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ABSTRACT

of the dissertation for the degree
of Doctor of Science

ECOLOGICAL AND ANATOMICAL STUDY OF SOME MEDICINAL PLANTS DISTRIBUTED IN THE MOUNTAINOUS AREA OF THE LESSER CAUCASUS UNDER EX SITU AND IN SITU CONDITIONS

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GENERAL CHARACTERISTICS OF THE WORK

Relevance and degree of development of the topic. At present, due to climate changes, edaphic environment destruction, urbanization, and industrial impacts, the structural-functional stability of ecosystems is undergoing degradation[1]. These alterations induce significant transformations in the morpho-anatomical structure, physiological processes, and metabolic potential of plant organs, particularly in species of medicinal importance[2,3]. Under such conditions, the study of anatomical and micromorphological traits of medicinal plants formed across diverse ecological zones holds special significance not only for fundamental botany but also for pharmacognosy, ecophysiology, biomonitoring, and biotechnology. This study, devoted to the comparative investigation of ecological-anatomical adaptations of medicinal plants distributed in mountainous ecosystems under both ex situ and in situ conditions, provides opportunities for the rationalization and scientifically grounded optimization of medicinal plant raw material resources. Furthermore, examining the structural adaptations of medicinal plants is critical for assessing their resilience to ecological pressures and for developing effective conservation strategies.

For the first time in the flora of Azerbaijan, a comparative ecological-anatomical analysis of medicinal plants used in folk medicine and phytotherapy was conducted under ex situ and in situ conditions[4,5].

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[4] Ibadullayeva, S.J. Traditional folk medicine of Azerbaijanis / S.J. Ibadullayeva - Baku: Savad, - 2024. - 264 p.

[5] Sardarova, A.S., Ibadullayeva, S.J. Ecological anatomical study of structural-plastic response reactions of the medicinally important species *Laurus nobilis* L. (Lauraceae Juss.) in various ecological conditions // - Baku: Plant & Fungal Research, - 2025. 8(1), - p. 23-35. Agris

The variability of stomata, trichomes, parenchyma and sclerenchyma tissues, secretory structures, and other anatomical indicators across different ecotypes holds both fundamental and applied significance for identifying adaptation mechanisms and assessing the degree of ecological plasticity. The comparative eco-anatomical analysis of medicinal plant species whose natural populations exist in the ex situ study area, based on three different samples, has demonstrated the relevance of investigating this group of plants under both mountainous in situ and ex situ conditions.This research enables a scientifically grounded evaluation of their adaptive potential and the establishment of structural-functional stability during the process of introduction. At the same time, it contributes to the understanding of the species' adaptive mechanisms, evolutionary potential, and systematic variation. One of the contemporary directions in ecological-anatomical research is the detection and analysis of accumulants in plant organs, the intracellular or intercellular origin of which remains unclear (presumably of exogenous origin)[6]. These accumulants are regarded, on the one hand, as biomarkers of plant adaptation and tolerance strategies, and on the other hand, as indicators of ecotoxicological processes. Their formation may be associated with the bioaccumulation of heavy metals, the synthesis of phytotoxins, the localization of secondary metabolites, and the metabolic restructuring that occurs under stress conditions[7,8,9].

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[9] Doğan, M. Civil Dere suyunda bulunan ağır metal iyonlarının *Allium cepa* L. (*Amaryllidaceae*)'da teşvik ettiği fizyolojik, sitogenetik ve anatomik değişimlerin araştırılması / M. Doğan, E. Yalçın, A. Acar [ve ark.] // Gaziosmanpaşa Bilimsel Araştırma Dergisi (GBAD), - 2018. 7 (2), - s. 01-13.

The integration of these anatomically visualized structures into phytochemical and biochemical studies opens new avenues for assessing the responses of medicinal plants to ecological risks[10,11].

During the study, nonspecific deposits were recorded in the cell and tissue structures of medicinally important species collected from polluted environments. An important point of the research is that, although the plants displayed normal development in terms of morphological indicators, anatomical investigations confirmed their exposure to contamination processes. This finding substantiates that anatomical analyses serve as more precise biomarkers and as sensitive indicators of ecological pressure. Such results also carry fundamental significance for assessing the risks associated with the medicinal and nutritional use of plants collected from contaminated areas.

The ecological-anatomical study of medicinal plants belonging to different ecological groups allows for the identification of their morpho-physiological adaptation mechanisms. Such comparative analyses are particularly important for evaluating the influence of ecological factors on structural changes at the cellular and tissue levels[12,13]. Consequently, it becomes possible to scientifically substantiate the ecological resilience, adaptive potential, and eco-structural prospects of medicinal plants. Comparative ecological-anatomical studies of medicinal plants across diverse ecosystems reveal the range of their morpho-physiological adaptations and the degree of their ecological plasticity. These investigations hold fundamental significance for ecosystem stability and the conservation of plant diversity.

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[10] Korkmaz, S. Endemik *Prometheum chrysantum* subsp. uludaghense Ulu kaya göbeği (*Crassulaceae*/Damkoruğugiller) alt türü üzerinde morfolojik ve anatomik özelliklerin araştırılması: / Biyoloji Anabilim Dalında Yüksek Lisans tezi. / - Bursa, 2024. - 35 s.

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[12] Tutayuq, V.X. Bitki anatomiyası və morfologiyası / V.X. Tutayuq - Bakı: Maarif, - 1967. - 193 s.

[13] Hümbətov, Z.İ. Bitki morfologiyası və anatomiyası / Z.İ. Hümbətov - Bakı: Apostroff, - 2017. - 691 s.

In our country, a number of researchers have contributed to the study of plant anatomy[14,15,16,17,18]. However, unlike those works, the present research is dedicated specifically to the ecological anatomy of medicinal plants. Studies directed toward ex situ and in situ investigations have to some extent been conducted by foreign scholars[19,20,21]. The comparative study of the ecological-anatomical characteristics of medicinal plants distributed in the mountainous areas of the Lesser Caucasus and of their ecotypes growing under ex situ conditions in the Ganja region is highly relevant for understanding the floristic diversity of the region and plant adaptation. In this line of research, determining

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[16] Aliyeva, I.F. Morphological and anatomical analysis of vegetative organs of *Avena pilosa* (Roem. & Schult.) Bieb // Bulletin of Science and Practice, - 2021. 7(4), - p. 28-31.

[17] Gurbanova, L. Morpho-anatomical analysis of the species *Origanum vulgare* L. (Lamiaceae Lindl.) // Nature & Science International Scientific Journal, - 2025. 7(4), - p. 14-18.

[18] Qəbilov, Y.M., Cahangirli, S.N. Zaqafqaziya kəklikotu (*Thymus transcaucasicus* L.) bitkisinin morfoloji-anatomik quruluş xüsusiyyətləri // Botaniki tədqiqatlarda yeni çağırışlar: Azərbaycan Milli Elmlər Akademiyası Botanika İnstitutu və Azərbaycan Botaniklər Cəmiyyətinin akademik Vahid Cəlal oğlu Hacıyevin 90 illiyinə həsr edilmiş konfrans materialları, Bakı, - 20-21 iyun, - 2018, - s. 296-298.

[19] Apostol, M. Morphological, anatomical, physiological and genetic studies of *Iris aphylla* L. wild species conservation in "ex situ" conditions / M. Apostol, L. Draghia, C. Sîrbu [et al.] // Agriculture, - 2024. 14, - 2358.

[20] Bulavin, I. Morphology, anatomy, ploidy level and genetic similarity investigation of the *Prunus persica* (L.) Batsch 'Dostoyniy' ex situ and in vitro / I. Bulavin, A. Sidyakin, N. Miroshnichenk [et al.] // BIO Web of Conferences IX International Scientific Conference on Agricultural Science 2024 "Current State, Problems and Prospects for the Development of Agricultural Science", - 2024. 141, - 01002.

[21] Khamraeva, D. T. Comparative anatomical study of underground and aboveground organs in Ferula tadshikorum Pimenov under natural and introduced environments / D. T. Khamraeva, D. N. Tukhtaeva, O. K. Khojimatov [et al.] // Acta Biologica Sibirica, - 2024. 10, - p. 9-29.

the structural and functional dynamics of secretory tissues that ensure the synthesis of biologically active components in medicinal plants is of scientific importance in terms of potential pharmacological use. Overall, the studies carried out create opportunities for integrating the ecological-anatomical features of medicinal plants with pharmacoecological, ecophysiological, metabolomic, and biotechnological perspectives. This is of fundamental scientific and practical importance both for the conservation and sustainable use of biodiversity and for the establishment of a pharmacological raw material base resistant to ecological stress.

Object and subject of the research. The object of the study consists of specimens of certain medicinal plants distributed in the mountainous areas of the Lesser Caucasus under both ex situ and in situ conditions, as well as medicinal plants collected from various ecosystems of the Lesser Caucasus. The subject of the study is the comparative ecological-anatomical investigation of medicinal plants obtained from ex situ and in situ environments. In addition, the research includes an analysis of the structural adaptation potential of several medicinal plant species distributed in the study area under conditions of ecological pressure.

Objectives and tasks of the research. The aim of the study is to investigate, through comparative ecological-anatomical methods, the structural and functional adaptation characteristics of medicinal plants in various ecotopes, taking into account their regular supply within the flora of Azerbaijan. In ecosystems subjected to ecological pressure, the study further seeks to perform eco-anatomical analyses of histostructural and anatomo-functional modifications and their restructuring. To achieve this aim, the following objectives have been established:

➢ Preparation of transverse and median-lateral longitudinal sections of generative and vegetative organs of medicinal plant specimens under ex situ and in situ conditions, followed by the application of reagents using histochemical methods.

➢ Microscopic analyses of transverse and longitudinal sections of generative and vegetative organs of medicinal plants studied under ex situ and in situ conditions, with the anatomical identification of ecotypic structural features of plant tissues (using objectives at magnifications of 4×, 10×, 40×, 60×, and 100×).

- Preparation of permanent slides from the most representative transverse and longitudinal sections of generative and vegetative organs of medicinal plants studied under ex situ and in situ conditions.
- Implementation of a statistical approach through the application of quantitative biometric analysis methods (including digital software, digital micrometer, eyepiece and stage micrometers) to compare micron-scale measurements in transverse and longitudinal sections of the studied medicinal plant organs, with calculated micron values mapped onto micrographs.
- Visual investigation of the structural configurational specificity of medicinal plants under ex situ and in situ conditions in terms of eco-anatomical, pharmacoecological, and ecophysiological aspects of tolerance.
- Micrographic analysis of the metabolomic and anatomically characterized phytogenic adaptations of medicinal plants distributed in the mountainous regions of the Lesser Caucasus.
- Comparative ecological-anatomical analyses of exogenous and endogenous tissues formed in medicinal plants under ex situ and in situ conditions, which hold phytochemical and diagnostic significance in pharmacy.
- To conduct micrographic observations of leaf tissue in transverse and lateral-longitudinal sections to study the structural and functional characteristics of stomatal aperture in terms of optimizing the aqua-conductive system for physiological adaptation under stress conditions.
- Eco-structural diagnostic anatomical investigation of medicinal plants from various ecological groups.
- Ecological-anatomical analysis of structural adaptations in medicinal plants in response to anthropogenic landscape dynamics resulting from urbanization, with a focus on tolerance aspects (including structural deformations and stomatal anomalies in medicinal plants exposed to urbanization).
- Microscopy of the restructuring process and anomalous intracellular and intercellular inclusions in medicinal plants subjected to

phytocontamination.

➢ Identification of the eco-physiological structural configurational characteristics of certain medicinal plants with bioremediation potential that contribute to ecosystem balance and biodiversity.

➢ Ecological-anatomical investigation of the structural-functional adaptive capacities of medicinal plants from arid and saline areas, with abiotic stress as an ecological pressure factor.

Research methods.

1. Longitudinal and transverse sections were obtained from the medicinal plants under study using anatomical methods, and histochemical techniques were applied for differential staining of tissues with histological dyes.
2. The use of histochemical and technical reagents, as well as auxiliary agents, ensured high-quality and long-lasting preparations and enhanced the effectiveness of staining.
3. Temporary and permanent slides were prepared using various mounting media, with the application of appropriate technical mounting tools.
4. Microscopy methods were employed for detailed structural analysis of the obtained anatomical sections, utilizing all objective magnifications (4×, 10×, 40×, 60×, and 100×).
5. Micrometric measurements of the anatomical sections were determined using biometric methods. Comparative quantitative indicators of structural dimensions in different tissue components of plant ecotypes under *ex situ* and *in situ* conditions were statistically analyzed.

The main provisions put forward for defense. As a result of this study, the anatomical adaptation structures of medicinal plants formed under different ecological conditions in the flora of Azerbaijan were comparatively investigated, and their ecological plasticity range was determined based on quantitative indicators.

As a result of the conducted studies, the following conceptual approaches were developed and formulated as propositions:

➢ For the first time, a comparative analysis of medicinal plants under in situ and ex situ conditions was conducted, leading to the proposal of a new ecological-anatomical assessment concept based on the anatomical criteria of adaptive structures in these species, as well as the processes of acclimatization and naturalization during the introduction phase.

- For the first time, it has been demonstrated within the framework of ecological anatomy evolution that anatomical transformations are not only adaptive responses but also mechanisms for the emergence of stable ecomorphological innovations at the population level.
- In the arid and saline ecosystems of the Lesser Caucasus, adaptation indicators in medicinal plants, the accumulation of anomalous inclusions in species with phytocontamination and bioremediation potential, and tissue restructuring were studied; in urban ecosystems, developmental mechanisms and structural deformations were examined. The results have established the methodological foundation for modeling the ecological adaptation of plants.
- Based on the ecostructural analysis of medicinal plants, the differentiation of diagnostic anatomical features at the ecogroup level was carried out. At the same time, the functional adaptation mechanisms and ecological plasticity indicators across various ecopopulations were explained within a conceptual framework as objects of comparative evaluation on a quantitative basis.
- Anatomical changes formed under the influence of various ecological stress factors were interpreted through a new scientific concept as the induced morpho-physiological plasticity of plant tissues.

Scientific novelty of the research. For the first time in the flora of Azerbaijan, the ecological-anatomical adaptation structures of medicinal plants under in situ and ex situ conditions were comparatively studied on a quantitative basis, and the methodological foundation of ecotope-based differentiation and adaptive mechanisms was scientifically established. A comparative anatomical analysis of two ecotype samples of 20 medicinal plant species, widely used in both conventional medicine and folk remedies, was conducted under in situ and ex situ conditions, yielding species-specific results based on scientific novelty. In *Quercus iberica*, the presence of bicatenary palisade parenchyma, intensity of sclerenchyma, collenchyma, and trichomes, as well as the occurrence of capitate trichomes only in the in situ leaf specimens, were documented. In *Armoracia rusticana*, the presence of multilayered periderm, lysigenous cavities, and a compact vascular system was identified. In *Fragaria vesca*, polyderm activity in the rhizome and the exclusive detection of capitate trichomes on the petiole of in situ samples were observed. In *Salvia nemorosa*, ecotypic differences in root protoxylem and sclerification were identified for the first time as novel scientific findings. In *Papaver orientale* and *Fragaria vesca*, cryptostoma structures in in situ conditions and epistoma structures in ex situ conditions were incorporated into the scientific system for the first time. In *Mentha longifolia*, the perimedullary parenchymatic accumulation, the presence of bordered-pit structures in the medullary cells of the rhizome, and the activity of tectorial and capitate trichomes were identified in the in situ specimen as adaptive anatomical markers of the mountainous ecosystem.

In the leaf of the sciophyte-type medicinal plant *Convallaria majalis*, the atypical horizontal orientation of palisade cells was recorded for the first time in scientific literature. This structure exhibited more active modulation in in situ samples. Differential development of protective tissue in the rhizome under in situ conditions, and of the fundamental parenchyma under ex situ conditions, was confirmed through detailed investigation. In *Urtica dioica*, the intensity of endogenous and exogenous secretory tissues in in situ conditions was documented as an adaptive anatomical structure using micrographic indicators. In *Vinca herbacea*, *Persicaria hydropiper*, and *Silybum marianum*, the functional activity of schizogenous and lysigenous cavities, and in *Tragopogon pratensis*, *Papaver orientale*, and *Taraxacum officinale*, the functional activity of laticifer secretory tissues in in situ samples were determined based on scientific evidence. For the first time in the flora of Azerbaijan, the isobilateral (*Peganum harmala*) and pseudoisobilateral (*Tragopogon pratensis*) leaf structures have been identified and introduced into botanical science as novel leaf types, representing a scientific innovation in the field of plant morphology and anatomy. Under urban conditions, epidermal hypertrophy in *Taraxacum officinale* and stomatal anomalies in *Plantago lanceolata*, the isolation of anomalous inclusions in tissues under contamination conditions as adaptive anatomical responses of medicinal plants, the modified protoxylem with aerenchymatic structure in *Typha latifolia* as a marker of phytoremediation potential, and the detection of anomalous accumulates in the seeds of *Salix alba* at the microscopic level were all integrated into the scientific system.

For the first time in the flora of Azerbaijan, Kranz anatomical structures corresponding to the C_4 photosynthesis type - which limits photorespiration under high temperature and low CO_2 conditions - were identified in extreme ecosystems in *Salsola nodulosa*, *Tribulus terrestris*, and *Portulaca oleracea*, providing both theoretical and practical contributions to the scientific database. In xerophyte, xeromesophyte, hydrophyte, hygrophyte, and mesophyte species, anatomical structures exhibited adaptive differentiation consistent with the plant's ecological group. These findings reflect the scientific basis of eco-group level eco-anatomical analyses conducted for the first time in the flora of Azerbaijan. In the ecotypes of *Laurus nobilis* and *Tribulus terrestris*, trichomes, bicatenary palisade, sclerification, and subepidermal cell transformations were documented for the first time as novel scientific findings. As adaptive structures to arid and saline ecosystems, in *Zygophyllum fabago* and *Salsola nodulosa*, water-accumulative vacuoles, conservative bicatenary palisade parenchyma, cuticle thickening, sclerification intensity, and radical-succulent leaf structures were identified as anatomical markers corresponding to ecological pressures.

For the first time, a systematic eco-anatomical analysis was conducted on 61 plant specimens belonging to 32 species of the flora of Azerbaijan under in situ and ex situ conditions, considering phytocontamination, bioremediation, urbanization processes, as well as various ecological groups and ecosystem levels. This study represents a significant scientific innovation, providing a contemporary and relevant research direction for the flora of Azerbaijan and facilitating integration with international methodological approaches.

Theoretical and practical significance of the study. For the first time, a comprehensive comparative analysis of the anatomical adaptation structures of medicinal plants under ex situ and in situ conditions has been conducted, providing a practical basis for ecological-anatomical diagnostics. The variations of root and rhizome polyderm, vascular and mechanical elements recorded in different ecotypes through comparative microscopy are considered practical indicators for assessing adaptation potential across ecosystems. Differences observed in trichomes with endogenous and exogenous secretory tissues, laticifers, and in schizogenous and lysigenous cavities provide practical material for bioanatomical and pharmacoanatomical phytodiagnostics. The intensity of development and morphotype diversity of tectorial, capitate, and stellate trichomes support the development of a morphological-anatomical indicator system for ecological monitoring.

Mesodermal heteromorphism, stomatal variation, and differential localization dynamics in secretory tissues can serve as biophysical markers of ecological plasticity. The quantitative study of differential tissue-level responses recorded in ecotypes of medicinal plants under ex situ and in situ conditions serves as a practical indicator of their structural adaptation potential. The differentiation of constitutive and ergastic substances formed under different conditions is significant for environmental diagnostics and can be applied in delineating ecological risk zones. Anatomical changes more pronounced in in situ samples, along with the polymorphism of pharmacoanatomical diagnostic structures, provide practical opportunities for regional rationalization of medicinal plant resources, as well as for optimizing introduction and conservation measures. These ecological-anatomical markers also provide a practical basis for biomonitoring in plant breeding, plant ecology, biodiversity conservation, plant physiology, phytochemistry, phytogeography, pharmacognosy, plant systematics, ethnobotany, and related fields. Analysis of specialized anatomical structures in diverse ecological conditions demonstrates their practical applicability in bioanatomical assessment of the environment. Results from ecological-anatomical analyses under ex situ and in situ conditions, as well as under phytocontamination, bioremediation, urbanization, and extreme stress conditions, play a key role in practical recommendations for evaluating the autoecology of medicinal plants. Reduction of assimilatory organs, radial-succulent structures, and water-accumulative cells provide practical bases for predicting resilience in extreme environments. The study demonstrates that the degree of differentiation of salt glands can serve as an indicator of ecological plasticity and be applied in salinization monitoring in arid and saline habitats. Under contamination, anomalous intracellular and intercellular inclusions, supernumerary periderm, and hypertrophy of palisade cells in medicinal plants represent tolerant anatomy reflecting ecotoxic environmental effects. These structures constitute primary material of practical significance as biomarkers for anatomical adaptation to industrial pollution. Aerenchyma in leaf mesophyll and modified protoxylem in medicinal plants with bioremediation potential can serve as bioindicators under hypo-xic conditions. These anatomical features are relevant for monitoring oxygen regimes of microorganisms in soil and aquatic ecosystems, and for assessing microbial efficiency in bioremediation processes. Hydroaccumulator cells and tissues observed during the study play a crucial role in water balance under drought conditions, and their analysis provides practical indicators for assessing resilience potential in arid zones.

Anatomical comparisons across different ecological groups show that systematic identification of ecogroup-specific anatomical markers provides a practical foundation for developing new ecological diagnostic methods in the future. In medicinal plants studied under urbanization conditions, epidermal hypertrophy, stomatal anomalies, and anomalous accumulations in tissues are interpreted as adaptive responses of plants to anthropogenic ecological pressure. These structures act as bioindicators, offering practical applications for assessing ecological resilience of medicinal plants and for urban phytostress monitoring in city and industrial-impacted ecosystems. For the first time in the flora of Azerbaijan, the study of plant anatomy has been conducted using modern, comprehensive, and practical methodological approaches, including anatomical, microscopic, histochemical, and statistical techniques. The systematic processing of materials was ensured, and permanent preparations were made from median-lateral longitudinal and transverse sections. Adaptive anatomical indicators of medicinal plants from various ecosystems were comparatively analyzed using a quantitative-statistical approach based on micron-level measurements. The results obtained from this research are of significant practical importance and can serve as methodological guidelines and educational materials for practical courses in botany and pharmacy. For the first time in the study of plant anatomy within the flora of Azerbaijan, micrometric-level statistical evaluations (Shapiro-Wilk, Levene, Mann-Whitney U, Welch ANOVA, One-Way ANOVA, and Independent Samples t-test) were applied, providing a modern methodological approach that ensures both scientific precision and practical relevance.

