

VITAMIN COMPOSITION AND ELEMENTAL ANALYSIS OF *MEDIASIA MACROPHYLLA* (REGEL & SCHMALH.) PIMENOV UNDER NATURAL AND CULTIVATED CONDITIONS

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ABSTRACT

This study evaluated the water-soluble vitamin and mineral composition of *Mediasia macrophylla* (Apiaceae), a rare endemic species of Central Asian mountain ecosystems, across four wild-population phenological/organ samples (flowering phase, wild ecotype, seed-bearing phase, and aboveground biomass) from the Nurota and Zomin State Reserves, and one cultivated plantation sample (Baxmal district, Jizzax region). Vitamins (B1, B2, B3, B6, B9, C) were quantified by HPLC-DAD and macro- and microelements by ICP-MS; each sample was a composite pooled from five individual plants and analyzed in technical triplicate (n=3), so the reported values are descriptive means without biological replication and no inferential statistical test was applied. Pyridoxine (B6) and ascorbic acid (C) reached their highest measured concentrations in the seed-bearing-phase sample (13.73 and 4.63 $\mu\text{g g}^{-1}$, respectively), while folate (B9) was highest in the aboveground-biomass sample (11.20 $\mu\text{g g}^{-1}$). Elemental profiling showed high concentrations of potassium, calcium, magnesium, phosphorus, iron, zinc, and copper across samples, while measured lead concentrations remained below the applicable WHO safety threshold in all five samples. The combined vitamin and elemental composition indicates that *M. macrophylla* is compositionally rich and warrants further investigation as a candidate functional-food or medicinal raw material; however, these findings are based on a single-season, non-replicated comparison across sites and phenological stages, and any nutraceutical or phytopharmaceutical application should be regarded as provisional pending biologically replicated sampling and direct bioactivity or bioavailability testing.

Keywords: *Mediasia macrophylla*, Apiaceae, water-soluble vitamins, HPLC-DAD, ICP-MS, Elemental composition, Phenological variation, Phytochemistry, Nutraceuticals, Medicinal plants, Central Asian endemics.

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1. INTRODUCTION

The family Apiaceae Lindl. (Umbelliferae) is celebrated for its diverse bioactive secondary metabolites, particularly essential oils, coumarins, and terpenoids (Han et al., 2025; Kavallieratos et al., 2024), and within the arid, mountainous biomes of Central Asia the subtribe Ferulinae Drude shows an outstanding degree of endemism (Panahi et al., 2015; Khassanov et al., 2024). A characteristic example is the monotypic genus *Mediasia* Pimenov, represented solely by the Central Asian endemic *Mediasia macrophylla* (Regel & Schmalh.) Pimenov, named for “Asia media” (Middle Asia) and for its notably large leaves (Khojimatov & Bussmann, 2023). High-resolution distribution mapping confirms that *M. macrophylla* is restricted to isolated micro-refugia within the Tien Shan and Pamir-Alay mountain systems of Uzbekistan and Kyrgyzstan, including the Nurota and Zarafshan ranges, where narrow habitat specificity and low population density expose it to elevated conservation risk (Khassanov et al., 2024; Tojibaev et al., 2025).

Beyond its taxonomic interest, *M. macrophylla* (locally known as “alqor”) has a long history of use in Central Asian ethnobotany as a food-flavoring and preservative herb, and as a folk remedy for rheumatism, nephritis, eczema, herpes, and gastrointestinal and hepatic disorders (Chernenko et al., 2002; Khojimatov & Bussmann, 2023). Early

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phytochemical surveys identified neutral lipids, glycolipids, and phospholipids together with chlorophyll and carotenoid pigments in the leaves (Baser et al., 1997), while subsequent chromatographic work isolated new glucosides, polyacetylenic glycosides, and furanocoumarins from the aerial parts, together with flavonoid derivatives such as quercetin glycosides (Kurimoto et al., 2010, 2011; Ikromova et al., 2026). Volatile-oil profiling by GC–MS and HPLC has further confirmed that the secretory canals of *M. macrophylla* act as localized hubs for essential-oil biosynthesis (Dzhumaev et al., 1988; Khojimatov & Bussmann, 2023).

Despite this accumulating phytochemical knowledge, a critical research gap persists in the holistic biochemical characterization of the species: the baseline profile of water-soluble vitamins and the macro- and microelement composition of *M. macrophylla* has remained largely unquantified. Water-soluble micronutrients, particularly B-complex vitamins and ascorbic acid, perform vital regulatory functions in both plant metabolism and human nutrition, and their endogenous accumulation is known to be highly dynamic, fluctuating with phenological stage, organ type, and abiotic stress (Noctor & Foyer, 1998; Hanson & Gregory, 2011). This phenological dynamism has been directly demonstrated in other taxa: in the orphan leafy vegetable *Cleome gynandra*, phenolic and flavonoid accumulation varies markedly between vegetative and seed-set stages and among plant organs (Maina et al., 2021), while B-vitamin profiling by UHPLC-DAD-qTOFMS in *Moringa oleifera* has shown comparably stage- and tissue-dependent variation (Ngwenya et al., 2025). Concurrently, macro- and microelement profiling is essential, since these inorganic constituents govern enzymatic reactions and physiological processes while directly defining the nutritional and phytopharmaceutical value of the finished herbal biomass (White & Broadley, 2003; Marschner, 2012; Chen et al., 2022).

Whether wild and cultivated populations of the same species converge or diverge in this respect is an active question elsewhere in the medicinal-plant literature, with mixed outcomes reported: cultivated *Zingiber striolatum* accumulated more soluble sugar and protein than its wild counterpart, whereas the wild population retained higher potassium, sodium, selenium, and vitamin C (Yang et al., 2023), and a comparable wild-versus-cultivated divergence in mineral profile, attributed to differences in substrate and management, has been reported for *Opuntia* species using ICP-MS (Boudjouan et al., 2024). These precedents indicate that neither direction of difference can be assumed a priori for *M. macrophylla*, and that any observed divergence between its reserve-grown and plantation-grown populations requires direct, site-matched measurement rather than extrapolation from other taxa.

