their biochemical composition. Existing biochemical data remain fragmentary and lack comprehensive integration. The biochemical composition of these species is still not well understood.

In higher plants, metabolic activity differs substantially among organs due to their functional roles (3). Leaves serve as the primary sites for photosynthesis and carbohydrate production,

while roots primarily participate in nutrient uptake, storage and nitrogen (N) metabolism (3, 4). Reproductive tissues, including stems and flowers, function as metabolically active sink organs and require constant energy and biosynthetic precursors (3). Such functional differentiation is usually manifested in the distribution of soluble metabolites and mineral elements in the plant body (5, 6).

Soluble carbohydrates, such as glucose, fructose and sucrose, not only contribute to cellular energy balance but also participate in signalling pathways that regulate growth and developmental processes (3). Their determination by high-performance liquid chromatography (HPLC)-based methods has been widely applied in plant biochemical studies (7–12). Free amino acids are closely related to N assimilation and stress response mechanisms (4) and are commonly quantified using derivatisation-based HPLC approaches (13, 14). Water-soluble vitamins, in particular ascorbic acid, play an important role in the regulation of enzymatic reactions and redox processes (15). In addition, mineral elements are necessary for structural stability, ion

homeostasis and reproductive development (5, 6). The relative ratio of these compounds often fluctuates between plant organs, reflecting metabolic specialisation (3, 5). Comprehensive profiling that combines chromatographic techniques with elemental analysis, following standardised analytical protocols, allows a more integrated evaluation of plant biochemical organisation (16). However, detailed metabolic data at the organ level for *Myosotis alpestris* F.W. Schmidt are not currently available. The present study investigated the distribution of soluble carbohydrates, free amino acids, water-soluble vitamins and mineral elements in roots, leaves and stem–flower tissues of *M. alpestris* using HPLC and multi-element analytical methods (11, 14, 16). The goal was to identify patterns of metabolic differentiation in plant organs and provide basic biochemical data for this species.

Materials and Methods

Plant material

Samples of *M. alpestris* were collected from natural populations during the vegetation period (Fig. 1). Roots, leaves and combined stem–flower tissues were separated immediately after collection. The plant material was washed with distilled water, air-dried at room temperature and ground into fine powder before analysis. All measurements were performed using three independent biological replicates ($n = 3$). For each organ (roots, leaves and stem–flower tissues), samples from the three biological replicates were processed and analysed separately, without pooling. Mean values were subsequently calculated and used for comparative analyses. Sample preparation followed commonly applied phytochemical procedures for plant biochemical analysis (15).

Determination of soluble carbohydrates (high-performance liquid chromatography–refractive index detector (RID))

Chromatographic separation was performed on a Supercoil LC-NH2 column (5 μ m, 4.6 $\times$ 250 mm). Under isocratic conditions, the mobile phase consisted of acetonitrile and water (82 : 18, v/v). The flow rate was set at 1.0 mL min⁻¹, the injection volume was 10 μ L and the column temperature was 35 °C. Determination of fructose, glucose, sucrose and maltose was based on comparison of retention times with certified standards. Quantification was performed using external calibration curves prepared for each sugar (6, 16).

Determination of free amino acids (high-performance liquid chromatography–diode array detector (DAD))

Free amino acids were analysed after precipitation of proteins with 20 % trichloroacetic acid (TCA). To obtain phenyl thiocarbamyl (PTC) derivatives, with minor modifications to the method described by Cohen and Strydom, the liquid above the precipitate was reacted with phenyl isothiocyanate (PITC) (17, 18). Chromatographic analysis was performed on the Agilent 1200 ultra-high-performance liquid chromatography (UHPLC) system, equipped with DAD. Separation was carried out on a back-phase C18 column under gradient conditions using sodium acetate buffer and acetonitrile. Detection was performed at 269 nm. Quantification was based on external standards for individual amino acids (18, 19).

Determination of water-soluble vitamins (high-performance liquid chromatography–diode array detector)

Determination of water-soluble vitamins (B1, B2, B3, B6, B9 and ascorbic acid) was carried out with HPLC coupled with DAD. Separation was carried out under gradient elution on an Eclipse XDB-C18 column, using 0.5 % acetic acid and acetonitrile as the mobile phase. Detection wavelengths were set at 254 nm and 290 nm, depending on the compound analysed. Identification was based on retention times of authentic standards and quantification was performed using external calibration curves (20, 21).

Elemental analysis

Concentrations of macro-, micro- and trace elements were determined following acid digestion of dried plant material. Multi-element analysis was performed using inductively coupled plasma (ICP)-based instrumentation according to standard procedures (22). Element concentrations were expressed as μ g g⁻¹ dry weight (DW).