Approbation and application. The results of the research work have been presented at the following conferences: "New Challenges in Botanical Research" (Baku, 2018); "Dialogue of Sciences and Cultures in the Modern World" (Bishkek, Kyrgyzstan, 2022); "Education and Research Activities in the New Era: Realities and Challenges" (Mingachevir, 2022); The XXXII International Scientific Symposium "Turk's Victory: from Chanakkale to Karabakh" (Kars-Eskişehir, Turkey, 2022); "Actual Problems of Science: in the Light of National Unity and Solidarity" (Kars, Türkiye, 2022); "Basic and Applied Research in Molecular Biology, Biochemistry, Biotechnology" (Almaty, Kazakhstan, 2023); IV International Conference on the Fundamentals of Science and Education (Baku, 2023); "Modern Approaches in the Study of the Plant Kingdom" (Baku, 2023); "Current Issues in Natural and Economic Sciences" (Ganja, 2024); "Sustainable Development Strategy: Global Trends, National Practices, and New Goals" (Mingachevir, 2024); "VIII International Scientific and Practical Conference on Basic, Rare, and Non-traditional Plant Species - from Study to Utilization (Agricultural and Biological Sciences)" (Kruty, Chernihiv Region, Ukraine, 13-14 March 2024); "The Role of National Leader Heydar Aliyev in Environmental Improvement in Azerbaijan" (Baku, 2024); "Modern Problems of Ecological Chemistry and Environmental Protection" (Baku, 2024); 7th Symposium on Eurasian Biodiversity (Erzurum, Türkiye, 2024); "Materials of the II International Scientific and Practical Conference Dedicated to the Memory of Honored Scientist of the KBR, Honored Agronomist of the Russian Federation, Dr. of Agricultural Sciences, Professor M. Kh. Khaniyev" (Nalchik, 2024); "Study and Sustainable Development of Forest Types in Azerbaijan" (Baku, 2025).

The scientific results of the dissertation have been published in 34 scientific works, including 28 articles (9 of which in foreign journals indexed in international databases) and 6 thesis materials. Among these publications, 16 were presented and discussed at international conferences.

Name of the organization where the dissertation work was performed. The dissertation was carried out at the Department of Biology of the Azerbaijan State Agricultural University.

Structure and Volume of the Dissertation. The dissertation consists of an introduction, 7 chapters, 28 paragraphs, 40 sections, results, recommendations, a list of 370 references, and a list of abbreviations and symbols. The work includes 238 figures, 23 tables, and 13 concepts. In the research, the introduction contains 23,493 characters, Chapter I - 64,639 characters, Chapter II - 45,501 characters, Chapter III - 177,394 characters, Chapter IV - 21,998 characters, Chapter V - 44,695 characters, Chapter VI - 26,514 characters, Chapter VII - 16,217 characters, results - 9,923 characters, recommendations - 6,170 characters, the list of references, and abbreviations - 2,103 characters. The total volume of the work, excluding figures, tables, concepts, and the list of references, is 438,647 characters and consists of 401 pages.

MAIN CONTENT OF THE DISSERTATION

CHAPTER I. LITERATURE REVIEW

During the study of the characteristic anatomical features of medicinal plants, as well as the patterns of variation in their individual anatomical structures under different ecological conditions, internet databases and other international academic sources were consulted. Findings from researchers working on similar topics in related fields were reviewed and synthesized. To discuss the results obtained by researchers both domestically and internationally, a literature summary has been presented in five paragraphs. The outcomes of scientific studies conducted in similar directions were extensively analyzed, with particular emphasis on aspects directly relevant to the present research.

CHAPTER II. MATERIALS AND METHODS OF THE RESEARCH

The dissertation is primarily devoted to the comparative eco-anatomical investigation of medicinal plants distributed in the mountainous regions of the Lesser Caucasus under ex situ and in situ conditions. The main focus is the analysis of plant adaptation mechanisms across different altitudinal zones and the assessment of the influence of topographic factors on anatomical structural modifications. The research was conducted during the years 2016-2025 and encompassed two main stages: field (expedition) studies and laboratory investigations. To enhance the relevance of the research and broaden its scientific scope, four additional chapters were included, based on specimens collected from the study areas, covering phytocontamination, bioremediation potential, various ecological groups, and ecosystems (including arid and saline habitats). For the first time in the flora of Azerbaijan, conducting ecological-anatomical analyses in these directions holds particular significance as a modern scientific approach. At the same time, the findings align with the priorities of the "COP" project and other international ecological programs, providing not only significant scientific and practical contributions to the study of the flora of Azerbaijan but also demonstrating, on international scientific platforms, the presence and quality of advanced methodological approaches applied in the country. It should be emphasized that the primary objective of the dissertation is the investigation of the ecological-anatomical characteristics of medicinal plants. The inclusion of these additional chapters, while expanding the structural framework, preserves the main focus of the dissertation and enables the results to be presented on a broader scale in a more comprehensive and systematic manner.

Within the scope of the study, 20 medicinal plant species were comparatively analyzed under ex situ and in situ conditions, with two different ecosystem samples each, totaling 40 plants. Additionally, three medicinal plant species collected from the study area were analyzed for their eco-anatomical adaptations in polluted environments during the bioremediation process. Comparative ecological-anatomical analyses were conducted on four specimens to determine the phytocontamination profiles of the plants. To investigate the influence of different ecosystems, two species (four plant specimens) were comparatively analyzed for their adaptive indicators across distinct ecosystems. Analyses conducted on five medicinal plant species belonging to different ecological groups allowed the identification of their anatomical adaptation mechanisms at the ecogroup level. Three medicinal plant species developing under urbanization in the Lesser Caucasus were examined for their adaptive strategies to anthropogenic impacts in urban ecosystems. Two medicinal plant species adapted to arid and saline environments were studied in terms of anatomical changes in response to varying levels of salinity and drought stress. Overall, eco-anatomical analyses were carried out on 61 plant specimens representing 32 species collected from the Lesser Caucasus region. During the study, medicinal plants under ex situ conditions were cultivated in container culture in the Bala Baghman area of Ganja city. After one year, they were translocated to open-field conditions for artificial cultivation. In situ plants were collected from natural populations, and comparative ecological-anatomical analyses were conducted based on both sets of specimens.

Prior to anatomical, microscopic, and biometric analyses, the studied medicinal plants underwent fixation using histochemical methods. This stage is crucial for preserving the structural elements of plant tissues in an ideal form and ensuring their observability[22,23]. For the fixation of generative organs, Karnoy and relatively weakened FAA (Formalin-Acetic-Alcohol) fixatives were used to ensure penetration, whereas for vegetative organs, high-concentration FAA and Kraf III fixatives were applied. After stabilization via the appropriate fixation method, plant materials were processed under laboratory conditions. Paraffin (BW Blended Waxes, Inc., USA) was employed both as an infiltrating medium and as an auxiliary medium during sectioning. Using a modern manual microtome (RADICAL, RMT-5, India) with a specialized micrometric adjustment screw, section thickness was carefully calibrated, and measurements were taken in microns. Section thicknesses obtained with the microtome were set at 6, 7, 8, and occasionally 9 µm. Following sectioning, histochemical methods were applied for differential staining using

[22] Chamberlain, C. J. Methods in plant histology / C. J. Chamberlain; - London: Forgotten Books, - 2020. - 264 s.

[23] Criswell, S., Gaylord, B., Pitzer, C. R. Histological methods for plant tissues // Journal of Histotechnology, - 2025. 48(1) - p. 58-67.

specific reagents. Histological staining was performed with methylene blue (KimyaLab, Turkey), Delafield's hematoxylin, toluidine blue, calcofluor, fast green, safranin O, Sudan III, and iodine (INOVATING SCIENCE, Amerika). The staining process, aimed at selective coloration of tissue components, was carried out stepwise using a decolorization technique[24,25,26]. During tissue processing, additional histochemical reagents such as aniline sulfate, strontium chloride, sodium hydroxide, and fluoroglucinol were used.

In addition to histological staining, technical reagents and auxiliary materials-including chlorinated lime, ethanol, carbolic acid, xylene (Mir Nauki, Russia), distilled water, benzine, and isopropyl alcohol-were applied to the sections for various purposes. For obtaining transverse and longitudinal sections, paraffin was used, while Canada balsam (INOVATING SCIENCE, USA), glycerin, or gelatin were selected as mounting media for specimen preparation. Microscopic slides were prepared using mounting technique tools, including dissection needles, tweezers, pipettes, glass slides, cover slips, Petri dishes, glass rods, and filter paper (INOVATING SCIENCE, USA). The prepared slides were placed in a special incubator (Carolina, USA) maintained at a constant temperature of 20-25 °C to ensure complete hardening of the Canada balsam. Once the hardening process was complete, the permanent slides were used for microscopic analyses.

During microscopic analyses, modern microscopes including the Motic BA 310 Digital LED, Leica Microsystems, Carl Zeiss Axio Imager A2 (ZEISS, Germany), and the LCD Digital Microscope NLCD-307B (Wincom, China) equipped with an LCD screen were used. The NLCD-307B and Leica models were primarily employed to

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[24] Da Silva, C. J. An inexpensive and environmentally friendly staining method for semi-permanent slides from plant material probed using anatomical and computational chemistry analyseas / C. J. da Silva, L. H. F. de Lima, P. M. de Paiva [et al.] // Rodriguésia, - 2020. 71, - e01662018.

[25] Engin, H., Kuzucu, F. C., Gökbayrak, Z. Odun çeliklerinin mikroskobik inceleme ve görüntülenmesinde farklı boyama tekniklerinin kullanımı üzerine araştırmalar // ÇOMÜ Zir. Fak. Derg. - 2024. 12 (1). - s. 108-120.

[26] Criswell, S., Gaylord, B., Pitzer, C. R. Histological methods for plant tissues // Journal of Histotechnology, - 2025. 48(1) - p. 58-67.

monitor the quality of transverse and longitudinal sections, to assess the efficiency of histological staining, and to obtain preliminary measurements. Final analyses, video observations, acquisition of micrographs, and statistical measurements on prepared slides were conducted using the Axio Imager A2 and Motic microscopes. The optical properties of crystalloid and ergastic substances were examined under polarized light using the Motic BA 310 Digital LED or Leica Microsystems microscopes. For anatomical structure identification, all objective magnifications (4×, 10×, 40×, 60×, 100×) were utilized, with immersion oil (RMY, USA) applied at 100× magnification to enhance optical resolution[27]. For macroscopic examination of samples, stereoscopic microscopes (Zeiss Stemi508, ZEISS; YK-SM067B2, Wincom) were used. For measuring tissue structures, eyepiece and stage micrometers (MUHVA, China) were used, and to enhance measurement accuracy, an automated micron measurement system integrated with the microscope was employed. Initially, the eyepiece micrometer was calibrated using the objective micrometer, after which the dimensions of anatomical elements in the microscopic preparations were calculated based on the micrometer scale readings. Prior to sectioning, the dimensions of the organs under study were standardized with precision using a digital micrometer (Jiavarry, China) according to micrometric principles. The obtained measurements were mapped onto photomicrographs and systematically organized for subsequent digital morphometric analysis[28]. Statistical analyses were performed using Jamovi software (version 2.6.26; University of Sydney, Australia). Based on micrometric measurements, mean values and standard deviations were determined. Normality of the results was assessed using the Shapiro-Wilk test, and homogeneity was evaluated using Levene’s test. To determine statistical significance, Mann-Whitney U, Welch ANOVA, One-Way

[27] Moyo, M., Aremu, A. O., Van Staden, J. Insights into the multifaceted application of microscopic techniques in plant tissue culture systems. // Planta, - 2015. 242, - p. 773-790.

[28] Jambor, H. Creating clear and informative image-based figures for scientific publications / H. Jambor, A. Antonietti, B. Alicea [et al.] // PLOS Biology, - 2021. 19 (10), - p. 1-12.

ANOVA, or Independent Samples t-test were applied.

The herbarium specimens prepared from the medicinally significant plants under study have been incorporated into the herbarium collection of the Department of Biology named after Academician Valida Tutayuq at the Azerbaijan State Agricultural University. They are preserved as a systematically organized botanical collection and are available for use as reference material in scientific research and educational activities[29].

CHAPTER III. COMPARATİVE ECOLOGİCAL-ANATOMİCAL STUDY OF ADAPTİVE STRUCTURAL DİAGNOSTİCS OF MEDİCİNAL PLANTS UNDER EX SİTU AND IN SİTU CONDİTİONS

The study of the ecological and anatomical characteristics of medicinal plants is significant for scientifically elucidating their developmental dynamics and adaptation mechanisms under various environmental conditions. Comparative research conducted under ex situ and in situ conditions provides deeper insights into the ecological adaptation mechanisms of plants. Different ecological factors cause structural modifications in the anatomy of medicinal plants and influence their phytotherapeutic potential[30,31,32].

In mountainous and foothill ecosystems, plants growing in situ develop adaptation mechanisms to abiotic and biotic factors, exhibiting distinct modifications in their histological structures as well as in their stomatal apparatus. Under ex situ conditions, however, the

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[29] Shipunov, A. How to make herbarium: a short manual / A. Shipunov, - Fargo: ND Minot State University, - 2019. - 20 p.

[30] Немерешина, О. Н. О механизмах адаптации и изменчивости анатомической структуры листа *Filipendula ulmaria* степной зоны Оренбуржья / О. Н. Немерешина, Н. Ф. Гусев, А. В. Филиппова [и др.] // Животноводство и кормопроизводство, - 2021. 104 (2), - с. 142-154.

[31] Sardarova, A.S. The anatomical characteristics of the vegetative and generative organs of the medicinal *Silybum marianum* L. spread in the mountainous region of the Lesser Caucasus. // - Bakı: Advances in Biology & Earth Sciences, - 2024. 9(3), - p. 381-388. Scopus

[32] Sərdarova, A.S. Adi çobanyastığı (*Matricaria chamomilla* L.) növünün ex situ və in situ şəraitində eko-anatomik tədqiqi // - Bakı: Botaniki tədqiqatlarda yeni çağırışlar, - 2018. - s. 188-190.

anatomical and metabolic features of plants are shaped by new environmental factors, leading to variations in stomatal number and size, the degree of sclerification, and the activity of endogenous and exogenous secretory tissues of pharmaceutical importance (Conc. 1-8). This study aims to comparatively investigate the ecological and anatomical characteristics of 20 medicinal plant species under ex situ and in situ conditions and to determine the functional relationships between their anatomical structures, pharmacological activity, and adaptive traits. The results hold both theoretical and practical significance for assessing the ethnobotanical, phytotherapeutic, and biotechnological resource potential of medicinal plants, contributing to biodiversity conservation, the advancement of experimental and applied botany at the international level, plant adaptation strategies, and the establishment of a medicinal raw material base (Fig. 1).

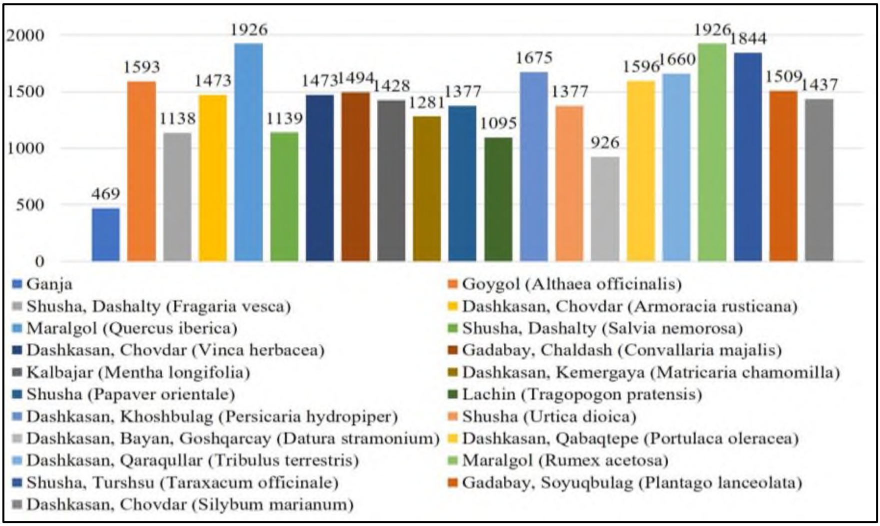

Figure 1. Panel of altitude diagrams (in meters) of the areas studied under ex situ and in situ conditions

3.1. Comparative ecological and anatomical study of medicinal plants absent in the ex situ research area under in situ and ex situ conditions

The study of medicinal plants under different ecological conditions - in natural (in situ) environments of high mountain and foothill zones, as well as under ex situ conditions at lower altitudes - allows the assessment of their altitudinal variation and adaptive potential (Fig. 2). Comparative analyses indicate that the diversity of ecological factors across vertical zonation leads to the formation of distinct anatomical adaptation structures in plants[33,34]. Such an approach is significant not only for the ecological-anatomical diagnostics of plants but also for establishing a scientific foundation for introduction and resource enhancement programs.

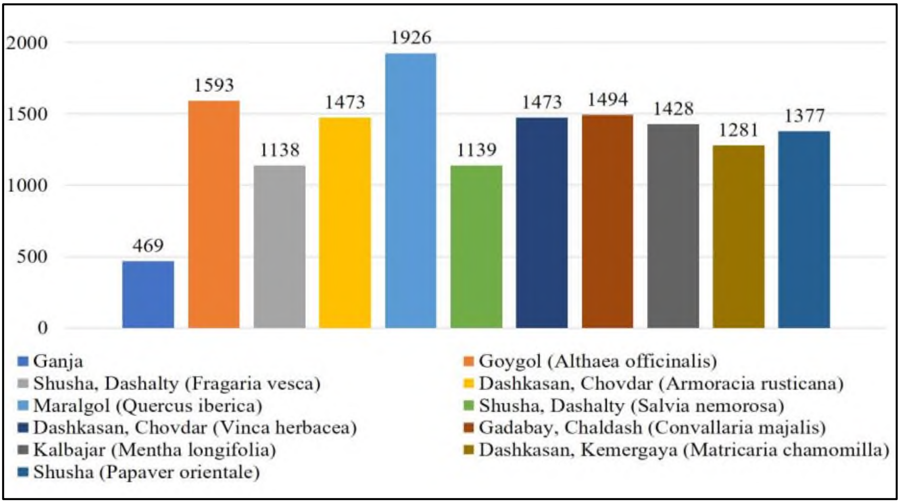

Figure 2. Altitude range by ecotypes (in meters) in in situ and ex situ populations of the studied medicinal plants

3.1.1. *Althaea officinalis* L.

When studying the ecological and anatomical characteristics of *Althaea officinalis* under ex situ and in situ conditions, it was observed that the species exhibits distinct structural elements specific to each growth environment.

Petal. Microscopic examination of anatomical sections revealed

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[33] Sardarova, A.S. Comparative ecological anatomical study of the structural adaptation of the medicinally important plant *Salvia nemorosa* L. under in situ and ex situ conditions // - Baku: Acta Botanica Caucasica, - 2025. 4(2), - p. 81-100. Agris

[34] Sardarova, A.S. Specific anatomical identification of *Convallaria majalis* (Asparagaceae), a medicinal plant with a sciophytic character // - Ukraine: Regulatory Mechanisms in Biosystems, - 2025. 16(3), - e25140. WoS, Scopus

that the transverse diameter of the petal is greater in the ex situ specimen. In the in situ sample, the petal lamina develops a biconvex shape along both the adaxial and abaxial sides in the regions containing vascular bundles (Fig. 3A). In contrast, the ex situ specimen exhibits a monoconvex structure only on the adaxial surface. As diagnostic anatomical indicators of plants from different ecosystems, two vascular bundles were observed in the central part of the petal in the in situ specimen, while a single vascular bundle was present in the ex situ one. A relative increase in the size of the conducting bundle was recorded in the ex situ specimen. The xylem vessels within the vascular bundles were more compactly arranged in the in situ specimen, whereas they were dispersed in the ex situ sample (Fig. 3B).

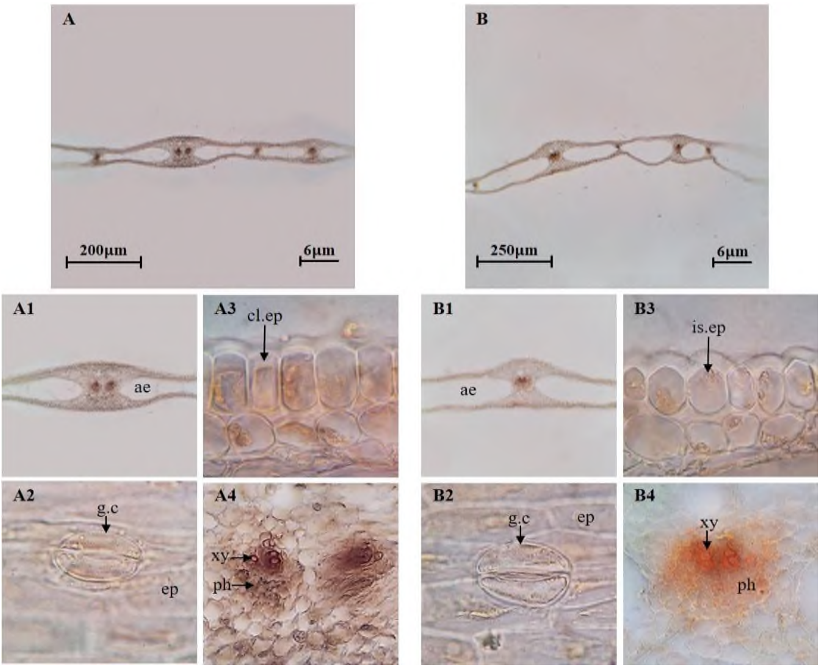

Figure 3. ***Althaea officinalis*****. Transverse section of the petal.** In situ - A (Goygol State Nature Reserve area), Ex situ - B (Bala Baghman area, Ganja city). A, B - general structure (4×16); A1, B1 - a part (10×); A2, B2 - morphology of stoma contour (100×); A3, B3 - upper epidermis (100×); A4, B4 - central vascular system (60×). ae-aerenchyma, er-ergastic substances, g.c-guard cells, ep-epidermis, cl.ep - columellar epidermal cells, is.ep - isodiametric epidermal cells, xy-xylem, ph-phloem

The accumulation of ergastic substances in the peripheral parenchyma of the vascular system was more intense in the in situ specimen. In the ex situ sample, the guard cells of the stomata were relatively larger and crescent-shaped. Observations showed that the stomata in this specimen were functionally open, indicating an optimal turgor state as an anatomical diagnostic feature. In the in situ specimen of *Althaea officinalis*, however, the stomatal aperture was microscopically observed to be closed, which may be associated with reduced cell turgor and a structural condition indicative of plasmolysis. The anatomical adaptation indicators reflecting ecotypic differences in the petals of *A. officinalis* were statistically confirmed (Table 1; Fig. 4).

Table 1. Summary of *Althaea officinalis* petals measurements and t-test analysis

Indicators	Mean ± SD (μm)		T-Test
	In situ	Ex situ	p
Thickness of the petal	213.01 ± 23.47	246.06 ± 25.43	0.0073
Height of upper epidermis cells	37.22 ± 3.61	33.32 ± 3.81	0.0304
Thickness of the outer periclinal wall in the upper epidermis	5.94 ± 1.06	7.63 ± 1.59	0.0119
Height of lower epidermis cells	39.42 ± 7.98	30.40 ± 6.87	0.0144
Thickness of the outer periclinal wall in the lower epidermis	6.56 ± 1.33	8.35 ± 1.83	0.0226
Diameter of parenchyma cells	32.38 ± 1.10	31.02 ± 0.94	0.0081
Height of the central vascula bundle	71.74 ± 14.52	98.27 ± 20.51	0.0037
Diameter of xylem vessels	11.59 ± 1.89	14.47 ± 2.60	0.0109

**Note:* SD – standart deviation. Shapiro-Wilk test confirmed normal distribution ($W > 0.05$, $p > 0.05$); t-test indicated a significant difference between groups ($p < 0.05$).