Understanding how these nutritional and inorganic components vary between wild populations and controlled cultivation is important for three principal reasons. First, tracking these fluctuations helps establish the phenological window associated with peak measured concentrations of specific compounds. Second, it clarifies whether environmental and edaphic factors are plausibly associated with the plant's biochemical composition an issue of direct relevance given ongoing efforts to domesticate *M. macrophylla* in experimental plantations to relieve harvesting pressure on its narrow, reserve-protected wild populations (Ikromova et al., 2025). Third, it provides descriptive baseline data that can inform, but does not by itself establish, standardized raw materials for the pharmaceutical, nutraceutical, and functional-food industries (Pimenov et al., 2011).

Consequently, the objective of the present study is to provide a comparative, descriptive evaluation of the vitamin profiles and elemental compositions of *Mediasia macrophylla* sourced from two natural reserve populations (Nurota and Zomin) across three phenological stages, and from one managed experimental plantation (Baxmal district, Jizzax region). We hypothesize that (i) water-soluble vitamin concentrations differ measurably across phenological stages, consistent with patterns reported in other taxa (Maina et al., 2021; Ngwenya et al., 2025), and that (ii) the elemental profile of the plantation-grown population differs from that of the reserve populations, consistent with the divergence reported for other wild-versus-cultivated comparisons (Yang et al., 2023; Boudjouan et al., 2024), though the direction of this difference is not predicted in advance. As the present sampling design uses technical rather than biological replication (see Section 2.5), these comparisons are reported descriptively, and confirmatory testing with biological replicates is identified as a priority for future work (Khazaei et al., 2026).

2. MATERIALS AND METHODS

2.1. Plant Material and Study Sites

Samples of *Mediasia macrophylla* (Regel & Schmalh.) Pimenov were collected from two protected natural populations — the Nurota State Reserve (Parandoz Mountain; 40.487° N, 66.778°E) and the Zomin State Reserve (Kulsay area; 39.591°N, 68.35°E) — and from a managed experimental plantation established in the Baxmal district of Jizzax region during the 2025–2026 vegetative seasons (Fig. 1, 2). Both reserve populations are located within officially protected areas with restricted access; sampling within reserve boundaries was conducted under Agreement No. 25/83, dated 15 March 2025, issued by Samarkand State University named after Sharof Rashidov, authorizing plant material collection for the present study, and no material was removed beyond the quantities required for analysis. Species identity was confirmed in the field against the diagnostic vegetative and floral

characters described for the species (composite umbels 5–10 cm in diameter with 13–23 unequal rays, broadly ovate leaves 20–60 cm long with a cordate base, and hollow, ridged, densely pubescent stems 0.5–1.5 m tall) (Eisenman et al., 2013).

To evaluate dynamic compositional shifts, raw biomass was systematically harvested across distinct phenological stages, including the vegetative phase, flowering period, and fruiting (seed-bearing) stage. The collected plant materials were separated into specific morphological organs (roots, stems, and leaves), shade-dried at ambient temperature until a constant weight was achieved, homogenized using a laboratory mill into a fine powder, passed through a 0.5-mm mesh sieve, and stored in hermetically sealed, light-protected containers at 4°C until chemical analysis (Pimenov et al., 2016).

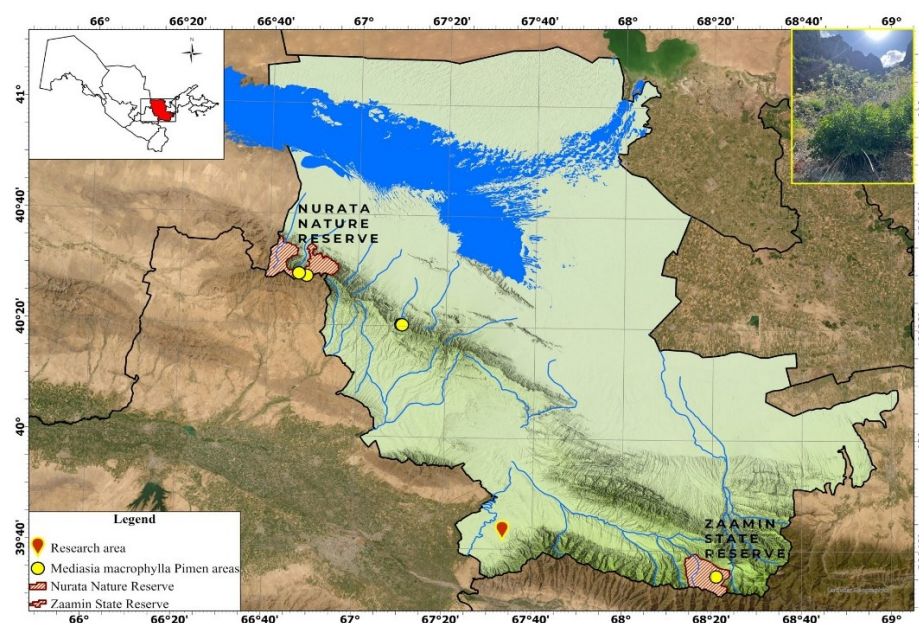


Fig. 1: Distribution of the studied *Mediasia macrophylla* populations in Jizzax and Samarkand regions, Uzbekistan. Yellow circles indicate known *M. macrophylla* occurrence areas within the Nurota and Zomin State Reserves; the marked point south of Nurota indicates the cultivated research plot (Baxmal district). Inset: natural habitat of *M. macrophylla* on rocky mountain slopes. Base imagery: Earthstar Geographics.



Fig. 2: Natural habitat and growth habit of *Mediasia macrophylla* at the Nurota State Reserve (Parandoz Mountain, 40.487°N, 66.778°E), corresponding to the wild-ecotype and flowering-phase samples summarized in Table 1 and Table 2.