Results

Soluble carbohydrate composition (high-performance liquid chromatography–refractive index (RI))

In all the organs examined of *M. alpestris*, four soluble sugars were identified—fructose, glucose, sucrose and maltose (Table 1). However, their distribution varied considerably between tissues. Stem–flower tissues showed the highest total sugar content (9.36 μ g g⁻¹ DW), more than twice that observed in leaves (4.16 μ g g⁻¹ DW) and over four times higher than in roots (2.00 μ g g⁻¹ DW). This difference was mainly due to



Fig. 1. General habit and floral morphology of *Myosotis alpestris*. A: whole plant in natural habitat; B: close-up view of the inflorescence.

Table 1. Soluble carbohydrate composition ($\mu\text{g g}^{-1}$ DW)

Carbohydrate	Stem-flower	Root	Leaf
Fructose	1.66	0.97	2.04
Glucose	7.59	0.75	1.87
Sucrose	0	0.26	0.05
Maltose	0.10	0.01	0.20
Total	9.36	2.00	4.16

the strong accumulation of glucose in reproductive tissues.

Glucose is the main carbohydrate in stem-flower tissues ($7.59 \mu\text{g g}^{-1}$ DW) and its concentration remains relatively low in leaves ($1.87 \mu\text{g g}^{-1}$ DW) and roots ($0.75 \mu\text{g g}^{-1}$ DW). In contrast, fructose is most abundant in leaves ($2.04 \mu\text{g g}^{-1}$ DW) and its content is higher in stem-flower ($1.66 \mu\text{g g}^{-1}$ DW) and root tissues ($0.97 \mu\text{g g}^{-1}$ DW).

Sucrose occurred only at low levels. It was detectable primarily in roots ($0.26 \mu\text{g g}^{-1}$ DW), while stem-flower tissues showed no measurable amounts and leaves contained only trace quantities ($0.05 \mu\text{g g}^{-1}$ DW). Maltose was present in minor concentrations across all organs, with slightly higher values in leaves ($0.20 \mu\text{g g}^{-1}$ DW) (Fig. 2). In general, the distribution of soluble carbohydrates showed a clear organ-specific pattern, indicating that the reproductive organs are the main place of sugar accumulation.

Flavonoid and phenolic profile (high-performance liquid chromatography–diode array detector)

During chromatographic analysis, the content of heterogeneous phenol was determined in the extracts of *M. alpestris* (Fig. 3). In the interval from 8–12 min of holding time, several distinct peaks were constantly observed. A prominent signal at approximately 9.1–9.3 min was recorded in all aerial organs. Peak intensity was noticeably higher in leaves and stem-flower tissues compared to roots. Additionally, the detected peaks appeared around 10.3 min and 11.6–12.0 min, which indicated the presence of numerous phenolic components. Aerial organs exhibited a more complex chromatographic pattern than roots and were characterised by a larger number of detectable peaks and higher signal intensity. In contrast, root extracts showed fewer dominant peaks and generally lower absorption values. Comparison with reference standards suggested that several chromatographic peaks corresponded to rutin, luteolin, silarioside and dehydroquercetin. However, these compound identifications are tentative and are based primarily on matching retention times with those of the reference standards. These identities remain approximate and are based on the adjustment of storage time.

Amino acid composition

A total of 20 amino acids were found in all the organs of *M. alpestris* (Table 2, Fig. 4). The total amount of free amino acids was slightly higher in stem and flower tissues at $3.041 \mu\text{g g}^{-1}$ of weight. This was compared to leaves, which had $2.929 \mu\text{g g}^{-1}$ DW of weight and roots which had $2.781 \mu\text{g g}^{-1}$ DW. Glutamine was present in amounts in all the organs. In roots and leaves it reached $0.774 \mu\text{g g}^{-1}$ of weight. In stem and flower tissues it was $0.608 \mu\text{g g}^{-1}$ DW. Glutamine was one of the abundant amino acids in *M. alpestris*. Cysteine showed an increase in stem and flower samples at $0.658 \mu\text{g g}^{-1}$ DW. Leaf concentrations of cysteine were much lower at $0.079 \mu\text{g g}^{-1}$ DW. Cysteine concentrations varied substantially among plant organs.

Asparagine was predominantly detected in non-photosynthetic tissues. The leaves have 0.406 asparagine g^{-1} DW and the roots had about 0.376 asparagine g^{-1} DW. Proline content was

highest in leaves ($0.368 \mu\text{g g}^{-1}$ DW). In contrast, tyrosine reached its maximum level in stem-flower tissues ($0.320 \mu\text{g g}^{-1}$ DW). Valine, leucine, isoleucine, methionine, phenylalanine, lysine, threonine and tryptophan were detected at low concentrations in all organs. Aerial organs (leaves and stem-flower tissues) contained slightly higher total amino acid concentrations than roots.