Stem. In the transverse section of the stem, numerous bifurcated and stellate trichomes with complex basal structures, as well as small-sized capitate trichomes on the epidermis, exhibited structural activity in the in situ specimen[35,36]. In the ex situ sample, an increase in the size of the stomata and substomatal chamber was confirmed micro-

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35 Gomaa, A. A.-R. Pharmacognostical studies of leaf, stem, root and flower of *Abutilon hirtum* (Lam.) Sweet / A. A.-R. Gomaa, M. N. Samy, S. Y. Desoukey [et al.] // International Journal of Pharmacognosy and Phytochemical Research, - 2016. 8 (1), - p. 199-216.

36 Said, W. M. Morphological and anatomical studies on some taxa of subfamily *Malvoideae* (*Malvaceae* s.l) / W. M. Said, T. R. Mohamed, A. A. Elhalwagi [et al.] // J. Sci. Res. Sci., - 2018. 35, - p. 345-357.

graphically. Sclerenchymatous fibers located at the boundary between the cortical and medullary regions of the vascular system displayed pronounced structural-functional activity in the in situ specimen (Fig. 5A). Under ex situ conditions, hyperplasia and hypertrophy processes resulted in comparatively larger dimensions of the cortical and medullary parenchyma (Fig. 5B).

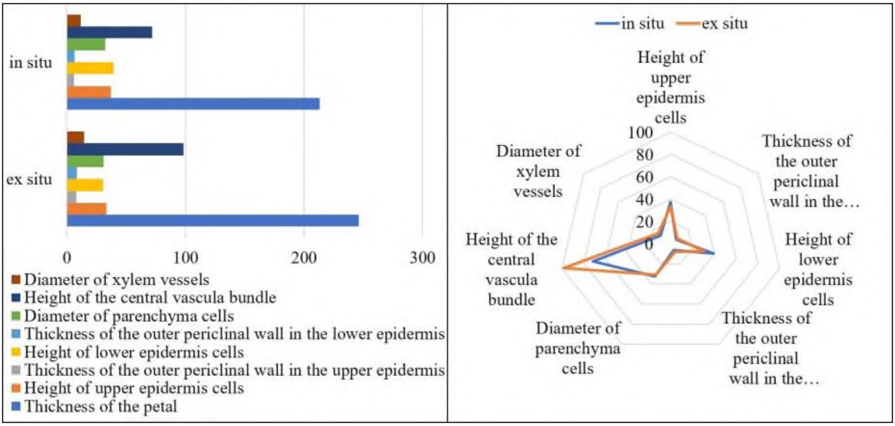

Figure 4. Statistical comparison of micrometric measurements conducted on the petals of in situ and ex situ ecotypes of *Althaea officinalis* applied in bar and radar charts

Anatomical analysis revealed a higher intensity of druse crystal accumulation within the phloem of the in situ specimen. The vascular system consists of xylem elements, beginning with protoxylem, progressing radially to larger metaxylem elements, and containing libriform fibers situated between metaxylem vessels. In situ specimens exhibited better differentiation of the xylem, higher element density, and more active secondary wall thickening in libriform fibers. The meristematic tissue at the xylem-phloem interface consists of thin fusiform cambial cells that ensure active periclinal division. The sclerenchyma fibers at the boundary of the xylem and medullary region consist of more elements in the in situ sample. The accumulation of ergastic substances in the medullary parenchyma was also more intense in the in situ specimen. The ecotypic adaptive structures determined through comparative ecological-anatomical analysis were supported by statistical and micrographic evidence (Fig. 6; Table 2).

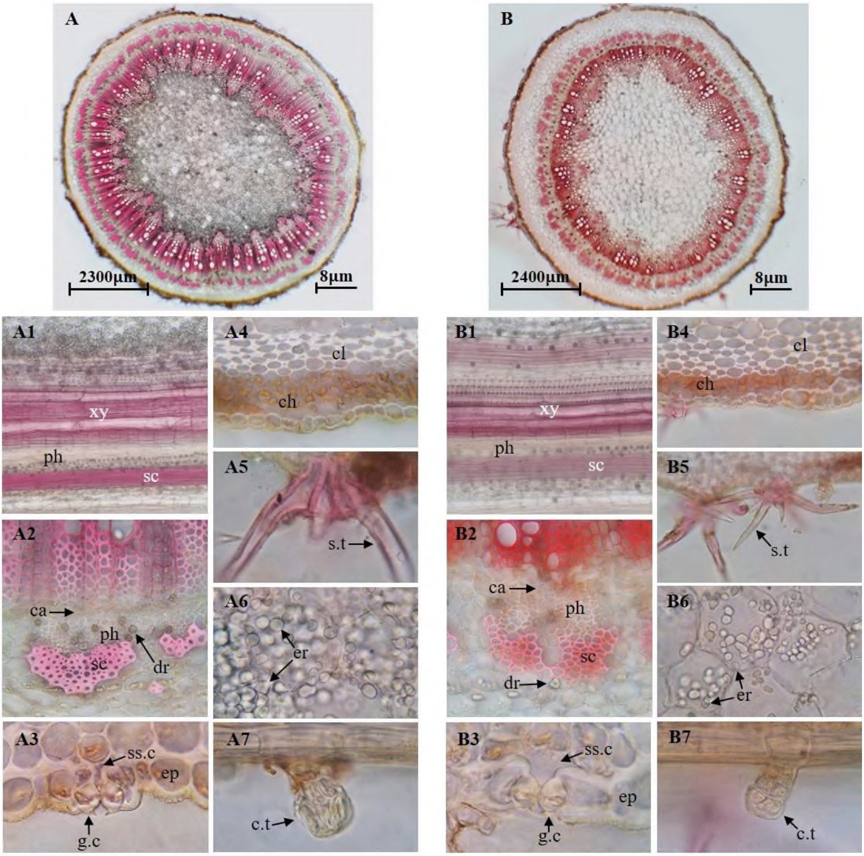

Figure 5. *Althaea officinalis*. Transverse and median longitudinal sections of the stem. In situ - A (Goygol State Nature Reserve area), Ex situ - B (Bala Baghman area, Ganja city). A, B - general structure (4×16); A1, B1 - vascular system in median longitudinal section (10×); A2, B2 - vascular and mechanical elements (40×); A3, B3 - structure of stomatal apparatus (100×); A4, B4 - peripheral part (40×); A5, B5 - trichomes (60×); A6, B6 - medullary region (60×); A7, B7 - capitate trichomes (100x). ca-cambium, ph-phloem, sc-sclerenchyma, xy-xylem, cl-collenchyma, ch-chlorenchyma, s.t-stellate trichome, c.t-capitate trichome, er-ergastic substances, dr-druse, ep-epidermis, ss.c-sub-stomatal cavity, g.c-guard cells

3.1.2. *Fragaria vesca* L.

Sepal. The transverse section of the sepal of *Fragaria vesca* shows that stomata on the abaxial epidermis are of the cryptostomatic type in the in situ sample and of the epistomatic type in the ex situ sample.

The chloroplast-containing parenchyma cells are statistically larger in the ex situ sample, though their density is lower. An increase in both the number and volume of intercellular spaces was also observed in this sample (Şək. 7B). In the in situ sample, druse accumulation was noted in the adaxial subepidermal zone, whereas in the ex situ sample it was observed in the perivascular zone (Şək. 7A).

Table 2. Summary of *Althaea officinalis* stems measurements and t-test analysis

Indicators	Mean ± SD (μm)		T-Test
	In situ	Ex situ	p
Thickness of the cortex	196.27 ± 21.72	226.27 ± 25.45	0.0110
Height of epidermal cells	16.67 ± 3.70	22.21 ± 5.58	0.0175
Thickness of chlorenchyma tissue	41.94 ± 8.46	29.05 ± 8.21	0.0028
Thickness of collenchyma tissue	50.17 ± 13.01	68.87 ± 13.70	0.0058
Diameter of cortex parenchyma cells	37.43 ± 12.20	53.63 ± 15.78	0.0194
Thickness of the vascular ring	449.23 ± 23.48	427.05 ± 22.34	0.0442
Thickness of sclerenchyma tissue	60.75 ± 2.23	58.55 ± 1.29	0.0147
Diameter of xylem vessels	54.89 ± 5.78	46.83 ± 6.28	0.0079
Diameter of medullary parenchyma cells	77.07 ± 5.92	83.73 ± 6.08	0.0232

**Note:* SD – standart deviation. Shapiro-Wilk test confirmed normal distribution (W > 0.05, p > 0.05); t-test indicated a significant difference between groups (p < 0.05).

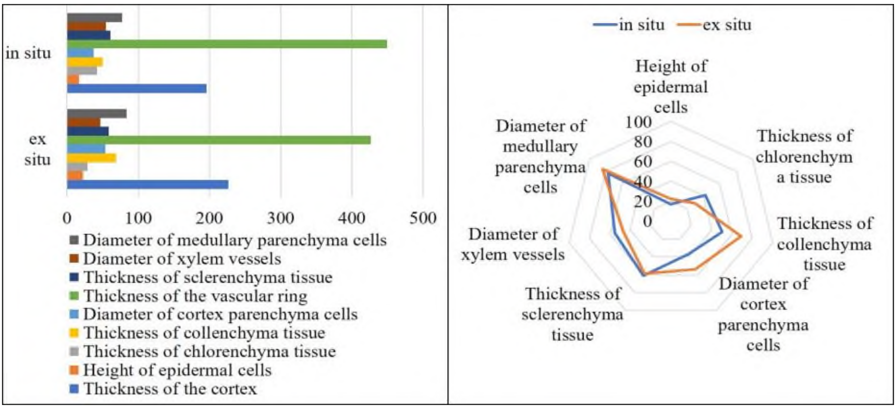

Figure 6. Statistical comparison of micrometric measurements conducted on the stems of in situ and ex situ ecotypes of *Althaea officinalis* applied in bar and radar charts

The diameter of cells surrounding the central and lateral vascular bundles of the sepal was significantly higher in the in situ sample (p < 0.05). Intense pigmentation was recorded in the main parenchyma and epidermal cells of the in situ sample. These adaptive ecotypic anatomical traits were statistically confirmed (Table 3).

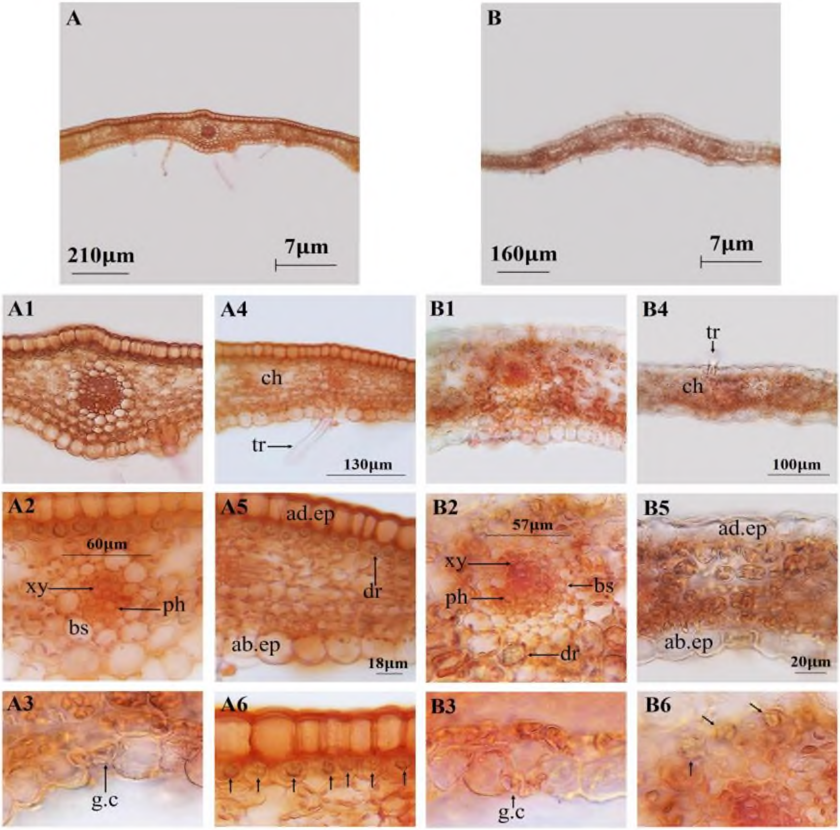

Figure 7. *Fragaria vesca*. Transverse section of the sepal. In situ - A (Shusha city, Dashalty village), Ex situ - B (Bala Baghman area, Ganja city). A, B - general structure (10×16); A1, B1 - central part (40×); A2, B2 - central vascular bundle (100×); A3 - cryptostoma; B3 - epistoma (100×); A4, B4 - lateral part (40×); A5, B5 - mesophyll (60×); A6, B6 - accumulation of druse crystals (indicated by arrows) (100×). tr-trichome; ad.ep-adaxial epidermis; ch-chlorenchyma; ab.ep-abaxial epidermis; ph-phloem; xy-xylem; bs-bundle sheath cells; dr-druse; g.c-guard cells

Root. In the transverse section, the root organ shows a secondary structure. In the in situ samples, the root axis of *Fragaria vesca* had a smaller diameter, and this morphometric difference was clearly visible in microscopic preparations (Fig. 8A).

Table 3. Comparative statistical analysis of quantitative parameters (μm) in in situ and ex situ samples of *Fragaria vesca*.

Organs	Indicators		In situ (Mean ± SD)	Ex situ (Mean + SD)
Sepal	Upper epidermis cells	height	28,24 ± 1,86	19,41 ± 1,61
		width	20,33 ± 3,42	27,59 ± 2,54
	Thickness of the outer wall of the upper epidermis cells		4,51 ± 0,97	1,95 ± 0,37
	Lower epidermis cells	height	29,37 ± 2,07	18,52 ± 2,21
		width	28,47 ± 2,67	21,12 ± 2,45
	Thickness of the outer wall of the lower epidermis cells		1,69 ± 0,54	1,26 ± 0,26
	Diameter of chlorenchyma cells		19,36 ± 2,43	23,92 ± 3,21
	Diameter of bundle sheath cells		17,08 ± 2,28	11,22 ± 1,62
Flower stalk	Epidermis cells	height	25,81 ± 1,55	34,41 ± 1,37
		widht	26,17 ± 1,68	25,86 ± 1,42
	Diameter of the cortex parenchyma cell		48,24 ± 4,13	51,32 ± 3,21
	Thickness of the sclerenchyma tissue		29,87 ± 3,47	23,43 ± 2,98
	Diameter of the xylem vessel		9,12 ± 0,61	12,03 ± 1,16
Stem	Epidermis cells	height	11,47 ± 1,13	15,63 ± 1,28
		widht	11,39 ± 1,06	8,37 ± 1,32
	Tangential thickness of the sclerenchyma tissue		47,46 ± 1,74	42,51 ± 1,85
	Diameter of the xylem vessel		15,73 ± 2,11	10,79 ± 1,89
Leaflet	Adaxial epidermis cells	height	32,18 ± 2,87	37,31 ± 2,79
		widht	40,03 ± 3,17	53,91 ± 4,29
	Thickness of the outer wall of the adaxial epidermis cells		3,57 ± 0,44	1,77 ± 0,15
	Abaxial epidermis cells	height	25,03 ± 2,96	20,54 ± 1,67
		widht	24,31 ± 3,14	21,32 ± 2,42
	Thickness of the outer wall of the abaxial epidermis cells		1,96 ± 0,45	1,53 ± 0,12
	Diameter of the xylem vessel		13,32 ± 1,94	12,69 ± 1,73
Petiolule	Epidermis cells	height	28,78 ± 2,25	26,57 ± 2,41
		widht	20,25 ± 2,14	18,83 ± 2,29
	Diameter of the parenchyma cells		47,91 ± 3,98	63,49 ± 4,19
	Diameter of the xylem vessel		17,19 ± 2,49	15,14 ± 1,42
Petiole	Epidermis cells	height	18,32 ± 1,73	18,83 ± 1,21
		widht	19,94 ± 1,24	18,81 ± 1,56
	Diameter of the parenchyma cells		62,82 ± 2,75	61,68 ± 5,48
	Thickness of the sclerenchyma tissue in the large vascular bundle		56,27 ± 3,54	51,87 ± 2,84
	Diameter of the xylem vessel		18,77 ± 2,36	21,51 ±3,46
Rosette	Diameter of the cortex parenchyma cell		36,59 ± 3,43	32,36 ± 3,84
	Diameter of the medullary parenchyma cell		43,12 ± 3,22	39,25 ± 2,92
	Diameter of the xylem vessel		17,79 ±3,51	12,81 ± 2,47
Rhizome	Diameter of the pith parenchyma cell		57,13 ± 5,83	39,76 ± 4,24
	Diameter of the xylem vessel		29,31 ± 3,15	25,19 ± 2,69
Primary root	Poliderm cells	height	9,64 ± 2,48	11,85 ± 2,27
		widht	21,44 ± 2,14	34,51 ± 2,89
	Cortex cells	height	15,14 ±1,91	17,25 ± 2,15
		widht	34,37 ± 3,69	31,34 ± 3,45
	Diameter of the xylem vessel		32,57 ± 6,18	33,03 ± 6,31
Tertiary root	Diameter of mesodermis cells		21,69 ± 3,17	32,66 ± 3,35
	Diameter of endodermis cells		7,62 ±1,03	6,52 ± 0,95
	Diameter of the xylem vessel		10,29 ± 1,31	17,35 ± 1,27

**Note* - SD - standard deviation.

Both ecotype samples exhibited a formed polyderm, whose individual cell layers underwent suberization, disrupting the metabolic connections between the primary cortex and central cylinder and gradually leading to the degradation of the initial tissue[37]. Pigmentation of the polyderm cells was observed in both samples, but higher intensity and additional presence in the parenchyma were noted only in the in situ sample.

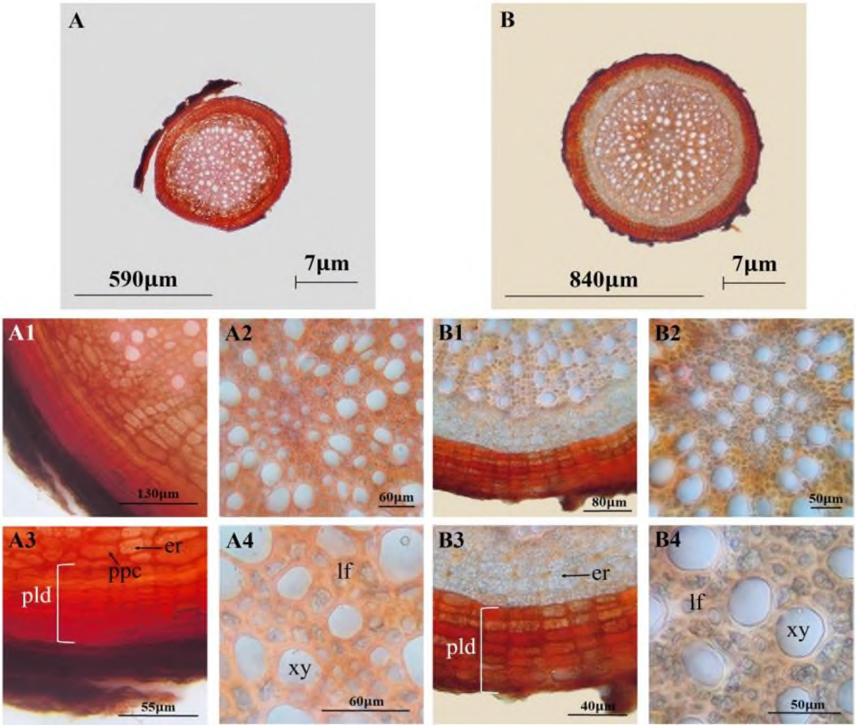

Figure 8. *Fragaria vesca*. Transverse section of the root. In situ - A (Shusha city, Dashalty village), Ex situ - B (Bala Baghman area, Ganja city). A, B - general structure (10×), A1, B1 - a part (40×), A2, B2 - xylem tissue (40×), A3, B3 - polyderm (100×), A4, B4 - structure of the xylem (100×). pld-polyderm; er-ergastic substances; ppc- pigmented parenchyma cells; xv-xylem; lf-libriform fibers.

The ex situ sample displayed a relatively low number (7-8) of large polyderm cells. In contrast, the in situ sample had smaller polyderm

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37 Sardarova, A.S. Comparative ecological anatomical characteristics of generative and vegetative organs of the medicinally important plant *Fragaria vesca* L. (Rosaceae Juss.) under in situ and ex situ conditions // - Baku: Transactions İnstitute of Molecular Biology & Biotechnologies, - 2025. IX(1), - p. 17-37. Agris

cells but in greater quantity (9-10). In both samples, ergastic compounds accumulated in the parenchyma cells located internally to the polyderm, though this structure was more active in the ex situ sample (Fig. 8B). In the central cylinder, the thickening of libriform fibers among the xylem elements exhibited higher structural-functional activity in the in situ sample. The observed structural differences in the root organ of in situ and ex situ *F. vesca* samples were statistically confirmed (Table 3).

3.2. Comparative ecological and anatomical study of medicinal plants with natural populations in the ex situ research area under mountainous ın situ and ex situ conditions

Comparative analysis of the ecological-anatomical features of medicinal plants along vertical zonation allows clarification of how altitudinal differences affect plant adaptation mechanisms (Fig. 9).

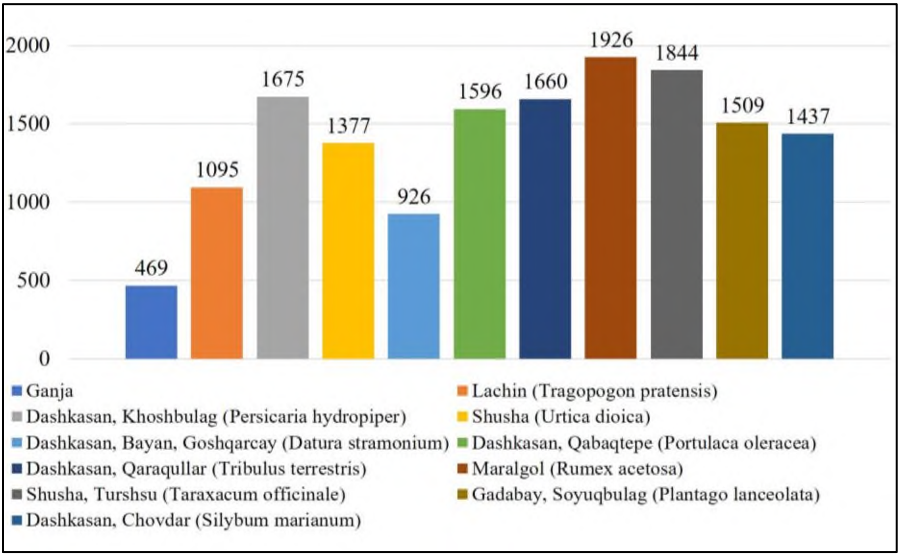

Figure 9. Altitudinal gradient (in meters) for in situ and ex situ ecotypes of medicinal plant specimens with natural populations present in the ex situ research area

The aim of the study is to conduct comparative ecological-anatomical analyses of medicinal plant species, whose natural populations also exist in the ex situ research area, under mountainous in situ and ex situ conditions. Correlative anatomical comparisons have also been carried out between these plants and their natural specimens in the ex situ area. This approach enables the evaluation of indicators of acclimatization and naturalization processes based on anatomical-diagnostic parameters and serves to identify ex situ adaptation mechanisms[38].