The plantation trial in Baxmal district was established on a 5×6 m experimental plot on brown (bo'z) foothill soils, with seeds sown at 60 cm inter-row and 40 cm intra-row spacing following the incorporation of organic fertilizer and biohumus prior to sowing; no supplementary irrigation was applied, as seasonal precipitation (400–500 mm year⁻¹, concentrated in spring and autumn) was sufficient for plant growth (Fig. 3–5). This cultivated population provided the fifth comparative sample series (Sample 5 in Table 2) alongside the four natural-population series corresponding to the flowering phase, wild ecotype, seed-bearing phase, and aboveground biomass columns of Table 1.

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Fig. 3: Floral morphology of *Mediasia macrophylla* used for phenological staging: (A) individual flower; (B) simple umbellule; (C) compound umbel inflorescence. These reference structures define the flowering-phase and seed-bearing-phase sampling points reported in Table 1.



Fig. 4: Sequential stages of anthesis (flower opening) in *Mediasia macrophylla*, documenting bud development through anther dehiscence. This developmental sequence underlies the definition of the “flowering phase” and “seed-bearing phase” sampling windows used for the vitamin and elemental analyses in Tables 1 and 2.

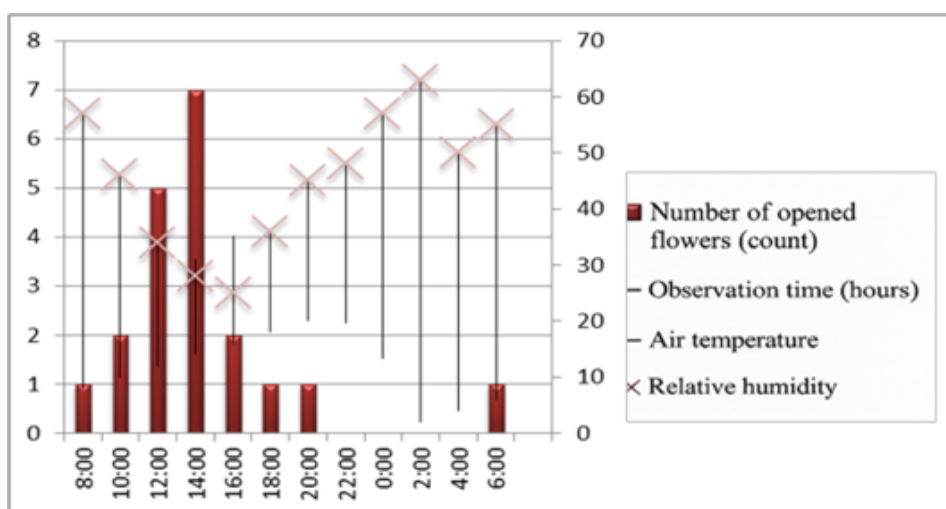


Fig. 5: Daily flowering rhythm of *Mediasia macrophylla*, showing the number of newly opened flowers, air temperature, and relative humidity recorded at four-hour intervals. Peak anthesis activity (12:00–14:00) informed the standardized daily sampling window used for tissue collection at the flowering and seed-bearing stages.

2.2. Extraction of Water-Soluble Vitamins

To isolate water-soluble vitamins (B1, B2, B3, B6, B9, and C) while preventing degradation of thermolabile constituents, an optimized, modified hydroalcoholic extraction protocol was developed. Accurately weighed aliquots (1.000 ± 0.001 g) of the pulverized plant tissue were transferred into a 300-mL flat-bottom flask and blended with 50 mL of a 40% (v/v) aqueous ethanol solution, a ratio selected to match the target polarity of both B-complex vitamins and ascorbic acid simultaneously.

Extraction was performed under continuous magnetic stirring coupled with a reflux condenser at a controlled temperature for 1 h to facilitate cellular rupture and maximize mass transfer into the liquid phase. Following reflux, the mixture underwent secondary maceration under constant agitation at room temperature (25°C) for a further 2 h. The primary extract was recovered by filtration; the residual biomass was re-extracted twice with separate 25-mL

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portions of 40% ethanol to ensure exhaustive recovery. All filtrate fractions were combined, adjusted to a final volume of 100 mL, and centrifuged at 7000 rpm for 10 min to remove residual particulates. The clear supernatant was used directly for HPLC quantification. Each phenological/organ sample was extracted and analyzed in technical triplicate ($n=3$), consistent with the precision limits reported in Section 2.3.

2.3. Chromatographic Quantification (HPLC) and Method Validation

Identification and quantitative determination of the water-soluble vitamins were performed on a high-performance liquid chromatography (HPLC) system equipped with a Diode Array Detector (DAD). Chromatographic separation was achieved using a reversed-phase analytical column maintained at constant temperature. Individual stock standard solutions for each target vitamin (B1, B2, B3, B6, B9, and C) were prepared at 1 mg/mL by dissolving 50.0 mg of high-purity crystalline reference standard in 50 mL of 40% ethanol; working standards spanning a multi-point concentration gradient were prepared by serial dilution.

The analytical methodology was validated in accordance with the International Council for Harmonisation (ICH) Q2 (R2) guideline (ICH, 2022), evaluating linearity, sensitivity, precision, and recovery. Five-point external calibration curves were constructed for each vitamin, yielding correlation coefficients $R^2 \geq 0.995$. The limit of detection (LOD) and limit of quantification (LOQ) were derived from signal-to-noise (S/N) thresholds of 3:1 and 10:1, respectively, spanning 0.01–0.05 $\mu\text{g/mL}$ (LOD) and 0.03–0.15 $\mu\text{g/mL}$ (LOQ). Intra-day precision (RSD, $n=3$) remained $\leq 3\%$, and inter-day precision monitored over three consecutive days yielded $\text{RSD} \leq 5\%$. Accuracy, assessed via standard-addition (spiking) experiments, gave recoveries of 92–105% with triplicate $\text{RSD} \leq 3\%$. Blank solutions and control standards were run within every analytical batch to monitor instrumental drift.