Vitamin composition

Water soluble vitamins were detected in all analysed organs of *M. alpestris*. The number of vitamins in each part was different. The distribution of water-soluble vitamins differed among roots, leaves and stem-flower tissues (Table 3). Folic acid, (vitamin B9) was the dominant vitamin in all analysed organs. The amount of the acid in the roots was $3.6 \mu\text{g g}^{-1}$ DW, while the amounts in the stem and flowers were $2.9 \mu\text{g g}^{-1}$ DW and $2.05 \mu\text{g g}^{-1}$ DW respectively, in the leaves. Riboflavin, also known as vitamin B2, was detected in the roots, stem and flowers at a concentration of $0.65 \mu\text{g g}^{-1}$ DW. However, its concentration in the leaves was much lower, at 0.08 mg g^{-1} .

Vitamin B6 was detected in the leaves at a concentration of $0.35 \mu\text{g g}^{-1}$ DW, which was higher than that in the stem and flowers ($0.20 \mu\text{g/g}^{-1}$ DW) and roots ($0.14 \mu\text{g g}^{-1}$ DW).

Ascorbic acid was found in every part of the plant and the highest amount was found in the stem and flowers which was $0.56 \mu\text{g g}^{-1}$ DW. Roots contained only minor amounts ($0.05 \mu\text{g g}^{-1}$ DW). Vitamins B1 and B3 were detected in negligible amounts in all organs. Overall, vitamin composition varied substantially among plant organs, indicating pronounced organ-specific accumulation patterns.

Elemental composition

Elemental analysis revealed substantial differences in mineral accumulation between plant organs (Table 4). Calcium (Ca) was the predominant mineral element in all analysed organs. The highest Ca concentration was recorded in stem-flower tissues $24806 \mu\text{g g}^{-1}$ DW (Supplementary Table 1). The roots had $21723 \mu\text{g g}^{-1}$ DW of weight and the leaves had $12999 \mu\text{g g}^{-1}$ DW. Potassium concentrations were relatively similar among all analysed organs, averaging approximately $3178 \mu\text{g g}^{-1}$ DW. Magnesium was higher in the stems and flowers at $2302 \mu\text{g g}^{-1}$ DW compared with the roots and leaves.

Iron (Fe) and aluminium (Al) concentrations were substantially higher in stem-flower tissues, reaching 3981 and $3142 \mu\text{g g}^{-1}$ DW respectively (Supplementary Table 2). In the roots and leaves the levels of these minerals were much lower. Zinc (Zn) and copper (Cu) were detected in all analysed organs. In the stems and flowers, Zn were at $26.2 \mu\text{g g}^{-1}$ DW. Amounts of cadmium (Cd) and arsenic (As) were also found. Rare earth elements, including lanthanum (La), cerium (Ce), neodymium (Nd) and samarium (Sm) were predominantly accumulated in stem-flower tissues (Supplementary Table 3). Only trace concentrations of these elements were detected in roots and leaves. The stems and flowers