3.2.1. ***Persicaria hydropiper*** **Delabre**

Stem. In the transverse section of the stem, intensive development of collenchyma tissue was recorded in the ex situ specimen. Around the stem's vascular system, lysigenous cavities were observed in both specimens, with their structural-functional activity notably confirmed in the in situ sample during the study (Figs. 10, 11A).

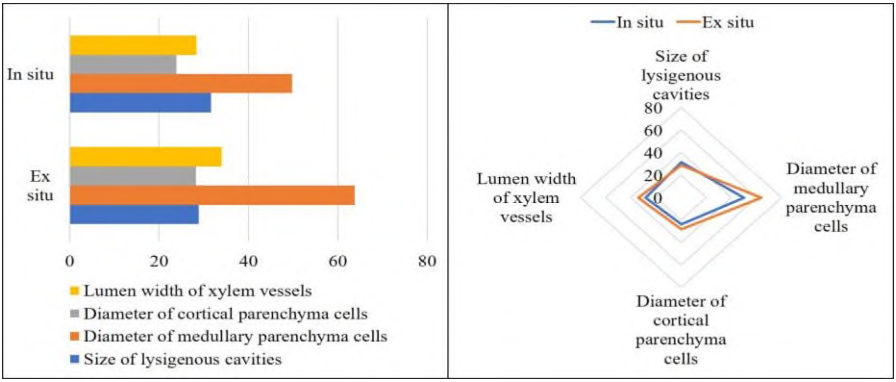

Figure 10. Statistical comparison of micrometric measurements in the stems of in situ and ex situ ecotypes of *Persicaria hydropiper* applied in bar and radar charts

Microscopic analysis revealed the formation of aerenchyma in the medullary region of the stem in the ex situ specimen. Unlike the in situ specimen, the medullary region in the ex situ sample exhibited an increase in volume (Fig. 11B). Although druses were present in the medullary parenchyma of both specimens, only the in situ sample showed intensive accumulation of druses and granular ergastic substances. Hypertrophy of cortical and medullary cells was observed in the ex situ specimen (Table 4). In the in situ sample, differentiation of xylem elements within the vascular system was identified.

38 Sardarova, A.S. Anatomical identification and diagnostic characteristics of *Tragopogon pratensis* (Asteraceae) within the flora of Azerbaijan // - Ukraine: Biosystems Diversity, - 2025. 33(3), - e2545. WoS, Scopus

Table 4. Results of micrometric measurements and ANOVA test conducted on stem samples of *Persicaria hydropiper*

Indicators	Mean ± SD (μm)		ANOVA	
	In situ	Ex situ	F	p
Size of lysigenous cavities	31.64 ± 2.08	28.92 ± 2.17	27.95	0.0016
Diameter of medullary parenchyma cells	49.75 ± 9.31	63.77 ± 8.73	27.88	0.0002
Diameter of cortical parenchyma cells	23.84 ± 2.31	28.27 ± 4.04	22.26	0.0013
Lumen width of xylem vessels	28.39 ± 3.42	34.05 ± 3.55	27.96	0.0001

**Note:* SD – standard deviation. ANOVA test results indicated a significant difference between the groups ($p < 0.05$).

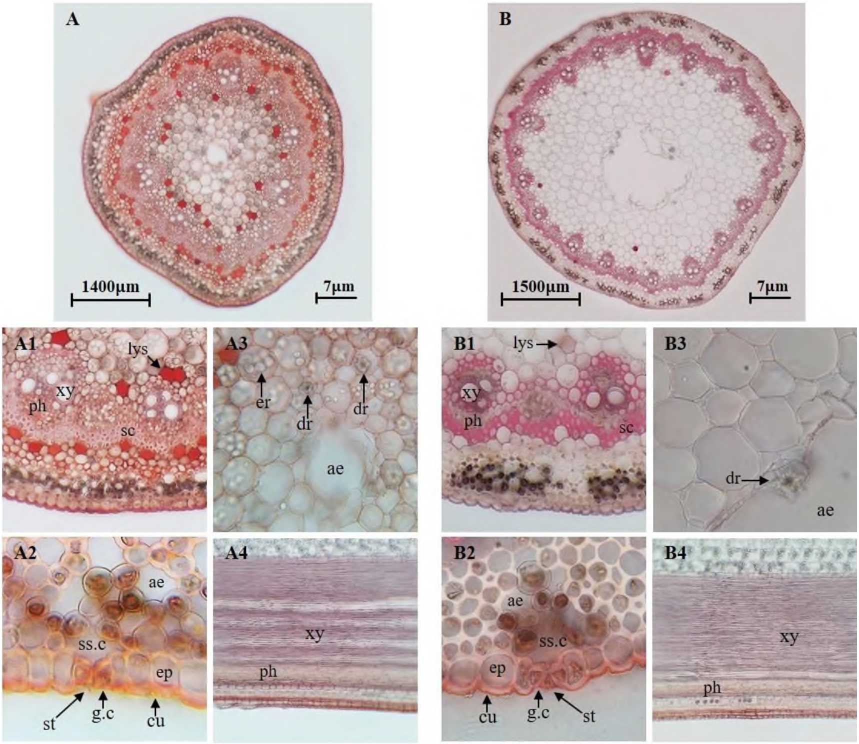

Figure 11. *Persicaria hydropiper*. Transverse and median longitudinal sections of the stem. In situ - A (Dashkasan District, Khoshbulaq Village), Ex situ - B (Bala Baghman area, Ganja city) A, B - general structure (10×16); A1, B1 - a part (40×); A2, B2 - stomata (60×); A3, B3 - medullary region (40×); A4, B4 - vascular system and cortex in median longitudinal section (10×). lys-lysigenous cavity, xy-xylem, ph-phloem, sc-sclerenchyma, er-ergastic substances, dr-druse, ae-aerenchyma, ep-epidermis, ss.c-sub-stomatal cavity, st-stoma, g.c-guard cell, cu-cuticle

3.2.2. *Rumex acetosa* L.

Root. Anatomical transverse sections revealed that grouped sclerenchyma elements around the cortex and xylem were present only in the in situ specimen. The central cylinder in the ex situ specimen was of large diameter but characterized by 5-6 incompletely formed xylem rays. In contrast, the in situ specimen exhibited 16-17 fully differentiated xylem rays (Fig. 12A). Ergastic substances were present in the cortical parenchyma cells of both specimens, but they accumulated at higher density in the in situ sample.

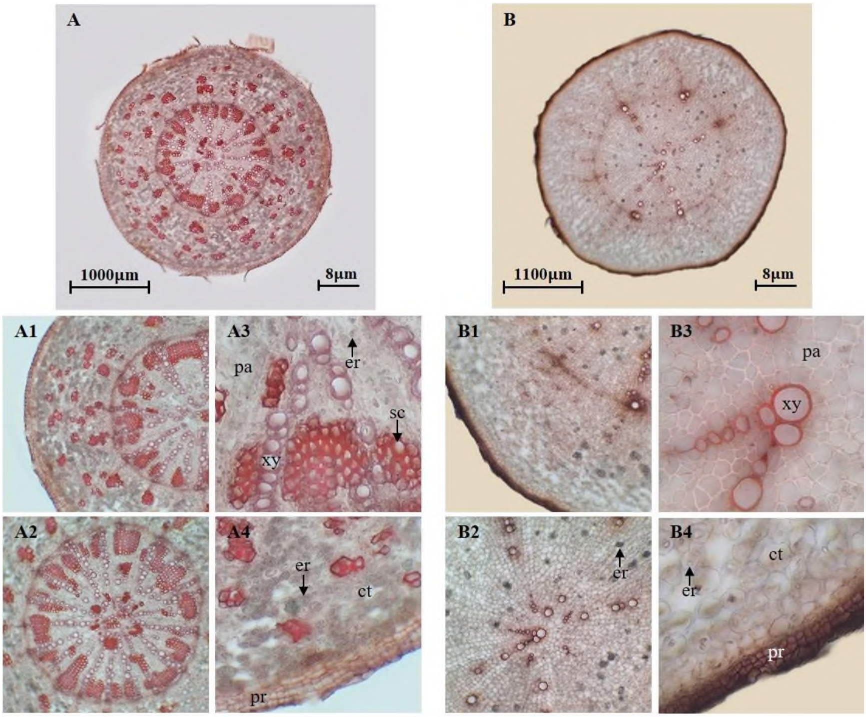

Figure 12. *Rumex acetosa*. Transverse section of the root. In situ - A (Maralgol Area), Ex situ - B (Bala Baghman area, Ganja city) A, B - general structure (4×16); A1, B1 - a part (10×); A2, B2 - central cylinder (10×); A3, B3 - vascular and mechanical tissue elements (40×); A4, B4 - peripheral part (40×). xy - xylem, pa - parenchyma, sc - sclerenchyma, ct - cortex, er - ergastic substances, pr - periderm

The periderm consisted of 2-3 layers in the ex situ specimen and 5-6 layers in the in situ specimen, with differences in size clearly observed (Fig. 12B). The different ecotypic structures observed in the comparative ecological-anatomical study were statistically confirmed (Table 5).

Table 5. Results of micrometric measurements and ANOVA test conducted on root samples of *Rumex acetosa*

Indicators	Mean ± SD (μm)		ANOVA	
	In situ	Ex situ	F	p
Diameter of the central cylinder	957.74 ± 69.08	1063.91 ± 78.92	15.37	0.0005
Height of cortical parenchyma cells	23.90 ± 2.36	31.84 ± 6.31	20.84	0.0002
Width of cortical parenchyma cells	41.53 ± 4.67	40.58 ± 5.07	0.29	0.5944
Height of periderm cells	17.96 ± 2.88	11.83 ± 1.90	47.28	$3{,}8\times10^{-7}$
Width of periderm cells	20.13 ± 2.96	13.59 ± 1.92	51.45	$2{,}1\times10^{-7}$

**Note:* SD – standard deviation. ANOVA test results indicated a significant difference between the groups ($p < 0.05$).

3.3. Ecological and anatomical comparison of structural adaptations in the medicinal plant *Silybum marianum* across in situ, ex situ, and locally natural populations within the ex situ research area

In this study, a targeted ecological-anatomical comparison of *Silybum marianum* was conducted using three plant samples: in situ, ex situ, and the natural population present in the ex situ area. The research demonstrated that the in situ mountain ecotype's structures do not fully stabilize when transferred to the ex situ research area, showing significant anatomical differences compared to the intraducent ex situ specimens.

The study was conducted based on three different habitat samples:

1. Mountainous in situ ecotype (Fig. 13A, D),
2. Specimens introduced spontaneously ex situ from the same mountainous ecosystem (Fig. 13B, E),
3. Naturally growing local population in the ex situ area (Fig. 13C, E).

Microscopic analyses indicate that the structures of *S. marianum* formed in situ are not completely stabilized when transferred to ex situ conditions, though criteria of anatomical similarity are partially preserved. Notably, even after a three-year introduction period, the specimens derived from the mountain ecotype exhibited significant anatomical differences compared to the natural population in Ganja city.

Figure 13. ***Silybum marianum.*** In situ - A (Chovdar village, Dashkasan district (D)); ex situ - B (Bala Baghman area, Ganja city (E)); local natural population - C (Bala Baghman area, Ganja city (E)).

3.3.1. Comparative ecological-anatomical analysis of *Silybum marianum* Gaertn. samples from in situ and ex situ conditions, as well as from the natural population in the ex situ area

In the ex situ research area, samples taken from the natural population exhibited a significant increase in the transverse dimensions of sepal, leaf, stem, and root organs due to hyperplasia of parenchyma cells. The observed transverse expansion in the organs of ex situ specimens was quantitatively confirmed as a result of the hypertrophy process. In contrast, in the in situ specimens, the parenchyma was conservatively arranged, consisting of a mosaic combination of thick-walled large and small cells.

Sepal. In the in situ specimen, the abaxial subepidermal region of the sepal showed intense sclerenchyma development, whereas this process was weak in the ex situ specimen and absent in the local natural population. Although intercellular and intracellular inclusions were observed in the parenchyma cells of the ex situ and local population sepals, their activity was relatively higher in the natural population specimens. In situ specimens showed even more active development. Microscopic analysis revealed aerenchyma tissue in the sepals of all three specimens, with its most active development observed in the local population (Table 6; Figs. 14, 15). The marginal region ended in a rounded blunt tip in the in situ and ex situ specimens, while in the local population it was relatively acute. Trichomes were absent in the in situ specimen, weakly developed in the ex situ specimen, and intensively developed in the local population.

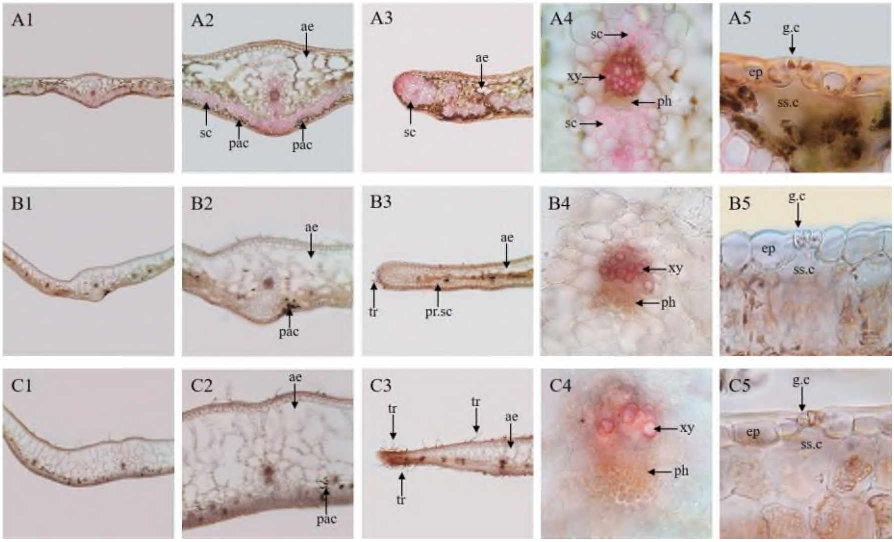

Figure 14. Comparative eco-anatomical analysis of transverse sections of sepal samples of *Silybum marianum* taken from in situ conditions (A), introduced ex situ conditions (B), and natural populations within the ex situ research area (C). 1 - general structure, 2 - central part, 3 - margin, 4 - vascular bundle, 5 - stoma. ae - aerenchyma, sc - sclerenchyma, pr.sc - primary sclerenchyma, pac - parenchymatic accumulation, tr - trichome, xy - xylem, ph - phloem, g.c - guard cell, ss.c - sub-stomatal cavity, ep - epidermis

Table 6. Micrometric measurements and ANOVA test results on sepal samples of *Silybum marianum*

Indicators	Mean ± SD (μm)			ANOVA	
	In situ	Ex situ	Natural population of the ex situ study area	F	p
Thickness of the sepal	359.77 ± 20.74	402.47 ± 30.51	464.08 ± 69.89	21.41	$3{,}9\times10^{-6}$
Thickness of the aerenchyma tissue	181.95 ± 14.45	195.98 ± 29.69	351.82 ± 62.63	51.10	$3{,}7\times10^{-9}$
Height of the upper epidermis cells	35.37 ± 2.27	37.79 ± 1.42	33.73 ± 1.83	23.46	$1{,}2\times10^{-6}$
Diameter of the cells in the upper subepidermal layer	33.53 ± 4.67	51.24 ± 8.50	54.00 ± 2.63	107.04	$1{,}1\times10^{-12}$

**Note:* SD – standard deviation. ANOVA test results indicated a significant difference between the groups ($p < 0.05$).

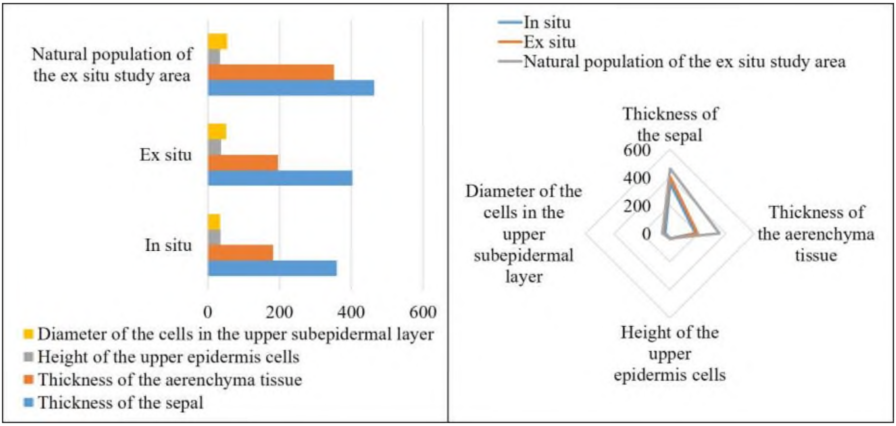

Figure 15. Statistical comparison of micrometric measurements conducted on sepal samples of *Silybum marianum* applied in bar and radar charts

Leaf. In the natural population specimen at the ex situ research site, the transverse volume of the leaf mesophyll was larger, with five vascular bundles formed in the central region, compared to four in the in situ specimen and three in the ex situ specimen (Fig. 16). In the transverse section of the local population's leaf, a prominent exospheric protrusion developed in the area of the vascular bundle, indicating structural differentiation (Table 7, Fig. 17).

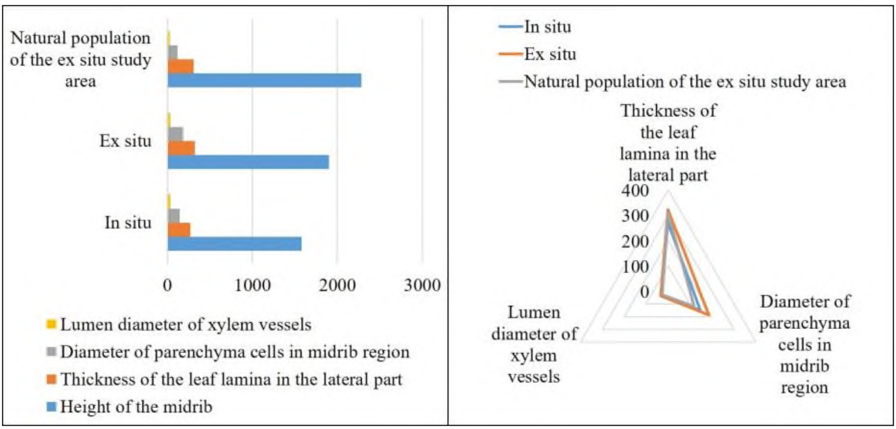

Figure 16. Statistical comparison of micrometric measurements conducted on leaf samples of *Silybum marianum* applied in bar and radar charts

Table 7. Micrometric measurements and ANOVA test results on leaf samples of *Silybum marianum*

Indicators	Mean ± SD (µm)			ANOVA	
	In situ	Ex situ	Natural population of the ex situ study area	F	p
Height of the midrib	1578.40 ± 93.88	1897.66 ± 159.32	2283.86 ± 146.96	122.76	$4{,}4\times10^{-14}$
Thickness of the leaf lamina in the lateral part	271.72 ± 22.38	321.77 ± 25.67	310.00 ± 16.54	19.45	$5{,}8\times10^{-6}$
Diameter of parenchyma cells in midrib region	147.39 ± 14.07	185.06 ± 21.59	119.13 ± 16.95	42.42	$4{,}2\times10^{-9}$
Lumen diameter of xylem vessels	29.72 ± 3.12	34.07 ± 3.34	26.86 ± 2.98	19.03	$6{,}0\times10^{-6}$

**Note:* SD-standard deviation. ANOVA test results indicated a significant difference between the groups ($p < 0.05$).

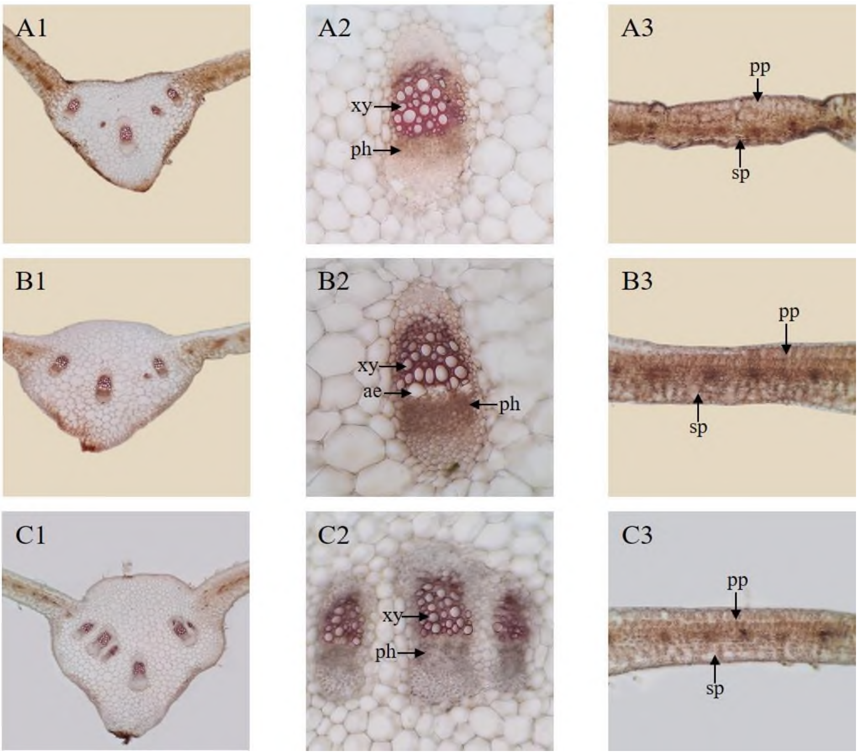

Figure 17. Comparative eco-anatomical analysis of transverse sections of leaf samples of *Silybum marianum* taken from in situ conditions (A), introduced ex situ conditions (B), and natural populations within the ex situ research area (C). 1 - midrib, 2 - structure of the vascular system, 3 - lateral part of the leaf. xy - xylem, ph - phloem, ae - aerenchyma, pp - palisade parenchyma, sp - spongy parenchyma

Stem. In the in situ condition, the perimedullary zone of the stem exhibited intensive development of a perivascular sclerenchyma complex surrounding the circularly arranged vascular bundles. The vascular system was compactly organized. Additional vascular bundles, arranged in smaller numbers toward the cortex, were also observed (Fig. 18). In the ex situ specimen, even after three years of introduction, this structure was preserved.