2.4. Macro- and Microelement Profiling via ICP-MS

Multi-elemental fingerprinting of *M. macrophylla* tissues was performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) preceded by an optimized microwave-assisted wet-digestion workflow, broadly consistent with established approaches for elemental analysis of medicinal plant matrices (WHO, 2007; Chen et al., 2022). Homogenized, moisture-free plant fractions (0.0500–0.5000 g) were weighed into high-pressure Teflon vessels with concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). Microwave digestion was executed using a Berghof MWS-3+ system employing a multi-stage thermal program up to 180–200°C to ensure complete organic matrix destruction. Digests were diluted to 50–100 mL with 0.5% (v/v) analytical-grade HNO_3 and filtered; method blanks were prepared in parallel.

Elemental profiling was conducted on an ICP-MS instrument (NEXION-2000) in multi-element scanning mode under ultra-pure argon plasma ($\geq 99.995\%$) with RF power of 1200–1500 W. Method validation using matrix-matched external multi-element standards showed calibration linearity $R^2 \geq 0.999$, an LOD envelope of 0.001–0.01 mg/kg, and precision of $\text{RSD} \leq 5\text{--}7\%$. Accuracy was continuously monitored using Certified Reference Materials (CRMs), giving recoveries of 90–110%. Quality-control protocols included systematic insertion of blank matrices, duplicate samples, and internal-standard drift monitoring. Five comparative sample series were profiled: four correspond to the natural-population phenological/organ series in Table 1 (flowering phase, wild ecotype, seed-bearing phase, aboveground biomass), and the fifth corresponds to the cultivated plantation population (Baxmal, Jizzax; Sample 5 in Table 2), enabling a direct wild-versus-cultivated elemental comparison.

2.5. Sampling Strategy and Statistical Analysis

For each phenological stage/organ combination in the wild populations, and for the cultivated Baxmal plantation, aerial biomass from five individual plants (spaced ≥ 50 m apart to reduce the likelihood of sampling clonally related individuals) was pooled prior to processing. This composite-sampling strategy was adopted specifically to obtain a representative sample of each population while minimizing the destructive removal of biomass from the reserve-protected, narrowly distributed wild populations of *M. macrophylla* (Tojibaev et al., 2025). Each pooled composite was then extracted and analyzed in technical triplicate ($n=3$ injections per composite), and the values reported in Table 1 and Table 2 are the means of these technical replicates. Collection was carried out during the 2025 growing season, timed to the flowering period (for flowering-phase and floral-morphology samples) and to the subsequent seed-set period (for seed-bearing-phase samples), with the cultivated Baxmal plantation sampled concurrently for comparability.

Because we did not replicate at the individual-plant level, the values reported here describe the sampled population at the time of collection. No inferential statistical test (e.g., ANOVA, t-test) was applied to compare phenological stages, organs, or sites, and apparent differences between samples are reported throughout as observed compositional differences rather than as statistically demonstrated effects. This is a deliberate constraint of working with a narrow-range, conservation-sensitive endemic rather than an oversight, and confirmatory studies using independently pooled composite samples per stage/site (i.e., true biological replication at the population level) are identified as a priority for future work (Section 5).

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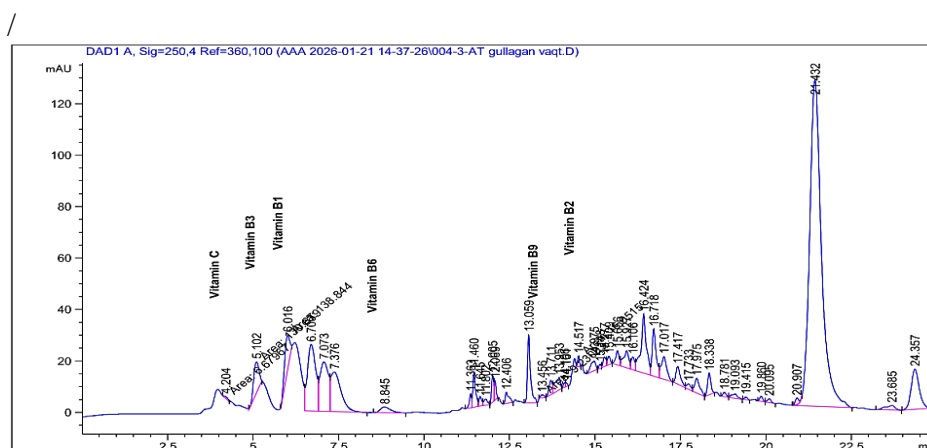
3. RESULTS

3.1. Dynamic Quantitative Profiling of Water-Soluble Vitamins

High-Performance Liquid Chromatography coupled with Diode Array Detection (HPLC-DAD) demonstrated that the synthesis and endogenous accumulation of water-soluble vitamins (B1, B2, B3, B6, B9, and C) in *Mediasia macrophylla* are highly dynamic and strictly regulated by phenological stage and habitat conditions (Table 1; representative chromatograms in Fig. 6–9). Values represent means of technical triplicates ($n=3$) from composite samples pooled from five individual plants per stage/site (Section 2.5), consistent with the intra- and inter-day precision limits reported in Section 2.3 ($RSD \leq 3-5\%$). The broad variation observed across phenological stages is described in detail below; possible physiological interpretations of this pattern are discussed in Section 4.1.

Table 1: Water-soluble vitamin composition ($\mu\text{g/g}$ dry weight) of *Mediasia macrophylla* at distinct phenological phases and ecotypes.