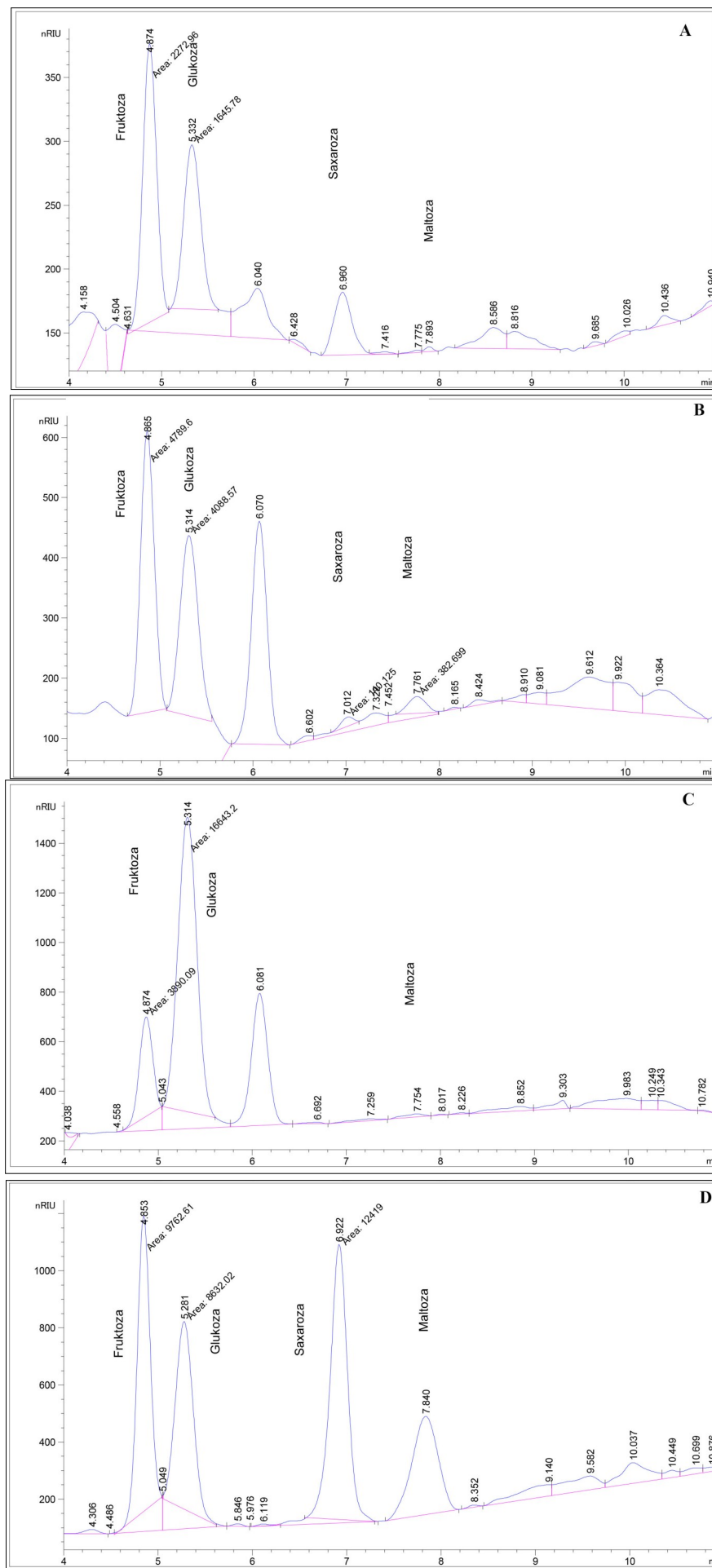


Fig. 2. High-performance liquid chromatography (HPLC) chromatograms showing soluble carbohydrate composition in different organs of *Myosotis alpestris*. A: roots; B: leaves; C: stem-flower tissues; D: standard mixture.