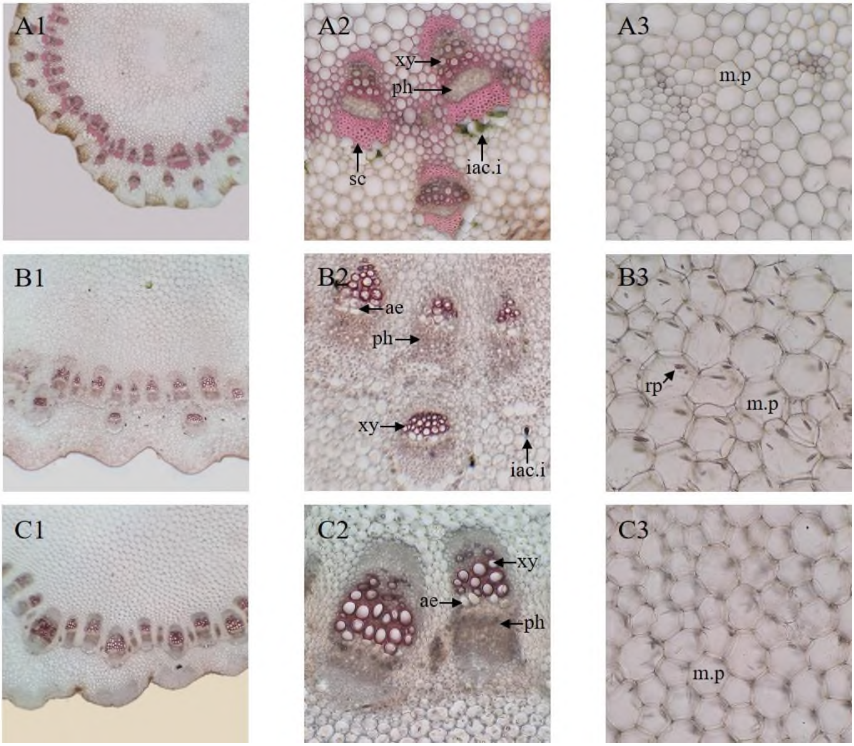

Figure 18. Comparative eco-anatomical analysis of transverse sections of stem samples of *Silybum marianum* taken from in situ conditions (A), introduced ex situ conditions (B), and natural populations within the ex situ research area (C). 1 - part of the stem, 2 - structure of the vascular system, 3 - medullary parenchyma. xy - xylem, ph - phloem, ae - aerenchyma, iac.i - intracellular inclusion, rp - raphide, m.p - medullary parenchyma

The differences were mainly in the weaker development of the sclerenchyma around the vascular bundles and the exogenous convexity observed in the area of secondary vascular bundles toward the cortex. Additionally, the vascular system displayed a more dispersed configuration. Overall, parenchyma tissue in both the cortex and medullary regions was actively developed (Table 8; Fig. 19).

Table 8. Micrometric measurements and ANOVA test results on stem samples of *Silybum marianum*

Indicators	Mean ± SD (μm)			ANOVA	
	In situ	Ex situ	Natural population of the ex situ study area	F	p
Cortex thickness	499.81 ± 24.26	576.97 ± 22.70	520.91 ± 26.05	42.59	$3{,}3\times10^{-9}$
Diameter of cortical parenchyma cells	42.24 ± 5.82	61.79 ± 6.14	50.40 ± 10.02	39.15	$1{,}0\times10^{-8}$
Height of vascular bundles	323.23 ± 36.82	458.06 ± 44.68	512.73 ± 30.99	115.17	$4{,}5\times10^{-14}$
Diameter of medullary parenchyma cells	77.82 ± 7.75	142.15 ± 14.21	97.17 ± 13.95	116.11	$1{,}4\times10^{-13}$
Lumen diameter of xylem vessels	16.46 ± 1.67	24.94 ± 2.28	31.65 ± 3.80	133.06	$2{,}4\times10^{-14}$

**Note:* SD-standard deviation. ANOVA test results indicated a significant difference between the groups ($p < 0.05$).

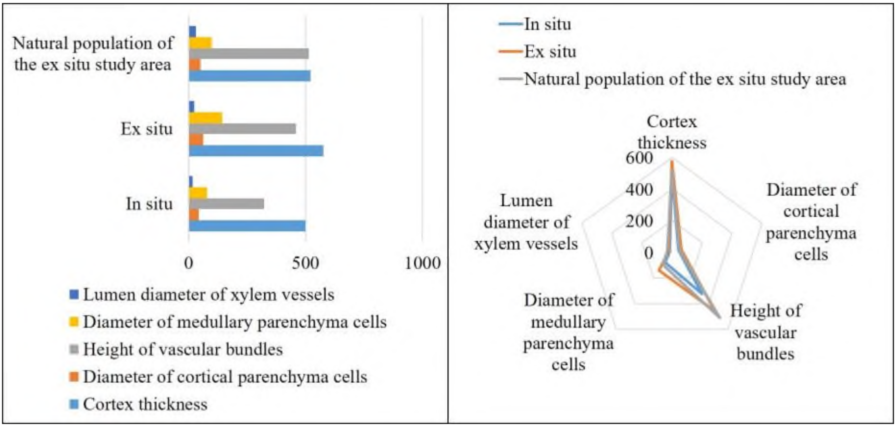

Figure 19. Statistical comparison of micrometric measurements conducted on stem samples of *Silybum marianum* applied in bar and radar charts

In the local natural population, apart from the pericyclicly arranged conductive bundles at the stem periphery, no vascular system was formed toward the cortex. Exogenous convexity was mainly observed in areas containing large-volume vascular bundles. Sclerenchyma development was weak, and the vascular system had a dispersed structure.

Root. In the ex situ specimens, the central cylinder was larger; in the in situ specimens, it was of medium size; and in the local natural population, it was relatively small (Fig. 20). In the ex situ specimens, the lumen diameters of xylem elements, particularly tracheids and vessel elements, were wider (Table 9).

Table 9. Micrometric measurements and ANOVA test results on root samples of *Silybum marianum*

Indicators	Mean ± SD (μm)			ANOVA	
	In situ	Ex situ	Natural population of the ex situ study area	F	p
Thickness of the periderm	132.87 ± 22.14	274.59 ± 15.46	281.89 ± 39.07	213.85	1×10^{-16}
Cortical parenchyma thickness	189.45 ± 13.15	498.63 ± 82.18	708.43 ± 87.81	340.68	7×10^{-16}
Diameter of the xylem area	1284.70 ± 77.56	1518.52 ± 96.50	1017.33 ± 83.55	114.95	$3{,}6\times10^{-14}$
Diameter of the xylem vessels	94.23 ± 5.78	132.32 ± 22.61	82.91 ± 16.91	23.66	$3{,}6\times10^{-6}$

**Note:* SD – standard deviation. ANOVA test results indicated a significant difference between the groups ($p < 0.05$).

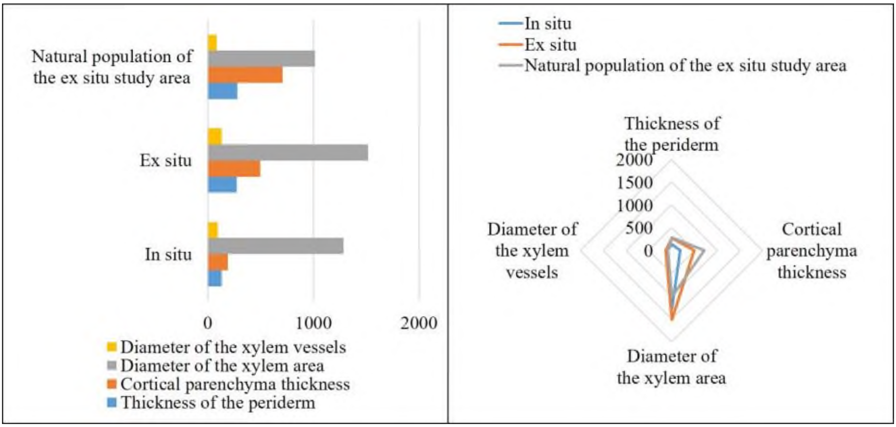

Figure 20. Statistical comparison of micrometric measurements conducted on root samples of *Silybum marianum* applied in bar and radar charts

Micrographic analysis showed that the structural-functional activity of lysigenous secretory cavities was high in the in situ specimens, moderate in the ex situ specimens, and low in the local population (Fig. 21). Anatomical investigation revealed that in the local natural population, the cortical parenchyma was strongly differentiated, comprising approximately two-thirds of the total root volume[39].

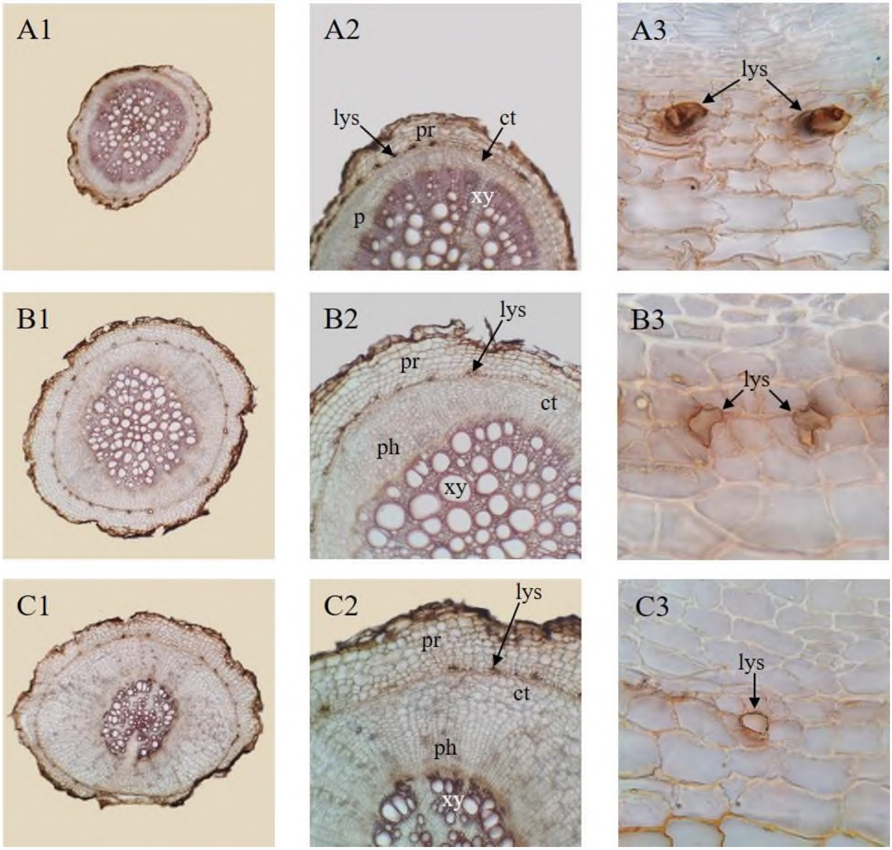

Figure 21. Comparative eco-anatomical analysis of transverse sections of root samples of *Silybum marianum* taken from in situ conditions (A), introduced ex situ conditions (B), and natural populations within the ex situ research area (C). 1 - general structure, 2 - part of the root, 3 - lysigenous cavities. pr - periderm, ph - phloem, xy - xylem, ct - cortex, lys - lysigenous cavity

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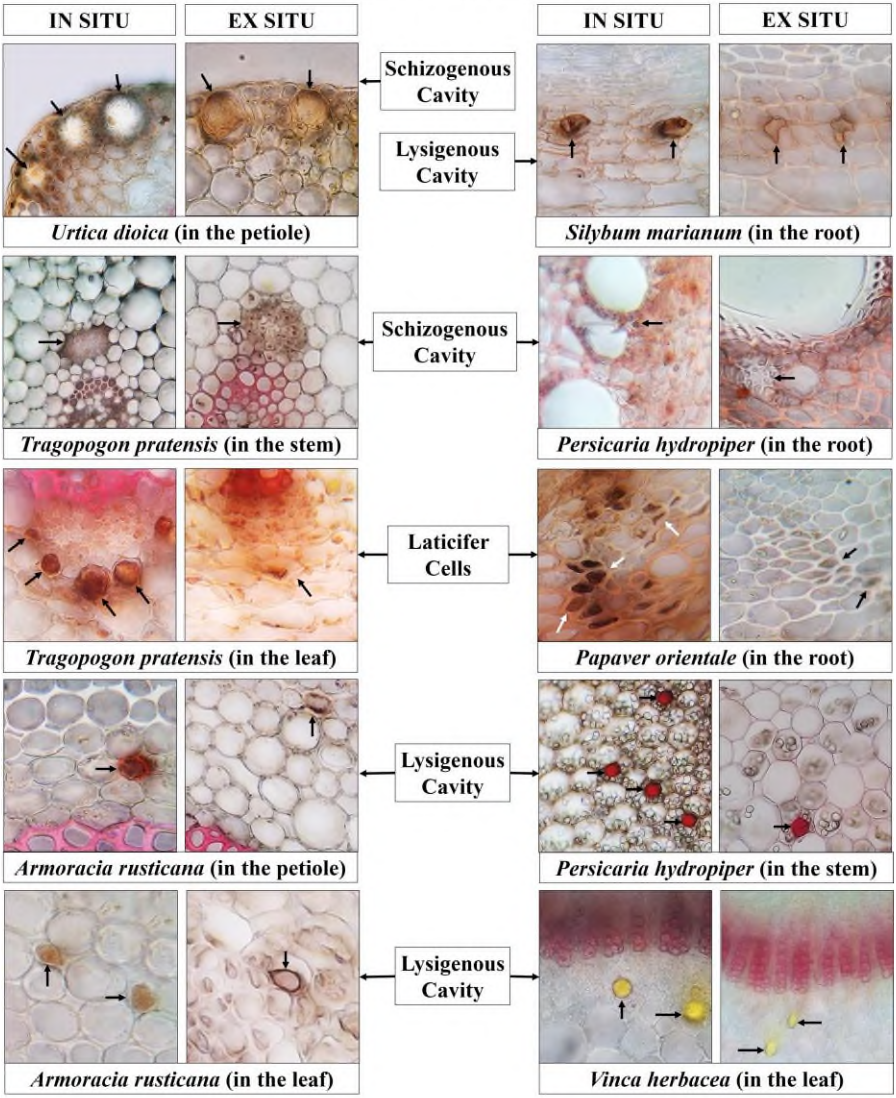
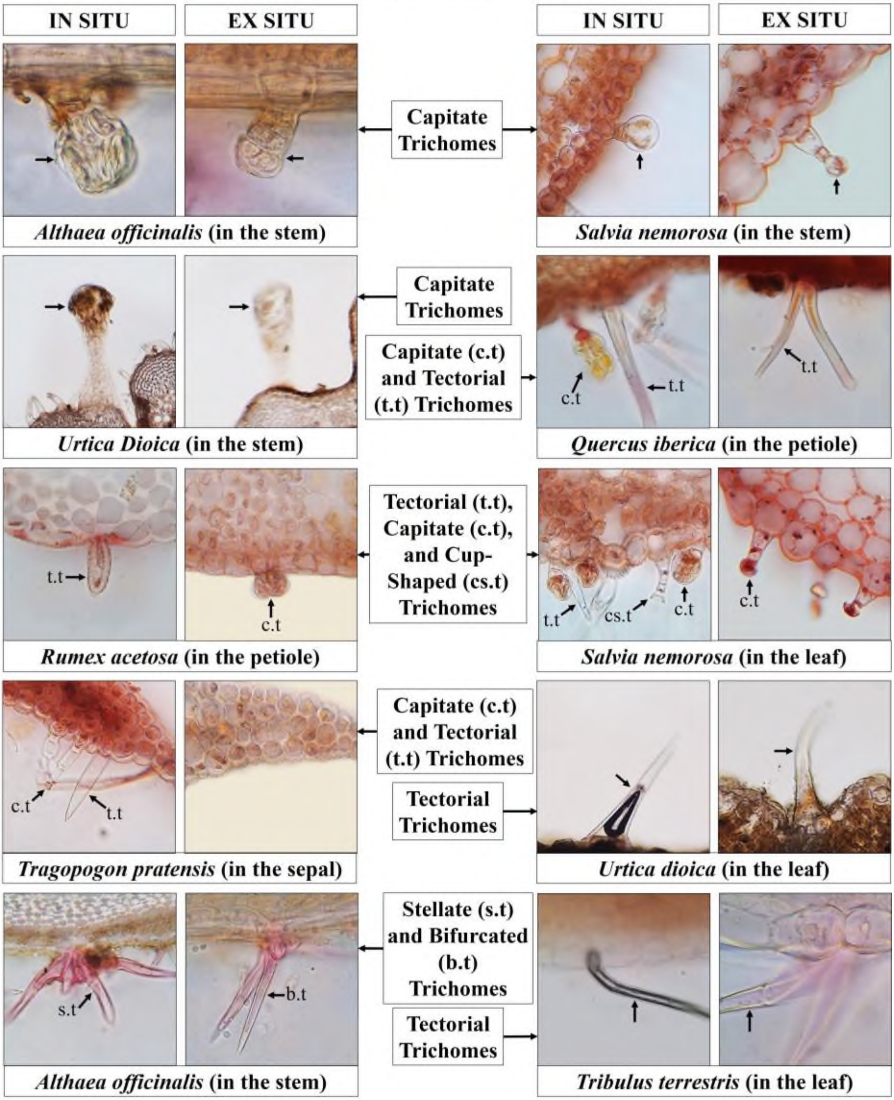
39 Sardarova, A.S. The anatomical characteristics of the vegetative and generative organs of the medicinal *Silybum marianum* L., spread in the mountainous region of the Lesser Caucasus // - Erzurum, Türkiye: 7th symposium on euroasian biodiversity (SEAB, TUBİTAK), - 2024, - p. 127.

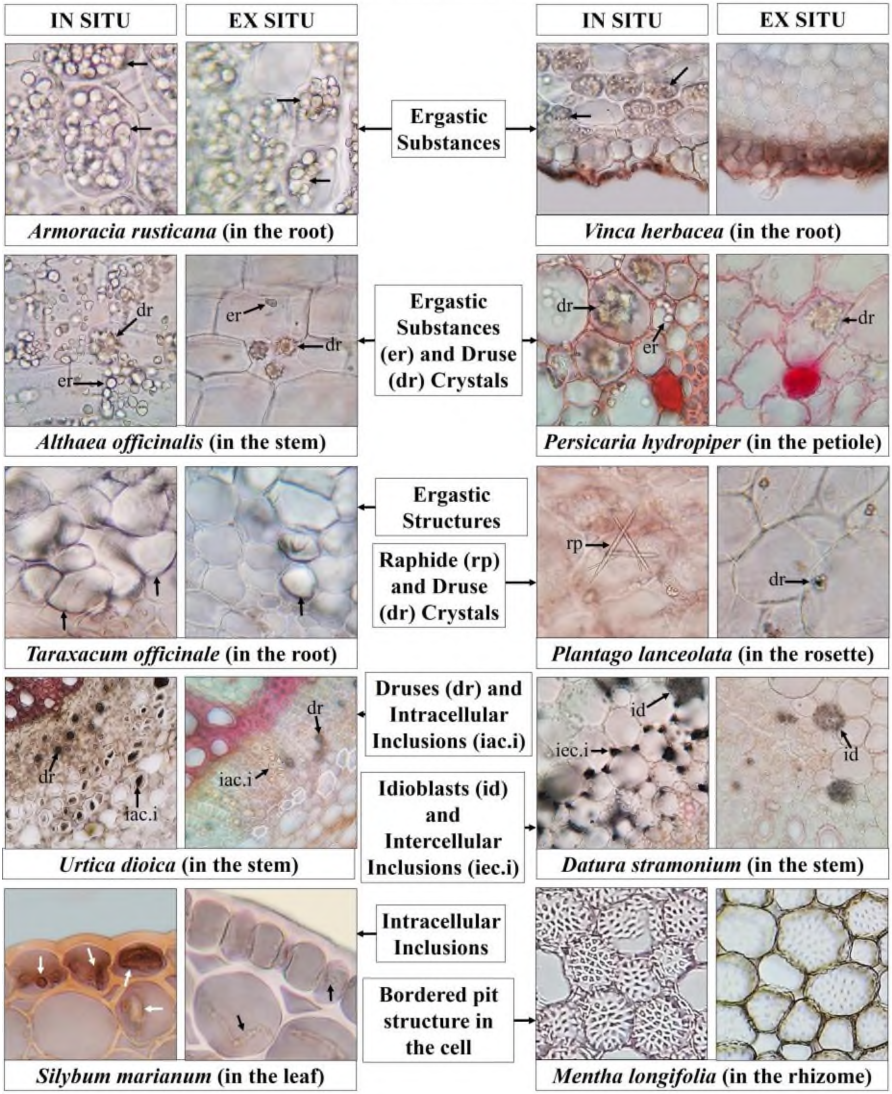
CONCEPT 1. CONCEPTUAL PRINCIPLES OF STRUCTURAL ADAPTATIONS IN PHARMACOLOGICALLY SIGNIFICANT ENDOGENOUS SECRETORY TISSUE OF SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS



CONCEPT 2. CONCEPTUAL PRINCIPLES OF STRUCTURAL ADAPTATIONS IN PHARMACOLOGICALLY SIGNIFICANT EXOGENOUS SECRETORY TISSUE OF SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS



CONCEPT 3. CONCEPTUAL PRINCIPLES OF STRUCTURAL ADAPTATIONS IN PHARMACOLOGICALLY SIGNIFICANT ERGASTIC AND CONSTITUTION STRUCTURES OF SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS



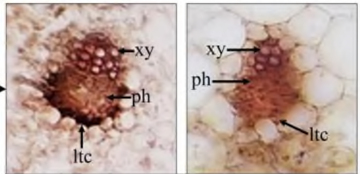
CONCEPT 4. CONCEPTUAL PRINCIPLES OF DIAGNOSTIC ANATOMICAL STRUCTURAL ADAPTATIONS IN SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS

Variations of the Vascular System at the Ecotypic Level

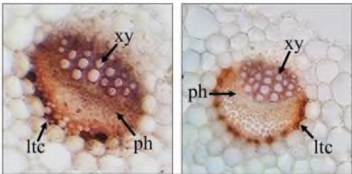
IN SITU	EX SITU		IN SITU	EX SITU

Taraxacum officinale **(in the leaf)**

xy – xylem
ph – phloem
ltc – laticifer

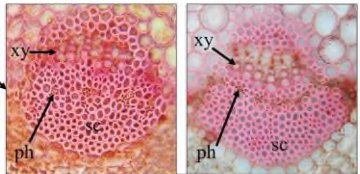


Taraxacum officinale **(in the leaf)**

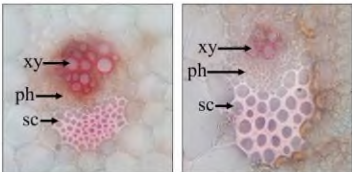


Taraxacum officinale **(in the petiole)**

Vascular Bundle
xy – xylem
ph – phloem
ltc – laticifer

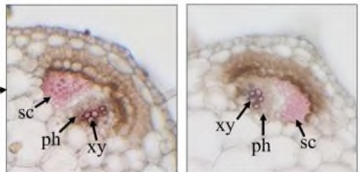


Matricaria chamomilla **(in the peduncle)**

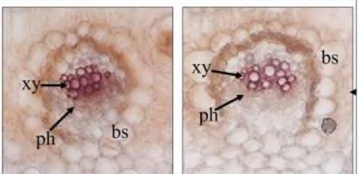


Tribulus terrestris **(in the petiole)**

Vascular Bundle
xy – xylem
ph – phloem
sc – sclerenchyma

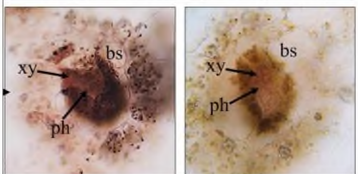


Tribulus terrestris **(in the petiole)**

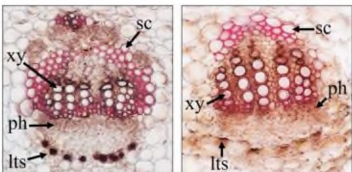


Tribulus terrestris **(in the leaf)**

Kranz Structure in the Vascular Bundle
xy – xylem
ph – phloem
ltc – laticifer
bs – bundle sheath cells

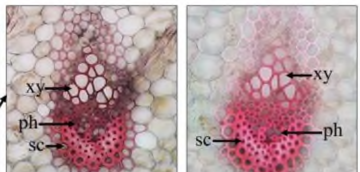


Portulaca oleracea **(in the leaf)**



Tragopogon pratensis **(in the leaf)**

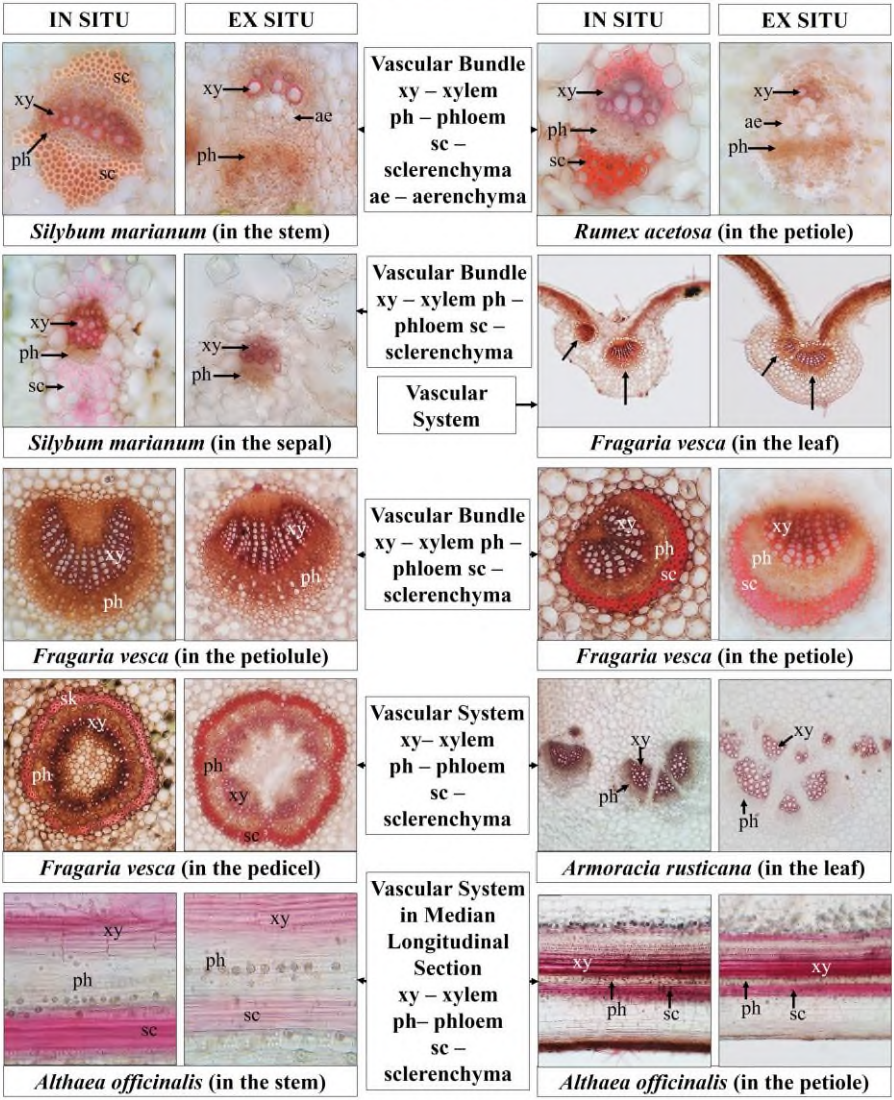
Vascular Bundle
xy – xylem
ph – phloem
ltc – laticifer
sc – sclerenchyma



Convallaria majalis **(in the leaf)**

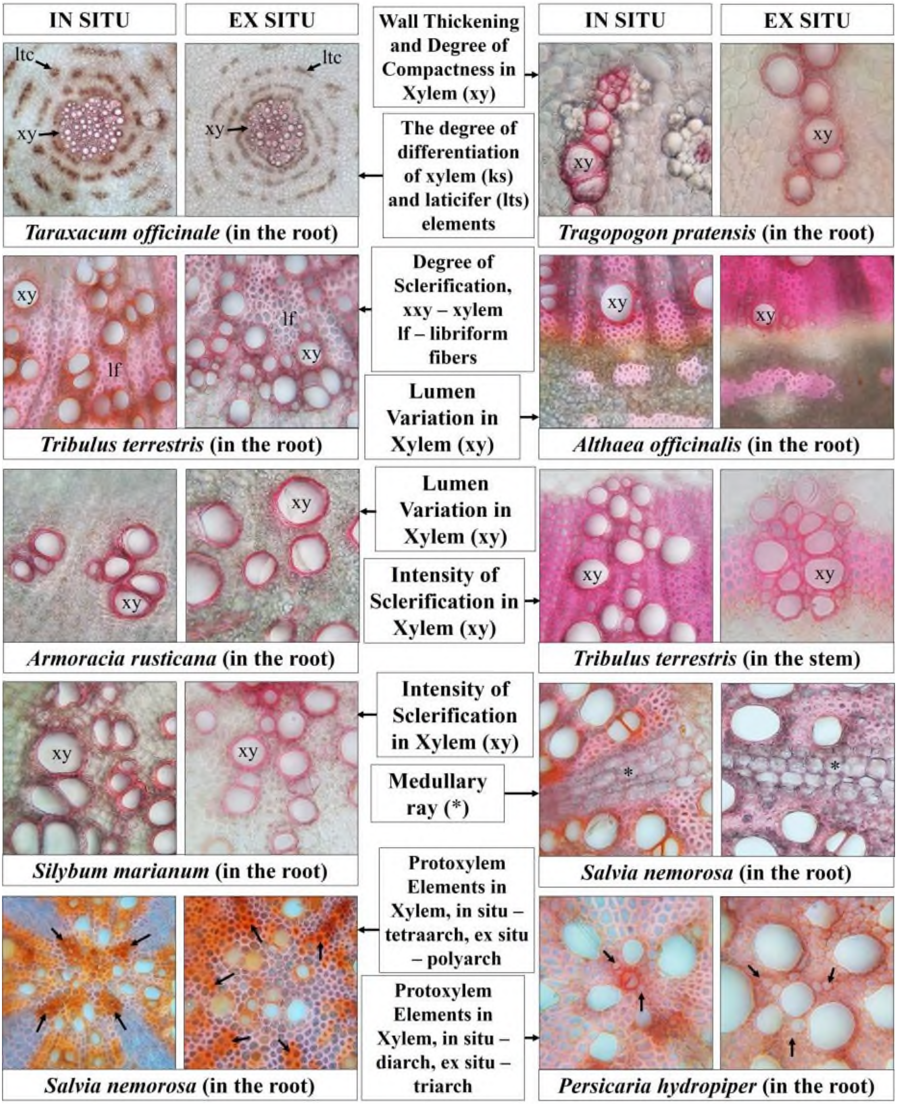
CONCEPT 5. CONCEPTUAL PRINCIPLES OF DIAGNOSTIC ANATOMICAL STRUCTURAL ADAPTATIONS IN SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS

Vascular System Variations at the Ecotypic Level

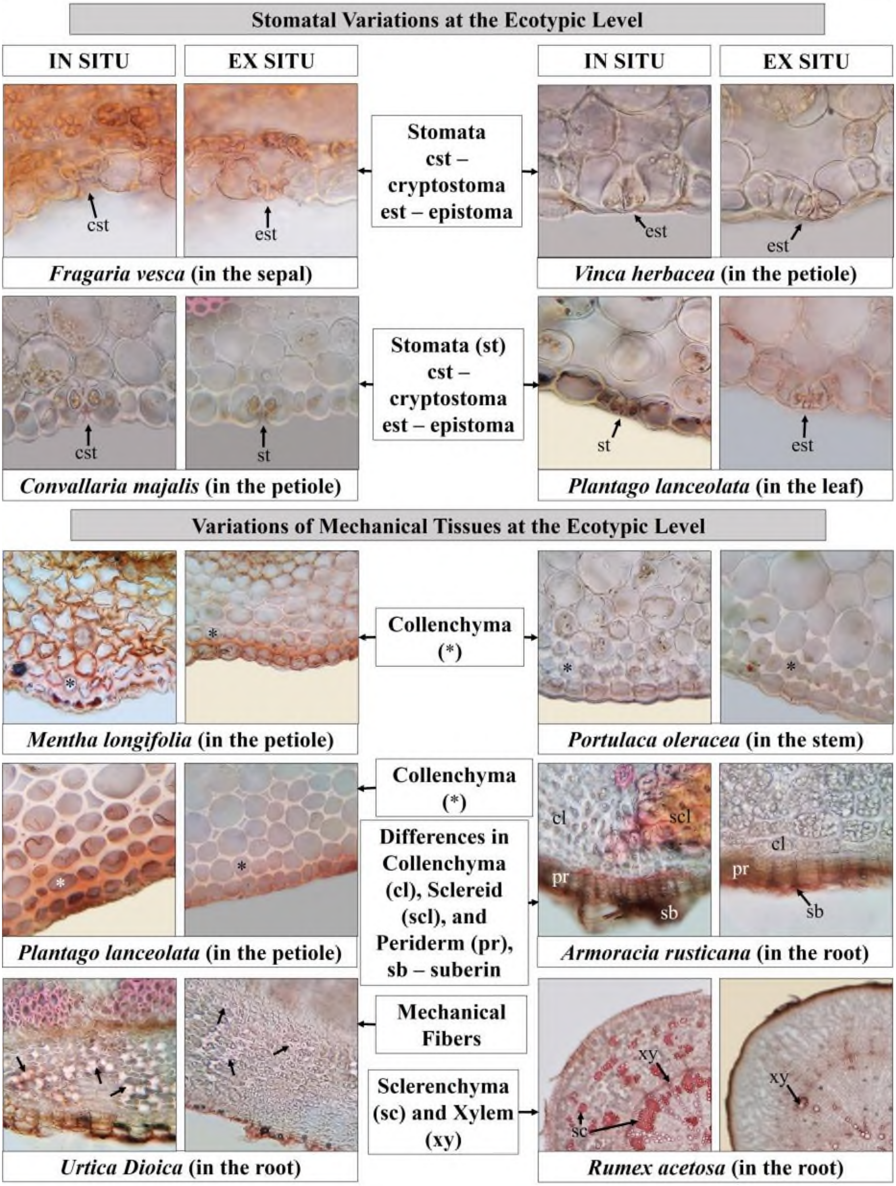


CONCEPT 6. CONCEPTUAL PRINCIPLES OF DIAGNOSTIC ANATOMICAL STRUCTURAL ADAPTATIONS IN SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS

Variations in the Vascular System at the Ecotypic Level



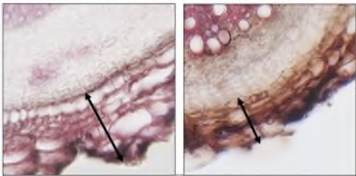
CONCEPT 7. CONCEPTUAL PRINCIPLES OF DIAGNOSTIC ANATOMICAL STRUCTURAL ADAPTATIONS IN SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS



CONCEPT 8. CONCEPTUAL PRINCIPLES OF DIAGNOSTIC ANATOMICAL STRUCTURAL ADAPTATIONS IN SPECIES STUDIED TO COMPARATIVE ECOLOGICAL-ANATOMICAL RESEARCH UNDER IN SITU AND EX SITU CONDITIONS

Variations of Protective Tissues at the Ecotypic Level

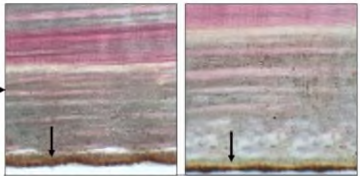
IN SITU | EX SITU



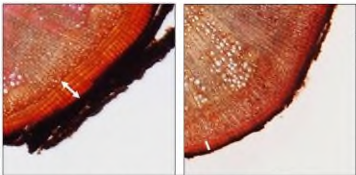
Plantago lanceolata (in the root)

Periderm

IN SITU | EX SITU



Althaea officinalis (in the root)



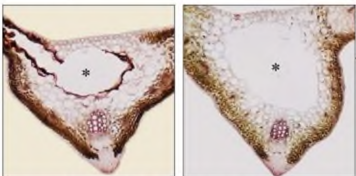
Fragaria vesca (in the root)

Polyderm

Epidermis, cl.ep – collimellar epidermis, is.ep – isodiametric epidermis

Althaea officinalis (in the petal)

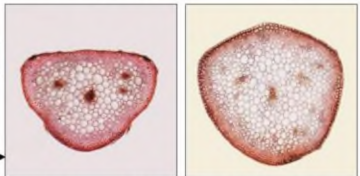
Variation of Anatomical Structures at the Ecotypic Level



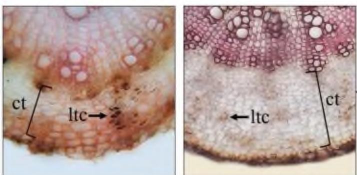
Tragopogon pratensis (in the leaf)

Aerenxima (*)

Ecotypic variation of tissue complexes

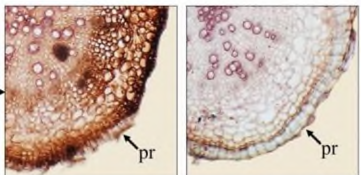


Silybum marianum (in the spine)

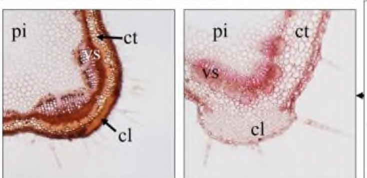


Papaver orientale (in the root)

Cortical Variations
ct – cortex
ltc – laticifer
pr – periderm

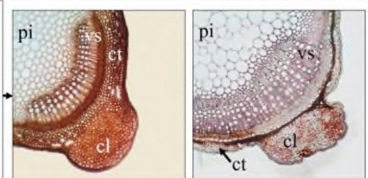


Portulaca oleracea (in the root)



Salvia nemorosa (in the stem)

Structural Variations
pi – pith
ct – cortex
cl - collenchyma
vs – vascular system



Mentha longifolia (in the stem)

HAPTER IV. ECO-ANATOMİCAL ANALYSİS OF ADAPTATİON FEATURES OF MEDİCİNAL PLANTS İN DİFFERENT ECOSYSTEMS

The distribution of medicinal plants across various ecosystems reflects their ecological plasticity, adaptive capacity, and phytogeographic status. Climate, soil composition, humidity, anthropogenic impacts, and topographic factors directly influence the anatomical and physiological traits of these plants (Fig. 22; Conc. 9).

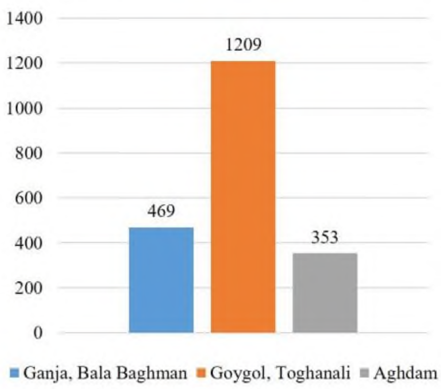


Figure 22. Ecotypic Height Profiles

This study aims to comparatively investigate the eco-anatomical characteristics of medicinal plants occurring in different ecosystems, identifying adaptation mechanisms at the tissue and cellular levels, while also examining the relationship between ecological conditions and pharmacological potential from a pharmaco-anatomical perspective. The findings can contribute to new scientific approaches regarding the biodiversity of medicinal plants, the formation of an effective raw material base, and ecosystem sustainability.

4.1. *Laurus nobilis* L.

Leaf. Comparative eco-anatomical studies revealed characteristic structural-functional features in a sample of *Laurus nobilis* collected from the Ganja region. Schizogenous and lysigenous cavities were formed in the leaf mesophyll. The presence of idioblast-type cells in the parenchyma surrounding the vascular bundles was observed through microscopic analysis (Fig. 23). The thickness of the photosynthetically active mesophyll varied according to the ecological conditions of the samples, as determined by anatomical analysis. In this sample, the spongy and palisade cells were relatively large, making the mesophyll more voluminous (Fig. 24; Table 10). In contrast, samples from the Toghanali area displayed differential characteristics.

Schizogenous secretory cavities in the Ganja sample were smaller compared to the larger cavities formed in the Toghanali sample. Adaptation structures were also highlighted by the development of trichomes on the epidermis and the higher number and organization of xylem and phloem elements. These anatomical differences demonstrate the adaptive mechanisms of *L. nobilis* in response to varying ecological conditions. Both samples possessed bistratified palisade parenchyma; however, it was more compact in the Toghanali sample. The xylem elements of the vascular system exhibited a species-specific polygonal arrangement in both samples, with lignification being more intense in the Toghanali sample. Notably, for the first time in the flora of Azerbaijan, trichomes were observed on the leaf epidermis of the *L. nobilis* sample from Toghanali, whereas several fundamental botanical sources report that trichomes are generally absent on this species' leaves. This finding can be interpreted as an indicator of morpho-anatomical plasticity in *L. nobilis* under ecological stress and represents a direct anatomical diagnostic adaptation structure influenced by the specific ecological factors of the regional environment.

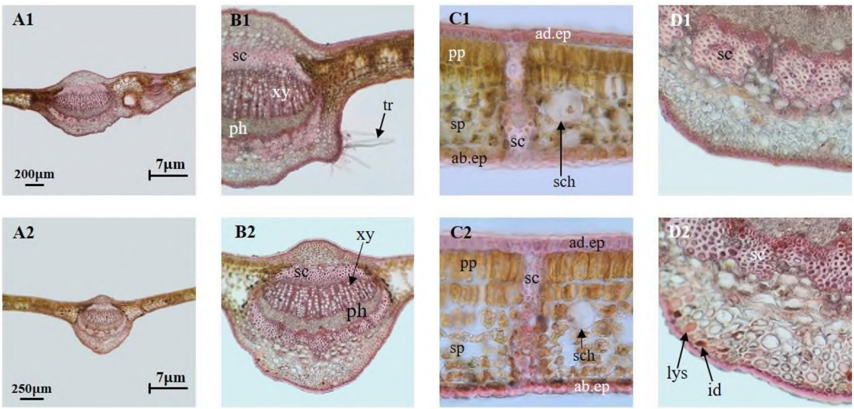


Figure 23. *Laurus nobilis*. Transverse section of the leaf (upper row - Goygol District, Toghanali Village; lower row - Ganja City, Bala Baghman Area). A1, A2 - general structure (4×16); B1, B2 - midrib (10×); C1, C2 - mesophyll region, D1, D2 - lower peripheral part of the midrib (40×). tr-trichome, xy - xylem, ph - phloem, sc - sclerenchyma, pp - palisade parenchyma, sp - spongy parenchyma, ad.ep - adaxial epidermis, ab.ep - abaxial epidermis, sch - schizogenous cavity, lys - lysigenous cavity, id - idioblast

Table 10. Comparative statistical analysis of the quantitative indicators of *Laurus nobilis* leaf (μm)

Indicators	Ganja (Mean ± SD)	Toghanali (Mean + SD)
Adaxial epidermis cell size	24,34 ± 2,15	20,78 ± 1,95
Abaxial epidermis cell size	18,53 ± 2,42	15,71 ± 1,98
Height of palisade parenchyma	95,08 ± 3,84	82,28 ± 2,85
Height of spongy parenchyma	135,86 ± 7,14	102,8 ± 5,62
Xylem vessel diameter	20,13 ± 3,55	20,32 ± 4,26
Cell group size in the width of the sclerenchyma	125,54 ± 7,03	146,88 ± 7,65
Diameter of schizogenous secretory cavities	47,14 ± 2,85	67,34 ± 2,04

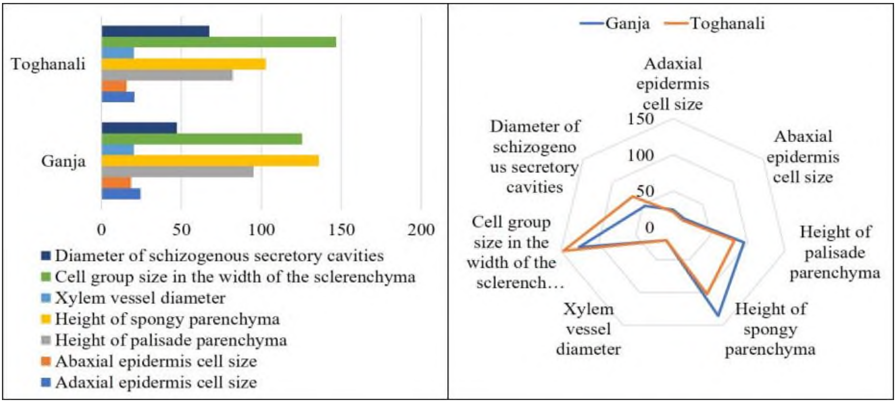


Figure 24. Statistical comparison of micrometric measurements conducted on leaf samples of *Laurus nobilis* applied in bar and radar charts

4.2. *Xanthium spinosum* L.

Stem. When the stem anatomy of *Xanthium spinosum* specimens collected from the Toghanali and Aghdam regions is compared, significant differences are observed (Table 11; Fig. 25).