Target Analyte	Flowering Phase	Wild Ecotype (Nurata)	Seed-Bearing Phase	Aboveground Biomass
Thiamine (B1)	0.86	0.14	0.23	0.90
Riboflavin (B2)	1.47	2.02	2.66	1.47
Niacin (B3)	1.13	0.54	2.65	1.63
Pyridoxine (B6)	6.38	3.05	13.73	4.58
Folate (B9)	2.46	3.83	6.56	11.20
Ascorbic Acid (C)	0.44	0.75	4.63	1.50



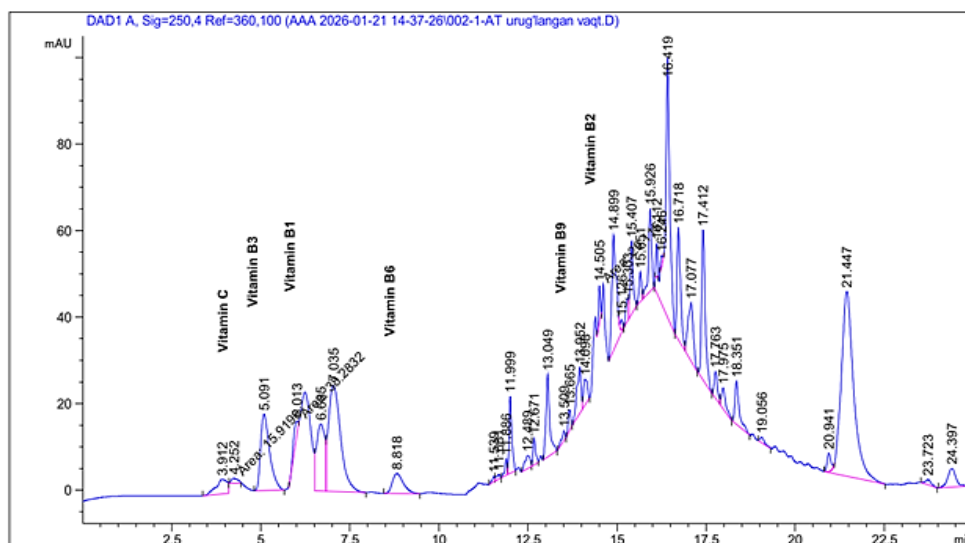


Fig. 8: HPLC-DAD chromatogram of the seed-bearing-phase extract (Sample 3), showing the elevated pyridoxine (B6) and ascorbic acid (C) peaks corresponding to the “Seed-Bearing Phase” column of Table I.

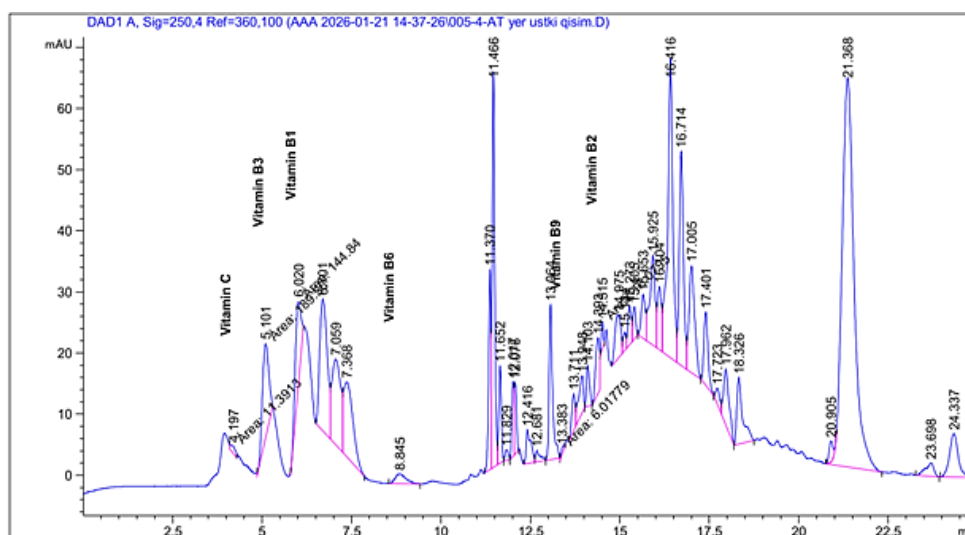


Table 2: Comprehensive elemental profiles (mg/kg dry weight) of *Mediasia macrophylla* samples.

No.	Order No.	Lab ID	Field ID	Sb	Te	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er
Analytical Detection Range							0.10-4000	0.50-4000	0.04-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000
1	1	1	1	<0.10	<0.30	0.065	48.8	0.257	0.501	0.068	0.262	0.054	0.016	0.034	<0.01	0.031	<0.01	<0.01
2	2	2	2	<0.10	<0.30	0.032	48.6	0.098	0.183	0.022	0.105	0.017	0.012	0.015	<0.01	0.014	<0.01	<0.01
3	3	3	3	<0.10	<0.30	0.040	27.3	0.200	0.405	0.047	0.215	0.038	0.013	0.030	<0.01	0.028	<0.01	0.014
4	4	4	4	<0.10	<0.30	0.042	33.0	0.210	0.394	0.049	0.551	0.038	0.013	0.032	<0.01	0.034	<0.01	0.016
5	5	Sample (Baxmal)	5	<0.10	<0.30	<0.02	1.31	<0.50	<0.04	<0.01	0.010	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