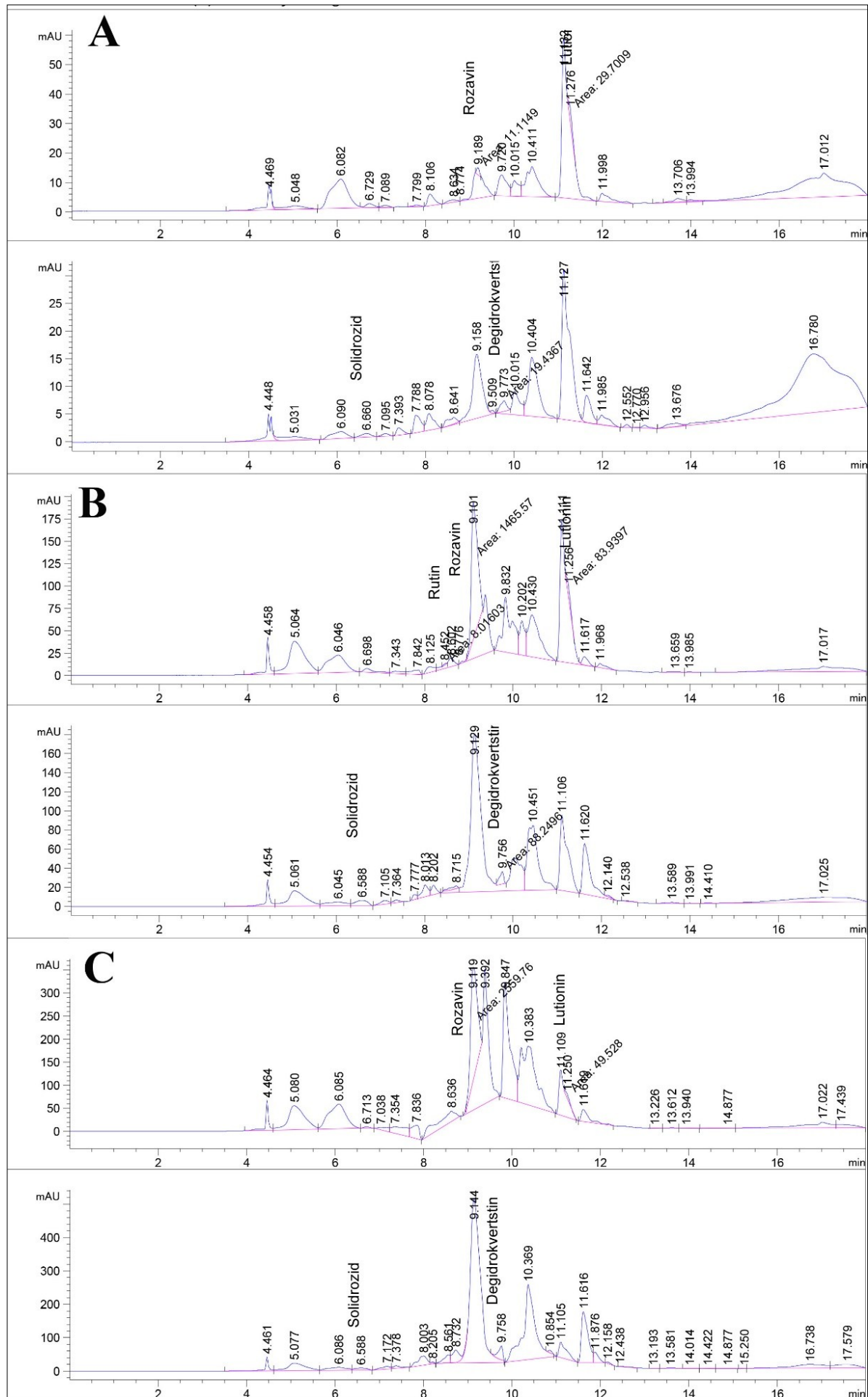
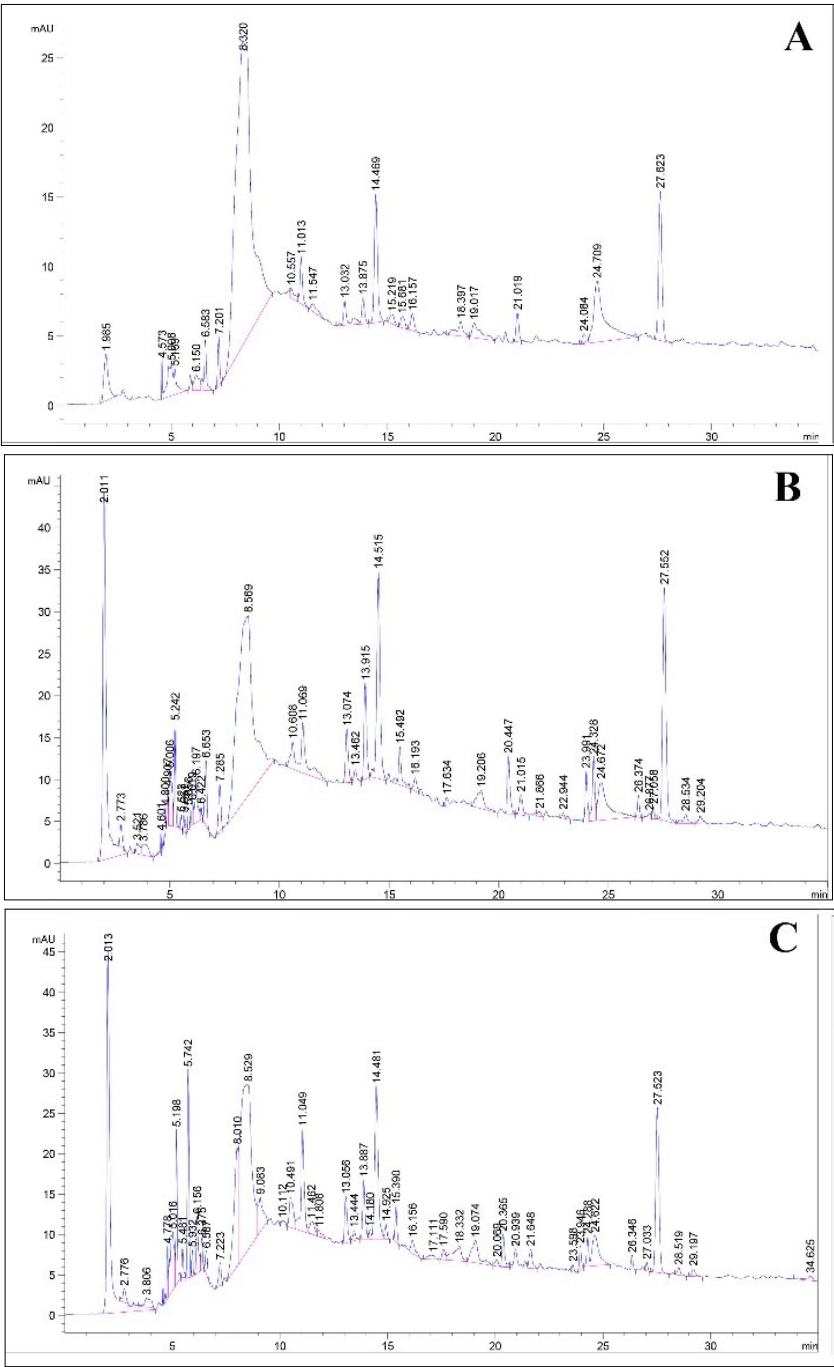


Fig. 3. High-performance liquid chromatography (HPLC) diode array detector chromatograms of flavonoid compounds in *Myosotis alpestris*. A: in leaf; B: in stem-flower; C: in root extracts. Major peaks correspond to phenolic compounds detected at 8–12 min retention time.