Table 11. Comparative statistical analysis of the quantitative indicators of the *Xanthium spinosum* stem (μm)

Indicators	Toghanalı (Mean ± SD)	Aghdam (Mean ± SD)
Diameter of medullary parenchyma cells	85,16 ± 6,76	76,65 ± 6,59
Diameter of cortical parenchyma cells	74,94 ± 7,18	49,39 ± 6,28
Sclerenchyma fiber cell wall thickness	5,12 ± 1.01	3,41 ± 0,73

**Note:* SD – standard deviation

In the Toghanali specimen, a greater number of cells and pronounced lignification are recorded in the sclerenchyma groups located at the boundary with the vascular system, along with thick-walled parenchyma, subepidermal aerenchyma, and schizogenous spaces in the cortex (Fig. 26).

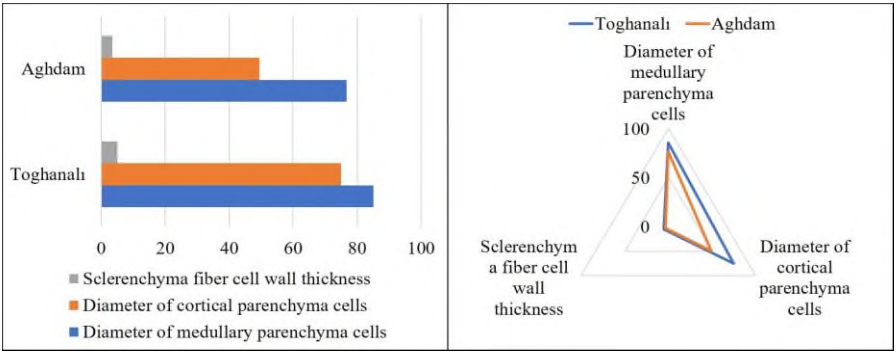


Figure 25. Statistical comparison of micrometric measurements conducted on stem samples of *Xanthium spinosum* applied in bar and radar charts

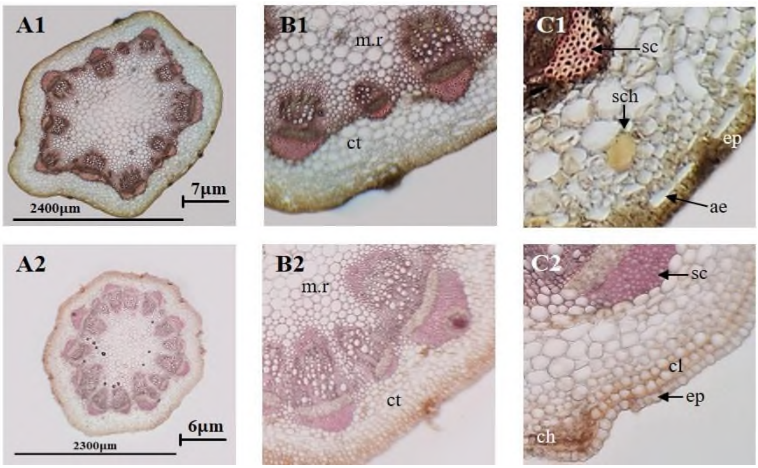
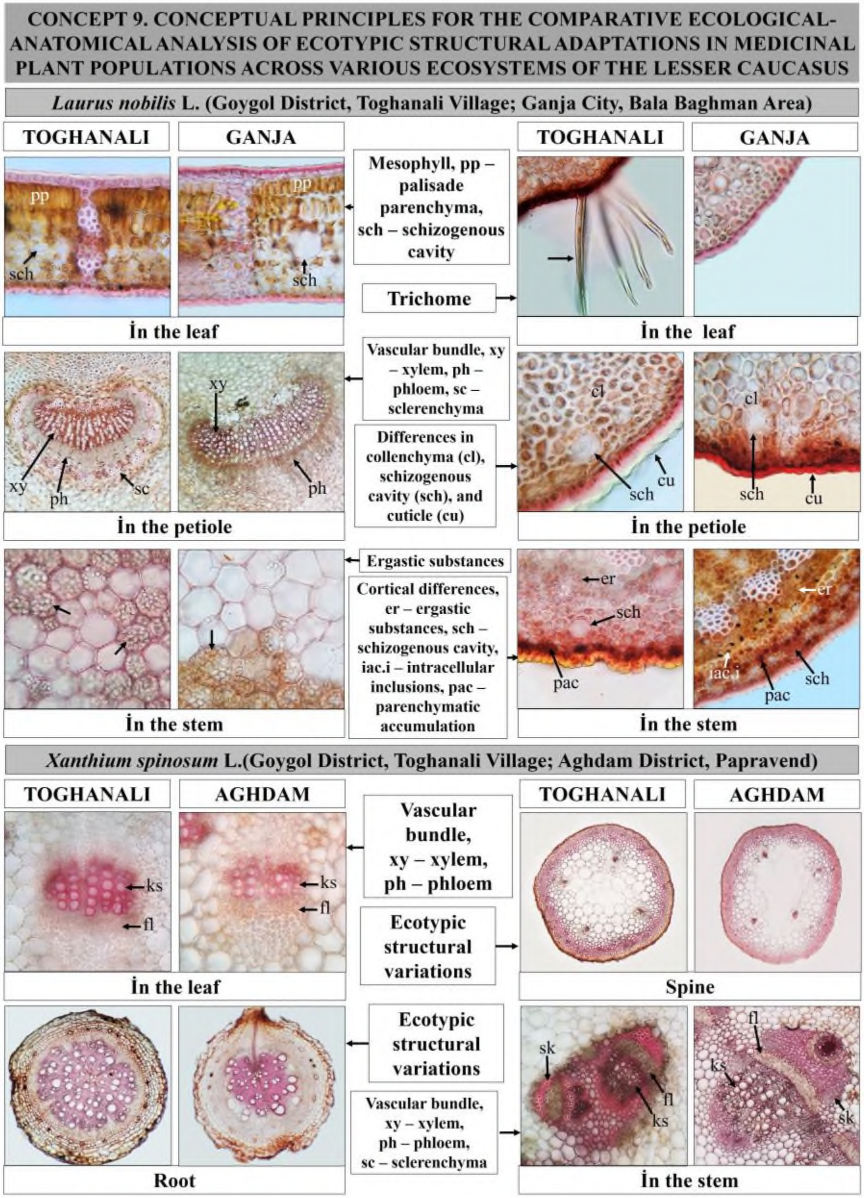


Figure 26. ***Xanthium spinosum*****. Transverse section of the stem (upper row - Goygol District, Toghanali Village; lower row - Aghdam District, Papravend Village).** A1, A2 - general structure (4×16); B1, B2 - a part (10×); C1, C2 - cortex (40×). m.r - medullary region, ct - cortex, ep - epidermis, ae - aerenchyma, sch - schizogenous cavity, sc - sclerenchyma, cl - collenchyma, ch - chlorenchyma

In contrast, the Aghdam specimen exhibits poorly developed sclerenchyma, thin-walled parenchyma cells, and a predominance of collenchyma in the subepidermal zone. These differences are explained by anatomical adaptations: in the humid mountainous ecosystem of Toghanali, structural reinforcement and regulation of aeration are emphasized, whereas in the semi-arid conditions of Aghdam, adaptations enhance elasticity and water retention capacity.



CHAPTER V. ECO-ANATOMİCAL ANALYSİS OF TOLERANCE LEVELS OF MEDİCİNAL PLANTS UNDER ECOLOGİCAL STRESSİNG CONDİTİONS İN THE LESSER CAUCASUS REGİON

Ecological stress factors are among the primary determinants directly affecting plant growth and distribution. Stresses such as drought, salinity, heavy metal contamination, and air and soil pollution induce various changes in the physiological and anatomical characteristics of plants (Conc. 10, 11). These factors not only influence plant metabolism but also lead to adaptive modifications in tissue structure. Under stressful conditions, plants develop a range of adaptation mechanisms to survive. For instance, in drought conditions, thickening of the cuticle, a reduction in stomatal density, and enhanced sclerenchymatization are observed. In saline soils, plants adapt through intracellular ion regulation and specialized structures for salt excretion. In plants exposed to heavy metal contamination, a more voluminous cuticular layer, cell wall thickening, increased isolation capacity, and functional degradation of stomata are observed, accompanied by an enhanced phytoremediation potential. Phytoremediation refers to the process through which medicinal plants accumulate environmental contaminants, particularly heavy metals, pesticides, and other toxic substances. These contaminants enter plants via soil, water, and air, affecting their therapeutic efficacy and biodiversity. Urbanization over recent decades has exerted substantial impacts on ecosystems, leading to significant alterations in the morphological, anatomical, and physiological traits of plants in urban environments. Plant survival and development in urban ecosystems are therefore constrained by multiple stress factors.

5.1. Eco-anatomical investigation of the structural-functional tolerance potential of medicinal plants in arid and saline areas under abiotic stress conditions

In arid and saline ecosystems, medicinal plants such as *Salsola nodulosa* and *Zygophyllum fabago* have developed specific adaptation mechanisms to withstand various abiotic stresses (Figs. 27-30). In these species, the maintenance of water balance, elimination of excess salts, and reinforcement of structural tissues ensure their tolerance potential. Therefore, the study of their ecological-anatomical characteristics is of great significance for understanding the mechanisms of resilience under stress conditions.

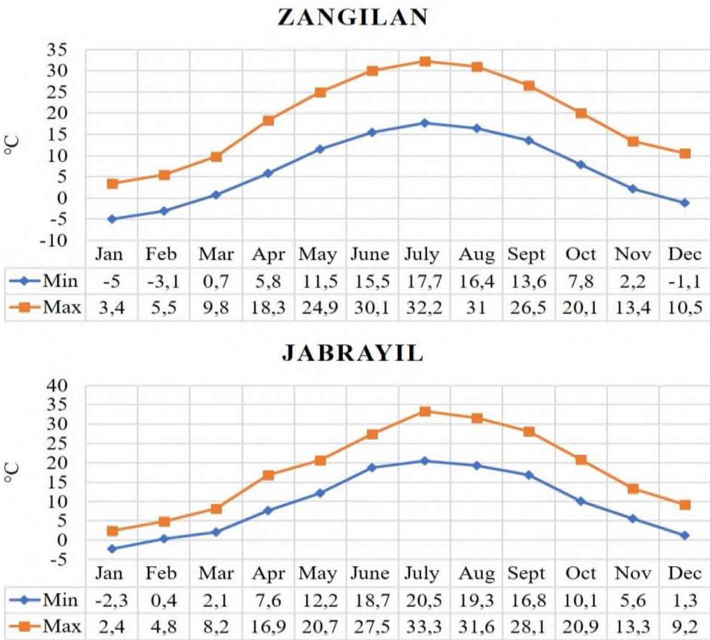


Figure 27. Annual temperature fluctuation amplitude in the Zangilan and Jabrayil regions

Figure 28. Drought indicators by regions

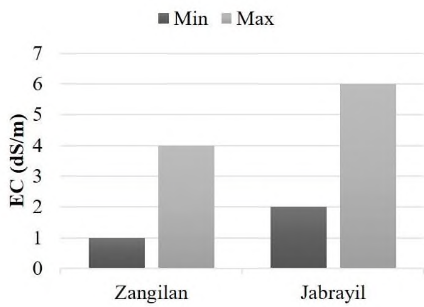


Figure 29. Salinity indicators by regions

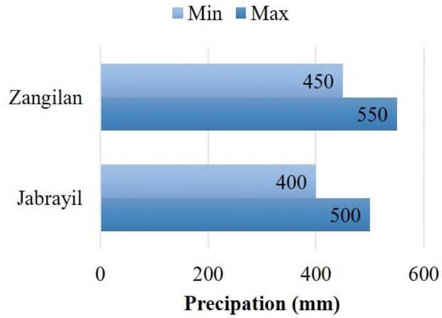


Figure 30. Annual precipitation amount

5.1.1. *Salsola nodulosa* Iljin

Leaf. In transverse section, the leaf of *Salsola nodulosa* exhibits a subdeltoid shape, which indicates succulence and high water-storage capacity. Large, heteromorphic storage parenchyma cells are located at the periphery of the central vascular system. The xylem elements, which undergo an intensive sclerification process, display an atypical polygonal structure (Fig. 31).

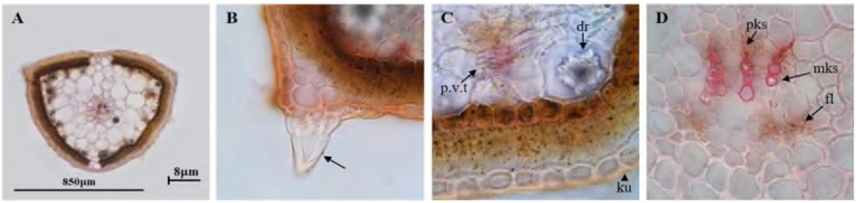


Figure 31. *Salsola nodulosa* (Zangilan District, Bartaz Village, near the Aras River). Transverse structure of the leaf. A - general structure (10×16); B - trichome-type salt gland (indicated by arrow); C - abaxial part of the leaf: cuticle (cu), druse in water-storing parenchyma (dr), peripheral vascular bundle (p.v.b); D - central vascular bundle (40×). pxy - protoxylem, mxy - metaxylem, ph - phloem.

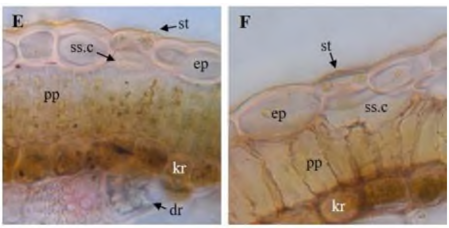


Figure 32. Peripheral regions of the leaf of *Salsola nodulosa* (E, F). ep - epidermis, st - stoma, ss.c - substomatal cavity, pp - palisade parenchyma, kr - Kranz cells, dr - druse.

In the epidermis, along with anomalous stomata characteristic of haloxerophytic plants, conical trichome-like salt glands are formed. Beneath the epidermis lies a single-row palisade parenchyma layer of conservative structure, followed internally by C_4-type Kranz cells (Fig. 32). For the first time, the presence of a *salsoloid* type of Kranz anatomy - limiting photorespiration and enhancing CO_2 fixation efficiency - has been identified in the flora of Azerbaijan.The presence of large druse crystals within the leaf parenchyma, possessing osmoregulatory, detoxifying, ion-balancing, mechanical, and protective functions, together with the Kranz structure, mesophyll organization, and the active development of mechanical tissues, represents key anatomical diagnostic traits of adaptation to arid and saline environments.

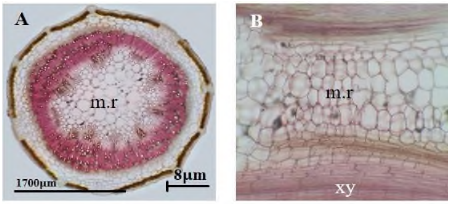


Figure 33. ***Salsola nodulosa*****. Transverse and median longitudinal structure of the stem.** A - transverse section of the stem (4×16), B - median longitudinal section of the stem (10×). m.r-medullary region, xy - xylem

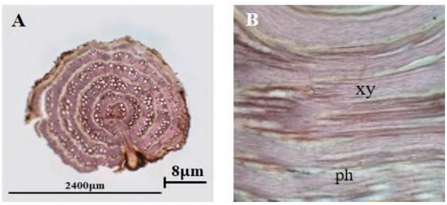


Figure 34. ***Salsola nodulosa*****. Transverse and lateral longitudinal structure of the root.** A - transverse section of the root (4×), B - lateral longitudinal section of the root (10×). xy - xylem, ph - phloem

Stem. The formation of large water-storing parenchyma tissue in the stem and an actively developed pericyclic vascular system in the perimedullary zone is regarded as a characteristic feature of succulence (Fig. 33).

Root. In the root, the organization of the vascular system in annual rings with consecutive zones, combined with pronounced lignification, represents a unique and rare tolerant anatomical structure characterizing a high adaptive capacity to arid conditions (Fig. 34).

5.1.2. *Zygophyllum fabago* L.

Stem. The stem of *Zygophyllum fabago* exhibits a suborbicular to ellipsoid shape in transverse section, reflecting the internal organization of its tissues. From the stele toward the cortex, parenchyma cells are interspersed with groups of sclerenchyma cells that have undergone extensive sclerification. Within the vascular system, a double row of fusiform initial cells is present between the phloem and xylem. Chloroplast-containing parenchyma cells are recorded in the peripheral zone of the stem. In the epidermis covering the stem, stomata are present with slightly protruding guard cells (Fig.

35). As a haloxerophytic species, *Z. fabago* in arid and saline conditions is characterized by a medulla surrounded by a pericyclic, actively developed vascular system and grouped sclerenchyma clusters, which enhance mechanical strength and optimize water transport[40]. The presence of asymmetric sclerenchyma zones and a thickened cuticle in the stem serves as an anatomical indicator of the species' adaptive mechanisms to its environment[41].

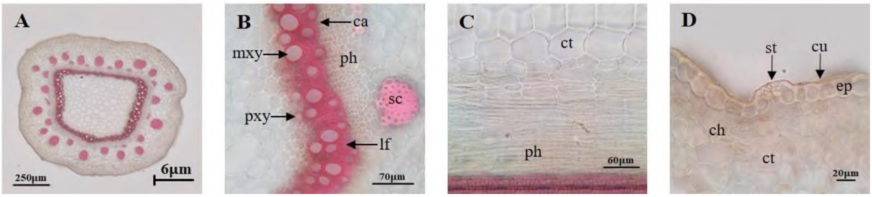


Figure 35. *Zygophyllum fabago* (Jabrayil District, Khudafarin Mehdili). Transverse and median longitudinal structure of the stem. A - general structure (4×16); B - vascular system (µm - xylem), C - cortex and phloem in the median longitudinal section (µm - parenchyma cell) (40×); D - cortex (µm - stoma) (60×). ca - cambium, ph - phloem, sc - sclerenchyma, pxy - protoxylem, mxy - metaxylem, lf - libriform fibers, ch - chlorenchyma, ct - cortex, ep - epidermis, st - stoma

5.2. Eco-anatomical analysis of tissue restructuring, deformation, and anomalies in medicinal plants under anthropogenic dynamics of ecosystems

5.2.1. Characterization of phytodiversification traits of medicinal plants based on eco-anatomical analysis under phytocontamination

The ecological-anatomical study of medicinal plants exposed to phytocontamination is particularly relevant for understanding their

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[40] Sardarova, A.S. Anatomical characteristics of *Zygophyllum fabago* L. plant adapted to environmental factors and medicinal value // - Kruyt, Ukraine: Основні, малопоширені і нетрадиційні види рослин - від вивчення до освоєння (сільськогосподарські і біологічні науки): Матеріали VIII Міжнародної науково-практичної конференції (у рамках IX наукового форуму «Науковий тиждень у Крутах - 2024», 13-14 березня 2024 р., с. Крути, Чернігівська обл., Україна), - 2024. Vol. 1, - с. 156-160.

[41] Gabr, D.G., Ragab, O.G. Morpho-anatomical characters of leaves and stems as a tool for the identification of some taxa of *Zygophyllaceae* of Eastern Saudi Arabia // Egyptian Journal of Botany, – 2023. 63 (2), – p. 389-402.

adaptive potential under industrial and anthropogenic pollution conditions. Investigations of pharmacologically important species such as *Tribulus terrestris* and *Peganum harmala* in this context allow for the identification of both tolerance mechanisms to ecotoxic environments and phytoremediation capabilities[42]. The results of such studies are of significant importance for assessing the impact of industrial pollution on vegetation and for the development of scientifically grounded sustainable ecosystem management strategies.

5.2.1.1. *Peganum harmala* L.

Root. The impact of phytocontamination on *Peganum harmala* was analyzed through ecological-anatomical investigations of its vegetative and generative organs. Comparative anatomical analyses of specimens collected from ecologically clean and contaminated sites revealed structural differences (Fig. 36; Table 12). In specimens from the ecologically clean area, xylem elements exhibit larger diameters, and sclerenchyma and phloem are arranged in consecutive layers within the cortex. The periderm shows lower quantitative values in terms of thickness. Ergastic substances are observed in the cortical parenchyma, while druse crystals are present in cells near the periderm. The periderm consists of 3-4 layers of suberized cells. In contrast, under contaminated conditions, the periderm comprises 6-7 layers, with an additional supernumerary periderm forming above it. The supernumerary periderm contains sclerenchyma fibers, ergastic substances, and anomalous parenchymatic accumulations. Xylem elements in these specimens are smaller, more densely arranged, and exhibit more intensive wall thickening (Table 13).

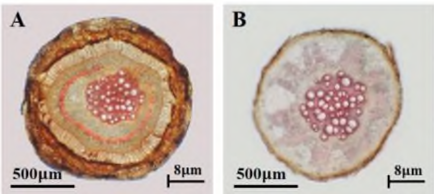
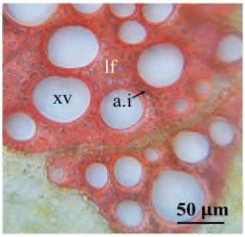
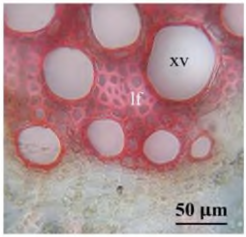
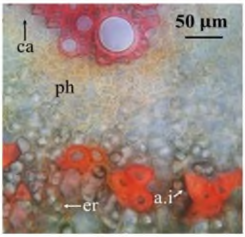
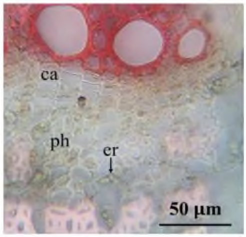
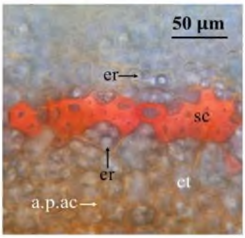
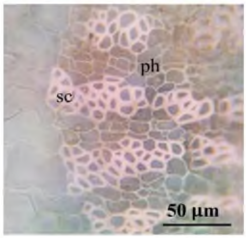
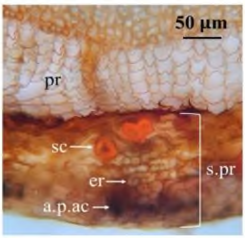
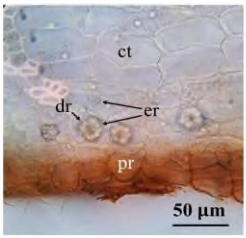


Figure 36. Transverse structure of the root of *Peganum harmala* (A - from the contaminated area of Aghdam Industrial Park; B - from the ecologically clean environment of Bartaz village, Zangilan district)

42 Krzesłowska, M. Morphology and physiology of plants growing on highly polluted mining wastes / M. Krzesłowska P. Goliński, M. Szostek [et al.] // in: Phytoremediation for Environmental Sustainability. Ed: R. Prasad; - Singapore: Springer, - 2021. - p. 151-200.

Anomalous intracellular inclu-sions are observed in the cortex, xylem, and phloem elements. The phloem displays a compact structure, and sclerification in mechanical elements is active. Reduced size of cortex cells rich in ergastic substances was statistically confirmed.