No.	Order No.	Lab ID	Field ID	Tm	Yb	Lu	Hf	Ta	W	Re	Pt*	Au *	Tl	Pb	Bi	Th	U
Analytical Detection Range							0.05-4000	0.04-4000	0.08-4000	0.01-4000	0.05-4000	0.05-4000	0.01-4000	0.1-4000	0.01-4000	0.01-4000	0.01-4000
1	1	1	1	<0.01	0.014	<0.01	<0.05	<0.04	<0.08	<0.01	<0.05	<0.05	0.011	1.21	0.019	0.082	0.026
2	2	2	2	<0.01	<0.01	<0.01	<0.05	<0.04	<0.08	<0.01	<0.05	<0.05	<0.01	0.929	<0.01	0.028	0.020
3	3	3	3	<0.01	0.012	<0.01	<0.05	<0.04	<0.08	<0.01	<0.05	<0.05	<0.01	0.977	<0.01	0.060	0.021
4	4	4	4	<0.01	0.015	<0.01	<0.05	<0.04	<0.08	<0.01	<0.05	<0.05	<0.01	0.641	<0.01	0.063	0.024
5	5	Sample (Baxmal)	5	<0.01	<0.01	<0.01	<0.05	<0.04	<0.08	<0.01	<0.05	<0.05	<0.01	0.485	<0.01	<0.01	0.017

Note: Values for regulated toxic elements (Pb, Cd, As) remained below the international safety thresholds established for botanical dietary matrices in all five sample series, including the cultivated population, consistent with WHO guidance for herbal materials (WHO, 2007). Full lanthanide-series (La–Lu) and additional ultra-trace element data (Ga, Y, Nb, Hf, Ta, W, Re, Pt, Au, Tl, Bi) were also recorded across all five samples at concentrations ≤ 1 mg/kg and are omitted from the summary tables for brevity; complete values are available from the authors on request.

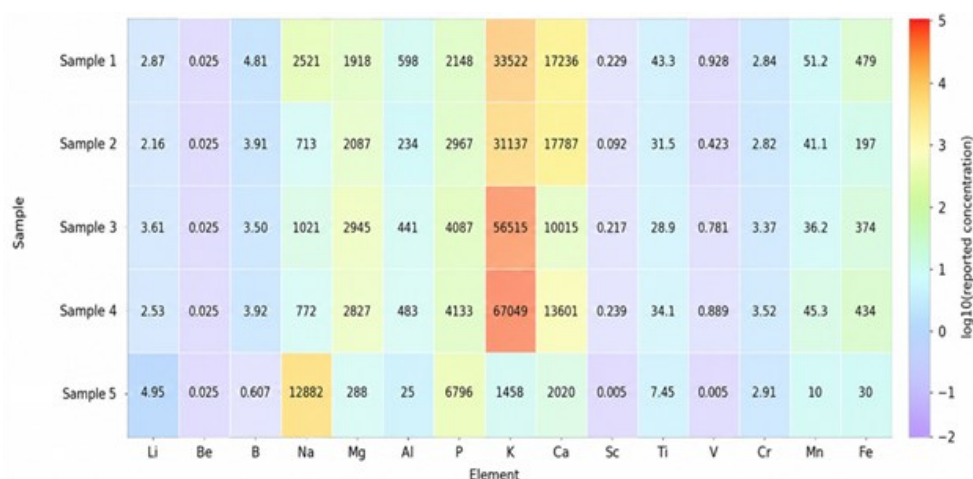


Fig. 10: Heatmap visualization of elemental concentrations in five analyzed samples. Values are presented as $\log_{10}$ -transformed concentrations, with color intensity indicating the relative abundance of each element. The heatmap highlights differences among samples, particularly for K, Ca, Na, Mg, and P, which exhibited comparatively higher concentrations, whereas Be, Sc, and V showed lower concentrations.

3.4. Essential Catalytic Micro-elements and Redox Centers

The micro-element profile revealed substantial quantities of essential catalytic metals, dominated by iron (Fe), which reached 479 mg/kg in the flowering-phase material, reflecting its role in electron-transport chains during mitochondrial respiration and chloroplast function, and its potential relevance to dietary iron-deficiency management. Zinc (Zn) remained within a stable range (10.9–15.9 mg/kg) across the wild-population series, consistent with tight physiological regulation of its structural roles in transcription factors and antioxidant-defense enzymes. Copper (Cu) values stabilized at 8.11–10.6 mg/kg, acting as a cofactor in cell-wall lignification and redox cascades. Low-level accumulation of specialized trace elements such as boron (up to 4.81 mg/kg), nickel (up to 4.72 mg/kg), and strontium (up to 124 mg/kg) reflects background uptake supporting minor enzymatic activity without indicating metabolic toxicity.

3.5. Wild versus Cultivated Elemental Profiles and Safety

A striking feature of the cultivated (Baxmal) population (Sample 5, Table 2) is its markedly lower potassium, calcium, magnesium, iron, and manganese content relative to the wild-population series, alongside a substantially higher sodium concentration (12,882 mg/kg versus 713–2521 mg/kg in the wild series). This pattern is consistent with the foothill, non-irrigated brown-soil setting of the Baxmal plantation described in Section 2.1, though possible contributing factors including soil salinity, mycorrhizal differences, and substrate heterogeneity were not directly

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measured and are discussed as hypotheses in Section 4.2. Antimony and tellurium were not detected ($< \text{LOD}$) in any sample series, and measured lead concentrations (0.485–1.21 mg/kg; Table 2) remained well below the WHO permissible limit of 10 mg/kg for botanical raw materials (WHO, 2007).

3.6. Representative Analytical Records

Representative HPLC-DAD chromatograms for each of the four natural-population sample series are presented in Fig. 6–9, documenting the resolved vitamin peaks (C, B3, B1, B6, B9, B2, in order of elution) underlying the quantitative values reported in Table 1.

4. DISCUSSION

4.1. Phenological Shifts and Metabolic Plasticity in Vitamin Biosynthesis

The quantitative profiles obtained here indicate a close correlation between the biosynthetic rate of water-soluble vitamins in *Mediasia macrophylla*, its ontogenetic stage, and local microclimatic conditions. This variability reflects the metabolic plasticity typical of medicinal xerophytes growing under harsh mountain conditions, where fluctuations in abiotic pressure drive up-regulation of primary and secondary metabolic pathways.