Table 2. Amino acid composition ($\mu\text{g g}^{-1}$ DW)

Amino acid	Stem-flower	Root	Leaf
Aspartic acid	0.125	0.031	0.020
Glutamic acid	0.175	0.039	0.083
Serine	0.157	0.117	0.063
Glycine	0.058	0.036	0.053
Asparagine	0.133	0.376	0.406
Glutamine	0.608	0.774	0.774
Cysteine	0.658	0.506	0.079
Threonine	0.066	0.020	0.094
Arginine	0.020	0.008	0.042
Alanine	0.100	0.117	0.155
Proline	0.080	0.136	0.368
Tyrosine	0.320	0.091	0.068
Valine	0.060	0.037	0.070
Methionine	0.078	0.074	0.063
Histidine	0.043	0.098	0.033
Isoleucine	0.029	0.023	0.045
Leucine	0.032	0.026	0.080
Tryptophan	0.024	0.008	0.148
Phenylalanine	0.081	0.161	0.016
Lysine	0.195	0.104	0.269
Total	3.041	2.781	2.929



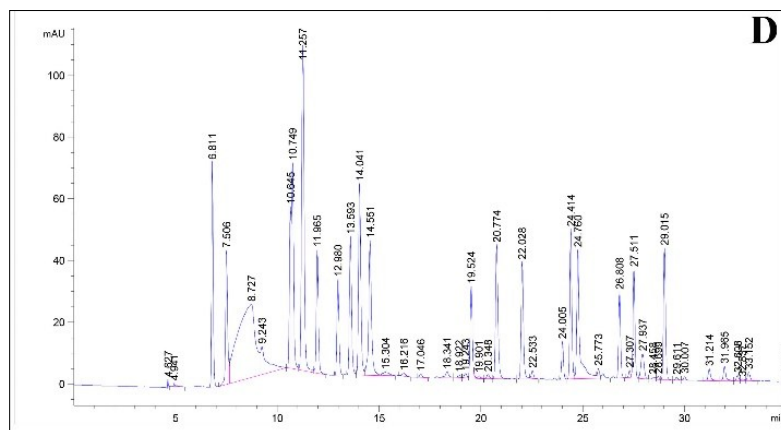


Fig. 4. High-performance liquid chromatography (HPLC) chromatograms of amino acid analysis (AAA). A: in root; B: in leaf; C: in stem-flower; D: in extracts and standard mixture.

Table 3. Vitamin composition ($\mu\text{g g}^{-1}\text{DW}$)

Vitamin	Stem-flower	Root	Leaf
B1	Not detected	0.01	Not detected
B2	0.65	0.65	0.08
B6	0.20	0.14	0.35
B9	2.90	3.60	2.05
B3	Not detected	Not detected	0.09
Vitamin C	0.56	0.05	0.20

Table 4. Macro-, micro- and trace element composition of different organs of *Myosotis alpestris* ($\mu\text{g g}^{-1}\text{DW}$)

Element	Root	Stem-flower	Leaf
Macroelements			
Calcium (Ca)	21723	24806	12999
Potassium (K)	3178	3178	3178
Magnesium (Mg)	1396	2302	1004
Phosphorus (P)	890	909	897
Sodium (Na)	445	327	666
Aluminium (Al)	348	3142	207
Iron (Fe)	503	3981	220
Manganese (Mn)	45.7	186	25.3
Titanium (Ti)	91.5	125	51.3
Microelements			
Zinc (Zn)	15.5	26.2	13.7
Copper (Cu)	7.15	10.6	11.8
Nickel (Ni)	1.10	3.92	1.21
Chromium (Cr)	1.71	4.77	1.67
Strontium (Sr)	54.8	90.8	51.2
Barium (Ba)	70.4	146	121
Molybdenum (Mo)	2.74	1.42	1.09
Lead (Pb)	0.858	3.76	1.47
Rare earth elements			
Lanthanum (La)	< 0.50	2.99	< 0.50
Cerium (Ce)	0.429	5.05	0.172
Praseodymium (Pr)	0.058	0.679	0.023
Neodymium (Nd)	0.231	2.15	0.090
Samarium (Sm)	0.045	0.430	0.018
Europium (Eu)	0.023	0.105	0.030
Gadolinium (Gd)	0.040	0.538	0.016
Dysprosium (Dy)	0.031	0.267	0.011
Holmium (Ho)	< 0.01	0.052	< 0.01
Erbium (Er)	0.017	0.126	< 0.01
Thulium (Tm)	< 0.01	0.016	< 0.01
Ytterbium (Yb)	0.012	0.080	< 0.01
Lutetium (Lu)	< 0.01	0.015	< 0.01
Trace/heavy elements			
Cadmium (Cd)	0.006	0.092	0.010
Arsenic (As)	0.196	1.28	0.165
Antimony (Sb)	< 0.10	0.213	< 0.10
Tin (Sn)	< 0.10	0.105	< 0.10
Thorium (Th)	0.095	1.07	0.037
Uranium (U)	0.017	0.114	0.016

also had a lead, at $3.76 \mu\text{g g}^{-1}$ DW (Supplementary Table 4). The leaves and roots had lead (Pb).

The observed patterns indicate organ-specific mineral allocation associated with physiological and reproductive functions.