The sharp increase in pyridoxine (B6) and ascorbic acid (vitamin C) during the seed-bearing stage represents a key biochemical turning point (Fig. 8). Vitamin B6, acting through its coenzyme form pyridoxal 5'-phosphate, drives nitrogenous flux, amino-acid transamination, and structural protein translation in developing embryonic tissue, so its up-regulation during seed formation reflects increased demand for nitrogen reserves during reproductive growth. Concurrently, the rise in ascorbic acid reflects a cellular defense strategy: the transition to reproductive maturity accelerates aerobic metabolism and reactive oxygen species (ROS) production, and the plant's expanded vitamin C pool strengthens ascorbate–glutathione (Asada–Halliwell) cycle activity, protecting reproductive tissue from oxidative degradation (Noctor & Foyer, 1998).

The high folate accumulation (B9, 11.20 $\mu\text{g/g}$) in the aboveground vegetative biomass further supports these findings. Folates are essential cofactors for one-carbon transfer pathways, critical for *de novo* purine synthesis and formylmethionyl-tRNA formation during rapid vegetative cell division (Hanson & Gregory, 2011), confirming that *M. macrophylla* shifts its metabolic allocation dynamically to balance vegetative expansion against reproductive readiness (Fig. 11).

A comparable pattern of stage-dependent phytochemical reallocation rather than uniform accumulation has been reported in other taxa: in *Cleome gynandra*, total phenolic content peaked in generative organs while flavonoids accumulated preferentially in younger vegetative tissue (Maina et al., 2021), a partitioning logic consistent with the organ- and stage-specific pattern observed here for B6, C, and folate.

4.2. Comparative Ecotype Analysis: Wild versus Cultivated Populations

Comparing the wild Nurota-Zomin populations with the cultivated Baxmal plantation shows that the wild samples exhibited a more balanced vitamin profile and higher concentrations of key micro- and macro-elements (Table 2). Several mechanisms could plausibly contribute to this difference heterogeneous, rocky mountain substrates favoring specialized root-absorption strategies; interaction of wild root systems with native mycorrhizal fungi and plant growth-promoting rhizobacteria; and exposure to fluctuating temperature, wind, and restricted moisture as an abiotic stress factor but none of these factors was directly measured in this study, and they are proposed here as hypotheses for future investigation rather than as demonstrated causes.

In contrast, the Baxmal plantation setup showed a more selective accumulation pattern, with markedly elevated sodium and comparatively depleted potassium, calcium, magnesium, and iron relative to the wild series (Section 3.2.3). This pattern is consistent with the non-irrigated, brown-soil setting of the plantation described in Section 2.1; possible contributing factors including soil salinity, differences in mycorrhizal association, and reduced substrate heterogeneity relative to the rocky reserve sites were not directly measured in this study and are proposed here as hypotheses for future investigation rather than as demonstrated mechanisms. Whether “wild-simulated” cultivation practices could shift the plantation profile toward that of the wild ecotype is addressed as a research priority in Section 5, rather than as an established recommendation (Degtjareva et al., 2013).

This pattern of divergence between wild and cultivated material is not universal across medicinal and food plants: cultivated *Zingiber striolatum* accumulated more soluble sugar and protein than its wild counterpart, while the wild population retained higher potassium, sodium, and vitamin C (Yang et al., 2023) a mineral-retention pattern broadly consistent with the present findings whereas a comparable ICP-MS-based comparison of wild and cultivated *Opuntia* found the direction of mineral divergence to depend strongly on the specific element and tissue examined (Boudjouan et al., 2024). The vitamin composition and elemental profile of *Mediasia macrophylla* should be considered in the broader context of plant responses to environmental conditions and cultivation practices. Previous research on aquatic

plants has demonstrated the applicability of plant-based biotechnological approaches to water quality improvement (Rakhmonov et al., 2026), while ecological and sanitary assessments of algae have emphasized the importance of biological resources as indicators of environmental conditions (Aytbayeva et al., 2026). Although these studies address different organisms and research objectives, they provide complementary environmental context for investigating plant biochemical characteristics. The present study extends this perspective by comparing the vitamin and elemental composition of *M. macrophylla* collected from natural habitats and cultivated conditions. Taken together, these precedents suggest that the wild-versus-cultivated elemental divergence observed here for *M. macrophylla* is plausible and directionally consistent with at least one closely comparable system, but is not a generalizable rule that would allow the Baxmal result to be predicted from first principles alone.

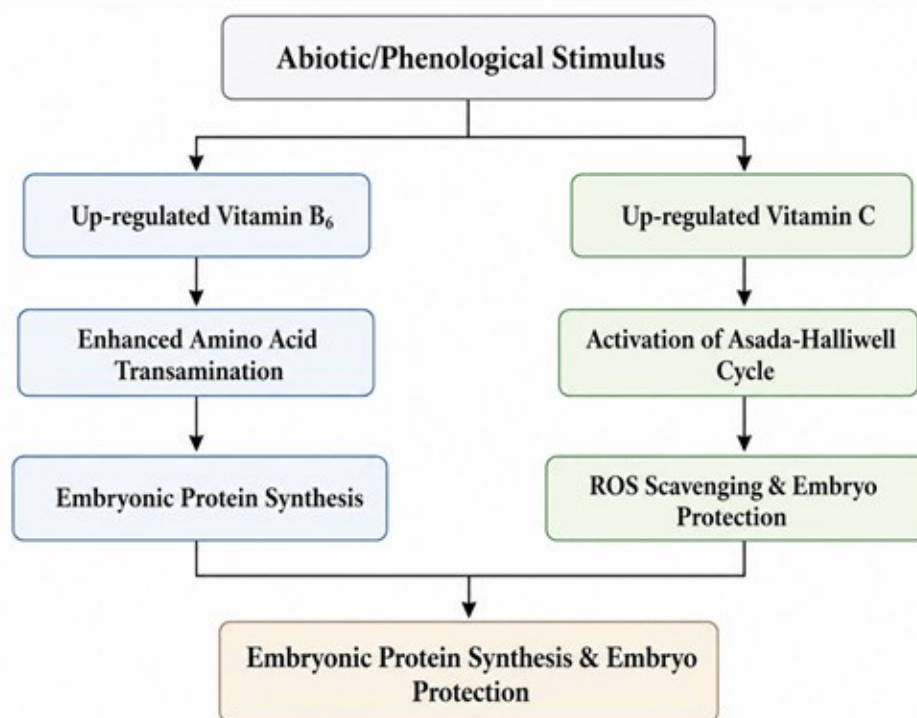


Fig. 11: Proposed biochemical response pathway linking phenological/abiotic stimulus to up-regulated Vitamin B₆ and Vitamin C accumulation and their convergent role in embryonic protein synthesis and oxidative protection during seed development, based on the patterns quantified in Table I.