Discussion

The observed distribution of metabolites in *M. alpestris* demonstrates pronounced metabolic specialisation among roots, leaves and reproductive tissues. Significant differences in the accumulation of carbohydrates, amino acids, vitamins and mineral elements indicate functional differentiation of plant organs.

Carbohydrate allocation and metabolic activity

Stem–flower tissues accumulated high concentrations of carbohydrates. The accumulation of carbohydrates in stem–flower tissues was consistent with the high energetic demands associated with flowering, reproduction and seed development. The fact that the stem and flower parts contained high amounts of glucose indicated that these tissues were metabolically active and had high energy demands. The leaves differed from the other organs, as they contained higher fructose concentrations. Elevated fructose concentrations in leaves likely reflect active photosynthetic carbon assimilation and carbohydrate metabolism. The higher fructose content in leaves is consistent with their role as the primary photosynthetic organs of the plant. The plant does not store a lot of sucrose in the leaves and stems. This is probably because the plant uses it rather than storing it.

The roots contained lower amounts of sugars. This is not surprising because the roots do not make food like the leaves do. The relatively low sugar content in roots may reflect their dependence on photo assimilates translocated from aerial source tissues. All these show that the plant has a system where the leaves make food and the flowers and seeds use it. Leaves function as primary source tissues, whereas flowers and seeds act as sink organs that utilise photosynthetically derived assimilates. These patterns support the classical source–sink model, in which leaves function as source tissues, whereas reproductive organs act as major carbohydrate sinks. Comparable organ-specific accumulation of soluble sugars has been observed in several herbaceous angiosperms, indicating a conserved strategy of carbon allocation among reproductive and vegetative organs.

Amino acid profile and nitrogen metabolism

Amino acid composition differed markedly among plant organs. Elevated concentrations of amino acids in stem–flower tissues may reflect increased N demand associated with flowering and reproductive development. Glutamine was detected in all analysed organs and represents one of the principal forms of N transport and remobilisation in higher plants. Higher proline concentrations in leaves may be associated with its well-known role in osmotic regulation, stress tolerance and protection against environmental stress. Increased cysteine accumulation in reproductive tissues may be related to sulphur (S) metabolism and the biosynthesis of S-containing compounds required during reproductive development.

The observed amino acid distribution patterns indicate strong metabolic specialisation among plant organs. Organ-specific accumulation of amino acids reflects differences in physiological functions and metabolic requirements. The predominance of

glutamine and proline is consistent with observations reported for other Boraginaceae and stress-adapted herbaceous species, where these amino acids play central roles in N transport and stress tolerance. The predominance of glutamine and proline is consistent with observations reported for other Boraginaceae and stress-adapted herbaceous species, where these amino acids play central roles in N transport and stress tolerance.

Nitrogen is an essential macronutrient required for the biosynthesis of amino acids, proteins, nucleic acids, chlorophylls and numerous secondary metabolites. In higher plants, nitrate and ammonium absorbed from the soil are assimilated into amino acids, which serve as the principal transport and storage forms of N. Therefore, elevated concentrations of amino acids detected in the leaves of *M. alpestris* may indicate active N assimilation and enhanced metabolic activity associated with photosynthetic tissues (23). Nitrogen metabolism is closely linked with secondary metabolism because N-containing compounds participate in the biosynthesis of phenylpropanoids and other specialised metabolites. Consequently, variations in amino acid accumulation may influence the synthesis of flavonoids and other antioxidant compounds detected in different plant organs (23).

Flavonoid accumulation and tissue specialization

Chromatographic profiles revealed more complex and intense phenolic patterns in aerial organs compared with roots. Several chromatographic peaks detected between 8 and 12 min likely correspond to flavonoids and related phenolic compounds commonly accumulated in photosynthetically active tissues.

Leaves are exposed to high solar radiation and temperature fluctuations, which may stimulate the accumulation of flavonoids. Therefore, the higher flavonoid content in leaves may contribute to protection against oxidative damage and photoinhibition caused by excessive solar radiation. Elevated flavonoid concentrations in reproductive tissues may additionally be associated with pigmentation, reproductive protection and defence functions during flowering.

In contrast, root extracts exhibited less complex chromatographic profiles. This pattern may reflect the reduced exposure of roots to environmental stressors and their distinct physiological functions. Reduced flavonoid accumulation in roots may reflect their limited exposure to ultraviolet radiation and other environmental stress factors compared with aerial organs. Increased flavonoid accumulation in aerial organs has been widely documented in mountain plants exposed to elevated ultra-violet radiation and temperature fluctuations.

The relatively high flavonoid content observed in *M. alpestris* is consistent with reports from other representatives of the Boraginaceae family, where phenolic compounds and flavonoids constitute important secondary metabolites involved in antioxidant defence and adaptation to environmental stress. Rosmarinic acid, caffeic acid derivatives, chlorogenic acid, quercetin, luteolin and kaempferol have been reported as characteristic phenolic constituents in numerous Boraginaceae taxa (24, 25). In addition, phenolic compounds in Boraginaceae species have been associated with strong antioxidant activity and protective functions against oxidative stress (24). The occurrence of these metabolites in *M. alpestris* suggests that the species may possess a biochemical profile like other Boraginaceae members, supporting its potential value as a source of natural antioxidant compounds and biologically active substances (24, 25).

Vitamin distribution and physiological roles

Water-soluble vitamins exhibited pronounced organ-specific distribution patterns. Folic acid plays an essential role in nucleotide biosynthesis, cell division and tissue growth. This may be because folic acid plays an important role in cell division and the synthesis of cellular components required for the formation of new cells. These processes occur extensively in the roots, where cells are continuously dividing and growing.

Ascorbic acid levels were highest in stem–flower tissues. Ascorbic acid functions as a major antioxidant involved in scavenging reactive oxygen species and maintaining cellular redox homeostasis. Ascorbic acid plays an important role in growth, development, embryogenesis and seed formation. This is because these processes require a substantial amount of energy. Elevated vitamin B6 concentrations in leaves may reflect its involvement in amino acid metabolism and protection against oxidative stress. Overall, vitamin distribution patterns indicate pronounced metabolic specialisation among plant organs, reflecting their distinct physiological functions and developmental requirements.

Mineral accumulation and ion homeostasis

Elemental analysis revealed notable differences in mineral content between organs. Calcium was the dominant macronutrient in all tissues, with the highest concentration recorded in stem–flower samples. The cell wall is very important. This plays a big role in keeping it stable. It is also involved in signalling when the plant is reproducing.

Iron and Al are high in the parts of the plant that're above the ground. Iron is essential for cellular respiration and photosynthesis and its higher concentration in aerial tissues may reflect increased metabolic activity in these organs. The relatively uniform distribution of potassium (K) among organs suggests effective maintenance of water balance and ion homeostasis. The presence of Zn and Cu in all parts of the plant is expected, as these essential micronutrients play important roles in the proper functioning of various plant enzymes.

Some other elements, like the earth elements are found more often in the stem and flower parts of the plant which suggests that the plant is moving these elements around in a special way. Although trace metals were detected at relatively low concentrations, their uneven distribution among organs suggests organ-specific uptake and translocation mechanisms.

Integrated metabolic perspective

Myosotis alpestris does not spread nutrients evenly throughout its parts. The parts that help with reproduction need a lot of energy and nutrients, so they have a lot of carbohydrates, amino acids, vitamins and minerals. The leaves are mainly in charge of taking in carbon and making important chemicals while the roots help keep the right balance of N and minerals.

This pattern of resource allocation may enable *M. alpestris* to optimise the use of its resources for growth, defence and reproduction. Therefore, *M. alpestris* must maintain a balance among these processes to ensure its survival and successful development.

To our knowledge, this study represents the first comprehensive organ-specific biochemical characterisation of *M. alpestris*, integrating carbohydrate, amino acid, vitamin, flavonoid and elemental profiles within a single analytical framework.

Conclusion

This study examined the organ-specific distribution of soluble carbohydrates, free amino acids, water-soluble vitamins, flavonoids and mineral elements in *Myosotis alpestris*. The results demonstrated pronounced metabolic differentiation among roots, leaves and stem–flower tissues. Reproductive organs accumulated high concentrations of carbohydrates and amino acids, whereas leaves were characterised by elevated fructose, proline and flavonoid contents. Roots showed relatively lower levels of most soluble metabolites but contained the highest concentration of folic acid. Elemental analysis further revealed organ-specific accumulation patterns of macro- and microelements, with calcium (Ca) and iron (Fe) particularly enriched in aerial tissues. These findings indicate a high degree of metabolic compartmentalisation associated with the physiological functions of different plant organs. The present study provides the first comprehensive organ-level biochemical characterisation of *M. alpestris* and contributes to a better understanding of its metabolic organisation. Future studies should focus on the identification of individual phenolic compounds, seasonal variation in metabolite accumulation and the ecological significance of biochemical adaptation in natural populations of this species. The identified patterns of metabolite accumulation may also provide a useful basis for investigations of the medicinal potential, phytochemical resource value and ecological adaptation of *M. alpestris*.

Acknowledgements

The authors sincerely acknowledge the Plant Cell Technology Laboratory of the Institute of Bioorganic Chemistry, Academy of Sciences of the Republic of Uzbekistan and the state project “Digital Nature: Development of a Digital Platform for the Flora of Central Uzbekistan” (2025–2029) conducted at the Institute of Botany, Academy of Sciences of the Republic of Uzbekistan.

Authors' contributions

DMM performed experimental analyses and data collection. KQK contributed to the study design and supervised the biochemical analyses. UAO assisted in laboratory work and data interpretation. GDP contributed to elemental analysis and methodological support. HMT participated in statistical evaluation and manuscript revision. GTK conceptualised the study, supervised the research, interpreted the results and prepared the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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