4.3. Multi-Elemental Homeostasis and Human Therapeutic Potential

The exceptionally high concentrations of potassium and calcium indicate that *M. macrophylla* biomass is compositionally rich in these macro-elements relative to many reported medicinal-plant matrices. Potassium is known to modulate intracellular osmotic pressure and membrane electrical potential in plant and animal cells alike (White & Karley, 2010), and calcium serves a comparable structural and signaling role (White & Broadley, 2003) whether these concentrations translate into a measurable cardiovascular or bone-health benefit in human consumers depends on bioavailability and dosage, which were not assessed here and would require dedicated nutritional or clinical study. Iron and zinc are likewise present at nutritionally relevant concentrations, consistent with their established cofactor roles (Chen et al., 2022), though the same bioavailability caveat applies (Önder et al., 2024).

4.4. Phytochemical Matrix Synergy and Phytopharmaceutical Implications

A key feature of *M. macrophylla* is its complex multi-component matrix, in which vitamins and minerals co-occur with previously documented secondary metabolites quercetin-derived flavonoids, polyacetylenic glycosides, and volatile essential oils (Dzhumaev et al., 1988; Kurimoto et al., 2010, 2011; Ikromova et al., 2026). The co-occurrence of vitamins, minerals, and these secondary metabolites raises the possibility of synergistic interactions conceptually related to the pharmacological “entourage effect.” This remains an untested hypothesis; no direct interaction or bioavailability data are available for *M. macrophylla*, and confirming or refuting it would require targeted pharmacological assays.

This structural integration offers a plausible scientific rationale for the traditional ethnomedicinal use of *M. macrophylla* in treating hepatic disorders and gastrointestinal inflammation (Chernenko et al., 2002; Khojimatov & Bussmann 2023). While the multi-component matrix suggests potential for a broader multi-target therapeutic response

than any single isolated compound, this synergy hypothesis remains to be directly tested through targeted pharmacological and bioavailability studies.

4.5. Industrial Applications and Agronomic Directions

From a practical and industrial standpoint, these findings provide directives for agronomy and natural-product processing:

The seed-bearing phase is identified as the optimal harvest window for maximizing yields of water-soluble vitamins, particularly B6 and C.

Whether “wild-simulated” cultivation practices for example, controlled-deficit irrigation or rocky/organic soil amendment, could shift the plantation's elemental profile closer to that of the wild ecotype is not established by the present descriptive comparison and should not yet be treated as an agronomic recommendation; it is proposed here as a testable hypothesis for future controlled cultivation trials.

The consistently low lead concentrations measured across all sample series, wild and cultivated, remained well below the WHO permissible limit (WHO, 2007), supporting further investigation of *M. macrophylla* biomass as a candidate raw material for functional-food and phytomedicinal applications, pending the additional bioavailability and safety data outlined above.

5. CONCLUSION

This study provides an integrated, descriptive phytochemical and multi-elemental characterization of *Mediasia macrophylla* (Regel & Schmalh.) Pimenov, indicating its potential as a compositionally rich botanical resource warranting further nutritional and pharmacological investigation. The combined vitamin and elemental profiles reveal a chemical composition that differed between phenological stages and between the wild and cultivated populations sampled. The measured concentrations confirm that *M. macrophylla* is a source of pyridoxine (B6), folate (B9), and ascorbic acid (C), with the highest measured values occurring in the seed-bearing stage and aboveground-biomass composite samples, respectively — patterns consistent with heightened reproductive metabolic demand and antioxidant defense reported for other taxa during seed maturation (Noctor & Foyer, 1998).

Beyond its vitamin profile, the species shows a mineral composition characterized by substantial macro-elements (K, Ca, Mg, P) alongside micro-elements (Fe, Zn, Cu) with established physiological roles in plant enzymatic activation and cell-wall stabilization. The comparison between the wild and cultivated composite samples further suggests that habitat and cultivation practice are associated with differences in both vitamin and mineral profile, a finding directly relevant to designing future, biologically replicated cultivation trials. Because this comparison rests on pooled composite samples analyzed in technical triplicate rather than independent biological replicates (Section 2.5), treat these associations as hypothesis-generating rather than conclusively demonstrated effects, and regard the phenological pattern identified here as a candidate harvesting window pending confirmation.

Future research should prioritize, in order of methodological precedence: (i) biologically replicated sampling (independent pooled composites per stage/site) to allow formal statistical testing of the patterns described here; (ii) in vivo bioavailability and pharmacokinetic evaluation of the vitamin–mineral–metabolite matrix; (iii) molecular and genetic characterization of the pathways regulating phenology-dependent metabolite biosynthesis; and (iv) controlled cultivation trials testing whether wild-simulated practices shift the plantation elemental profile toward that of the wild ecotype. In conclusion, *Mediasia macrophylla* represents a compositionally promising natural resource whose, nutritional and prospective pharmacological value warrants continued, methodologically rigorous evaluation to support its sustainable utilization.

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Data Availability: Data will be available at request.

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Author's Contributions: This study was a collaborative effort among all authors. Yulduzoy Ikromova, Zebiniso

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