Table 12. Comparison of anatomical structures in roots of *Peganum harmala* collected from ecologically clean and contaminated areas

Description of anatomical feature	Aghdam (contaminated)	Zangilan (clean)
Xylem tissue region. xv - xylem vessel, lf - libriform fibers, a.i - anomalous inclusions		
Cambium and phloem tissue region. ca - cambium, ph - phloem, er - ergastic substrances, a.i - anomalous inclusions		
Sclerenchyma tissue in the cortex. sc - sclerenchyma, ct - cortex, a.p.ac - anomalous parenchymatic accumulation, er - ergastic substrances		
Peripheral part. pr - periderm, s.pr - supernumerary periderm, dr - druse, a.p.ac - anomalous parenchymatic accumulation, sc - sclerenchyma, ct - cortex, er - ergastic substrances		

Leaf. Under phytocontamination conditions, anomalous inclusions were detected in the leaf mesophyll, stomatal apparatus, and substomatal chambers. Anomalous parenchymatic accumulations were also observed in the palisade and spongy tissues (Fig. 37). Nevertheless, the plant maintains the overall anatomical structure and vital functions, indicating a high capacity for structural plasticity.

Table 13. Comparative statistical analysis of the quantitative indicators of the *Peganum harmala* root (μm)

Indicators	Ecologically contaminated area (Mean ± SD)	Ecologically clean area (Mean + SD)
The height of the periderm	116,23 ± 2,99	36,31 ± 2,38
The height of the periderm cells	16,60 ± 1,14	19,37 ± 1, 06
Diameter of the cortex parenchyma cells	31,70 ± 2,68	52,05 ± 3,16
Diameter of the xylem vessels	60,42 ± 5,97	81,17 ± 7,45

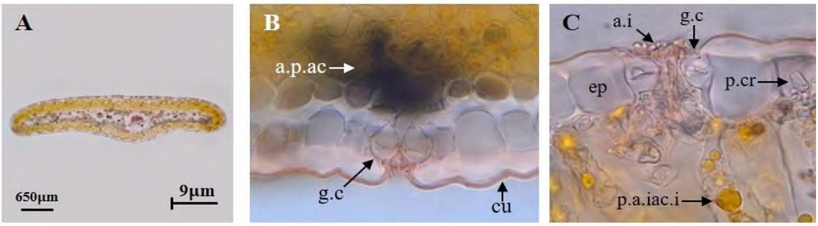


Figure 37. *Peganum harmala.* Transverse structure of the leaf. A - general structure; B, C - phytocontamination process in abaxial and adaxial stomata. a.p.ac - anomalous parenchymatic accumulation, g.c - guard cells, cu - cuticle, p.a.iac.i - pigmented anomalous intracellular inclusions, p.cr - prismatic crystal, ep - epidermis, a.i - anomalous inclusions.

Seed. In seeds collected from the contaminated area, anomalous intracellular inclusions accumulated in the endotesta layer, while the aleurone layer was poorly developed (Fig. 38).

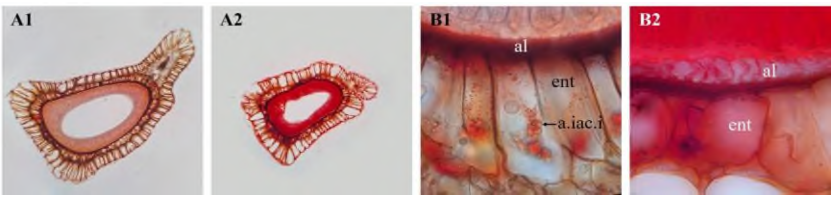


Figure 38. Micrographic comparison of seed samples of *Peganum harmala* collected from contaminated (1) and ecologically clean (2) environments. A1, A2 - general structure (10×16); B1, B2 - a part (40×). al-aleurone, ent-endotest, a.iac.i-anomalous intracellular inclusions

5.2.2. Eco-anatomical analysis of the effects of landscape changes caused by urbanization on medicinal plants

This study investigates the adaptive structural traits of plants in urban environments, assessing their tolerance mechanisms against anthropogenic impacts and identifying ecological-anatomical monitoring indicators for urban landscapes. Anatomical analyses of the effects of urbanization on medicinal plants contribute to the development of new scientific approaches in applied botany, pharmacology, ecology, and phytogeography. In this context, the ecological-anatomical study of herbaceous and tree species exposed to urbanization, such as *Taraxacum officinale*, *Plantago lanceolata*, and *Laurus nobilis*, is particularly relevant.

5.2.2.1. *Taraxacum officinale* L.

Leaf (lateral vascular system). Cell hypertrophy was recorded in the dorsal epidermis of *Taraxacum officinale* leaves. This outgrowth, originating from the protective tissue complex, serves as an anatomical indicator of stress under urbanization conditions. The hypertrophic papilla is considered a modification of trichomes and represents a diagnostic trait of the plant's morphofunctional adaptation to urban environments. Anomalous intracellular and parenchymatic accumulations of the anomalous type were observed in the epidermal cells as well as in the palisade and spongy parenchyma. Stomatal anomalies were also recorded in specimens exposed to urbanization (Fig. 39).

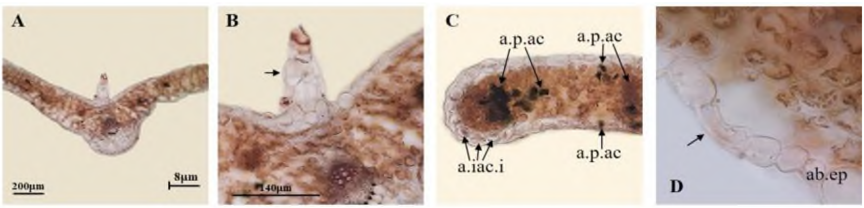


Figure 39. ***Taraxacum officinale*** **(Khankendi city). Transverse structure of the leaf (lateral vein).** A - general structure (4×16), B - hypertrophic outgrowth (indicated by arrow), C - marginal part (40×), D - stomatal anomaly (indicated by arrow) (100×). a.p.ac - anomalous parenchymatic accumulation, a.iac.i - anomalous intracellular inclusions, ab.ep - abaxial epidermis.

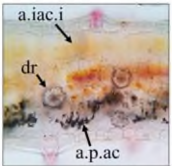
Root. Anomalous-type intracellular inclusions and parenchymatic accumulations were detected in the root parenchyma, subperidermal zone, and periderm, while non-specific inclusions were found in the vascular elements and at the periphery of laticifer cells. (Fig. 40).

CONCEPT 11. CONCEPTUAL PRINCIPLES OF ADAPTATION STRUCTURES OF MEDICINAL PLANTS IN ECOLOGICALLY STRESSED ECOSYSTEMS OF THE LESSER CAUCASUS REGION

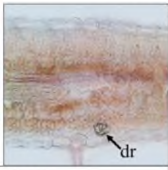
Ecological-anatomical analysis of anomalous accumulation and restructuring processes in medicinal plants under phytocontamination conditions

***Tribulus terrestris* L. (Aghdam Industrial Park Area; Dashkasan District, Qaraqullar Village)**

AGHDAM



DASHKASAN

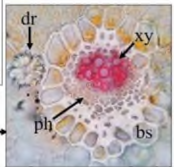


İn the leaf

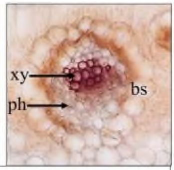
Mesophyll, dr – druse, a.p.ac – anomalous parenchymatic accumulation, a.iac.i – anomalous intracellular inclusions

Kranz-type vascular bundle, xy – xylem, ph – phloem, bs – bundle sheath cells, dr – druse

AGHDAM



DASHKASAN

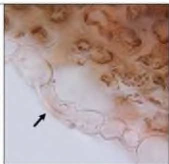


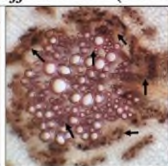
İn the leaf

Ecological-anatomical analysis of developmental mechanisms and structural deformations of medicinal plants in urban ecosystems

***Taraxacum officinale* L. (Khankendi City)**


Hypertrophied papilla in the leaf

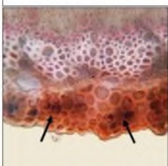

Stomatal anomaly in the leaf

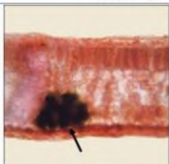

Anomalous inclusions in the root

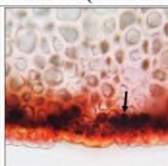

Anomalous inclusions in the xylem and phloem of the root

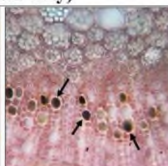

Anomalous accumulations in the laticifer cells of the root

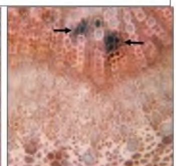
***Laurus nobilis* L. (Khankendi City)**


Anomalous parenchymatic accumulations in the leaf collenchyma

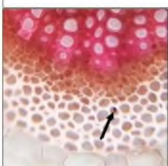

Anomalous parenchymatic accumulations in the leaf mesophyll

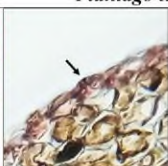

Anomalous parenchymatic accumulations in the petiole collenchyma


Anomalous intracellular inclusions in the stem xylem


Anomalous parenchymatic accumulations in the stem xylem

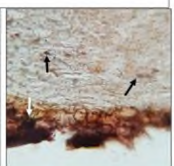
***Plantago lanceolata* L. (Khankendi City)**


Anomalous intracellular inclusions in the leaf vascular bundle


Stomatal anomaly in the leaf


Anomalous parenchymatic accumulation in the root xylem


Anomalous parenchymatic accumulation around the bundle in the petiole


Anomalous inclusions in the root cortex

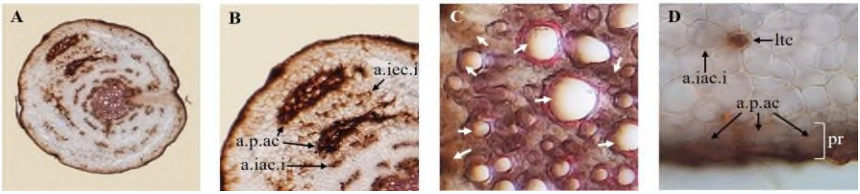


Figure 40. ***Taraxacum officinale*** **(Khankendi city). Transverse structure of the root.** A - general structure (4×16), B - a part (10×), C - anomalous accumulations in xylem (indicated by arrows), D - peripheral part of the root (60×). a.iec.i - anomalous intercellular inclusions, a.iac.i - anomalous intracellular inclusions, a.p.ac - anomalous parenchymatic accumulation, ltc - laticifer cell, pr - periderm

CHAPTER VI. INVESTİGATİON OF THE ECOSTRUCTURAL FEATURES OF MEDİCİNAL PLANTS FROM DİFFERENT ECOLOGİCAL GROUPS USİNG ECO-ANATOMİCAL METHODS

Medicinal plants belong to various ecological groups, occurring under different climatic conditions and exhibiting specific anatomical adaptations. Plants classified as xerophytes, mesophytes, hygrophytes, hydrophytes, xeromesophytes, sciophytes, and other ecological groups have developed distinct adaptation mechanisms in response to abiotic and biotic environmental factors (Conc. 12). Studying the anatomical structures of medicinal plants according to their ecological groups enables the assessment of how ecological factors influence their therapeutic components and the variation of their biological activity in relation to ecological plasticity. This study aims to identify the ecological-anatomical traits formed by medicinal plants from different ecological groups in response to their habitats and to determine their underlying adaptation mechanisms.

6.1. Mesophytic medicinal plants

Mesophytes belong to plant groups that occur in moderate and humid environments. The studied plants are characterized by a moderately thick cuticle, regularly arranged stomata (predominantly epistomatic), a dispersed arrangement of vascular elements and parenchyma tissues, and well-developed xylem vessels with large lumens (Fig. 41).

6.2. Xerophytic medicinal plants

Unlike mesophytes, xerophytes belong to plant groups adapted to a certain degree of drought. Xerophytes are characterized by a thick cuticle, sparsely distributed and sunken stomata, sometimes a bicellular-type palisade parenchyma, and well-developed mechanical tissues, all of which function to reduce water loss.

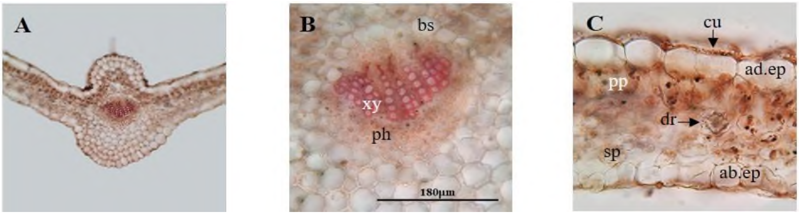


Figure 41. Viola odorata (Shusha city). Leaf transverse structure. A - general structure (10×16); B - central vascular bundle (µm - size), C - lateral part (40×). bs - bundle sheath cells, xy - xylem, ph - phloem, cu - cuticle, ad.ep - adaxial epidermis, ab.ep - abaxial epidermis, pp - palisade parenchyma, sp - spongy parenchyma, dr - druse

6.2.1. *Thymus serpyllum* L.

Leaf. In the leaf, a top-layer sclerenchyma complex is formed in the portion of the collateral-type central conducting system bordered by both phloem and xylem (Fig. 42).

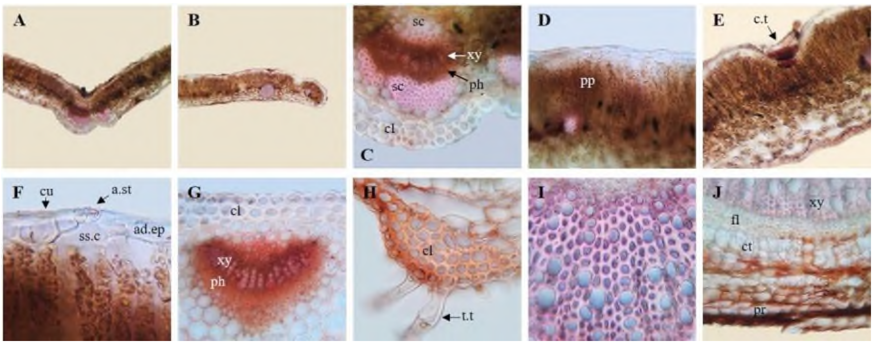


Figure 42. ***Thymus serpyllum*** **(Kalbajar district). Transverse structure of vegetative organs. A, B, C, D, E, F – leaf parts:** xy-xylem, ph-phloem, cl-collenchyma, pp-palisade parenchyma, c.t-capitate trichome, ad.ep-adaxial epidermis, cu-cuticle, a.st-adaxial stoma, ss.c-substomatal cavity.
G – vascular system in the petiole (40×): xy-xylem, ph-phloem, cl-collenchyma
H – collenchyma and trichome in the stem: cl-collenchyma, t.t-tectorial trichome,
I – xylem elements in the stem (40×)
J – part of the root (40×): xy-xylem, ph-phloem, ct-cortex, pr-periderm

Collenchyma is present in the subepidermal regions. In both epidermal layers, the outer periclinal walls are thickened. Capitate trichomes and amphistomatic-type stomata were observed on the leaf surface. In the dorsiventral leaf mesophyll, a conservatively structured bicellular-type palisade parenchyma and partially differentiated spongy parenchyma are present.

6.3. Xeromesophytic medicinal plants

Xeromesophytes are adapted to both dry and moderately humid conditions, exhibiting transitional characteristics between xerophytes and mesophytes.

6.3.1. *Xanthium strumarium* L.

Stem. In the stem, collateral vascular bundles composed of metaxylem and protoxylem were observed, with sclerenchyma grouped in the interfascicular regions and along the phloem boundaries. The exarch phloem is formed by fusiform procambial cells. Callose was detected in the sieve tubes of the phloem, while ergastic substances were present in the medullary and cortical parenchyma (Fig. 43).

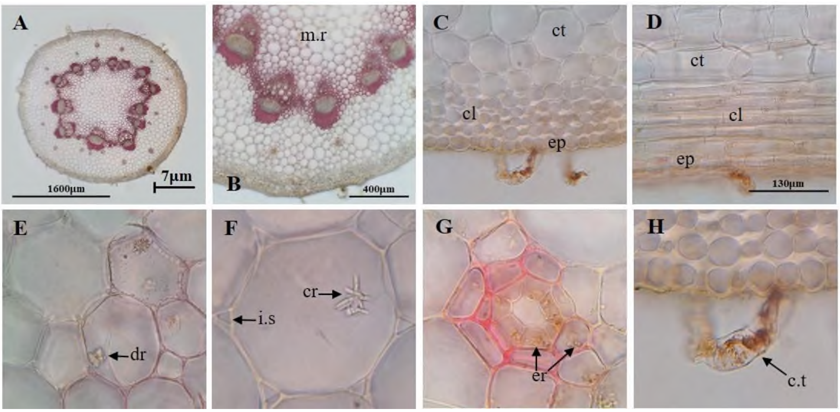


Figure 43. *Xanthium strumarium* (Aghdam district). Transverse and median longitudinal structure of the stem. A - general structure (µm - cylinder) (4×16); B - a part (µm - bundle) (10×); C - peripheral region; D - peripheral region in median longitudinal section (40×); E - medullary parenchyma (60×); F - crystal accumulations in the medullary region; G - schizogenous cavity; H - capitate trichome (100×). m.r - medullary region, ct - cortex, cl - collenchyma, ep - epidermis, c.t - capitate trichome, dr - druse, i.s - intercellular space, cr - crystals, er - ergastic substances.

Schizogenous cavities in the cortical parenchyma were surrounded by double-layered tapetum cells, and lignification was noted in the cell walls of the outer layer. Accumulation of ergastic substances in both tapetum layers and medullary cells was confirmed through anatomical analysis. A collenchyma band was observed subepidermally, and capitate and tectorial-type trichomes were recorded on the epidermis.

6.4. Hygrophytic medicinal plants

Hygrophytes are characterized by a thin cuticle, well-developed aerenchymatous tissue, numerous stomata, and poorly developed mechanical tissues (Fig. 44).

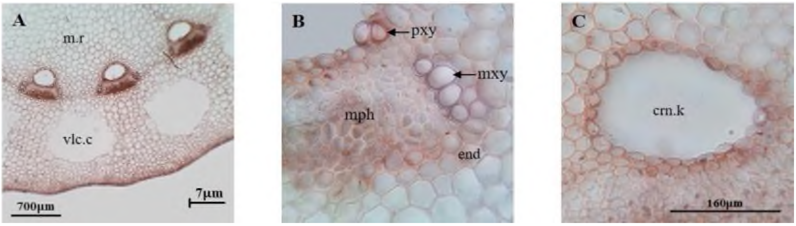


Figure 44. ***Equisetum arvense*** **(Shusha city). Transverse structure of the adult stem.** A - apart (µm - vallecular cavity) (4×16); B - vascular elements; C - carinal canal (µm - dimension) (40×). m.r - medullary region, end - endodermis, crn.k - carinal canal, vlc.c - vallecular cavity, mxy - metaxylem, pxy - protoxylem, mph - metafloem.

6.5. Hydrophytic medicinal plants

Hydrophytes are characterized by actively developed aerenchyma tissue, sparse and functionally passive stomata, partially differentiated epidermal, and other hydric adaptation structures (Fig. 45).

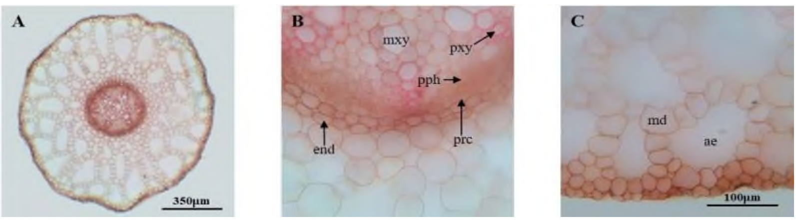
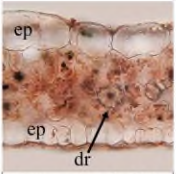


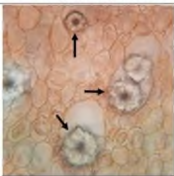
Figure 45. ***Nymphaea alba*****. Transverse structure of the root.** A - general structure (µm - cylinder) (10×16); B - a part of the central cylinder; C - cortex (µm - aerenchyma) (40×). ae - aerenchyma; md - mesodermis; pxy - protoxylem; mxy - metaxylem; pph - protofloem; prc - pericycle; end - endodermis.

CONCEPT 12. CONCEPTUAL PRINCIPLES OF ECOSTRUCTURAL ADAPTATION MECHANISMS IN MEDICINAL PLANTS BELONGING TO VARIOUS ECOLOGICAL GROUPS

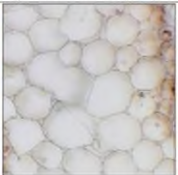
Viola odorata L. (Shusha City) (Mesophyte plant)



Druse crystals (dr) and large epidermal cells (ep) in the leaf mesophyll

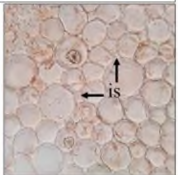


Druse crystals in the rosette



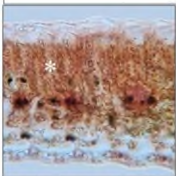
Parenchyma cells in the petiole

Vascular system in the stem, xy – xylem, ph – phloem



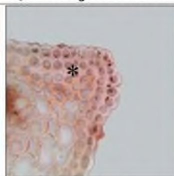
Intercellular spaces (is) in the stem pith parenchyma

Thymus serpyllum L. (Kalbajar District) (Xerophyte plant)

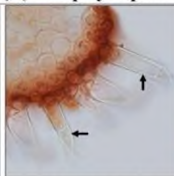


Bicellular palisade parenchyma (*) in the leaf

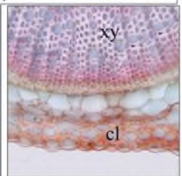
Intensity of sclerification in the leaf (*)



Intensity of sclerification in the petiole (*)

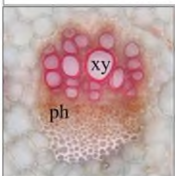


Trichomes on the flower stalk

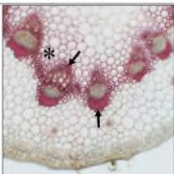


Intensity of sclerification in the stem, xy – xylem, cl – collenchyma

Xanthium strumarium L. (Aghdam District) (Xeromesophyte plant)



Vascular bundle in the petiole, xy – xylem, ph – phloem



Intensity of sclerification in the stem (*)

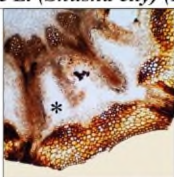
Collenchyma in the median longitudinal section of the stem (*)

Schizogenous cavity in the stem cortex (*)

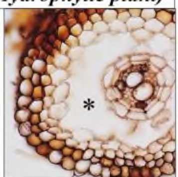
Schizogenous cavity in the root cortex(*)

Equisetum arvense L. (Shusha city) (Hydrophytic plant)

Vellicular cavities in the stem node



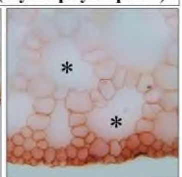
Aerenchyma in the rhizome node (*)



Aerenchyma in the root (*)

Nymphaea alba L. (Hydrophytic plant)

Aerenchyma spaces in the root mesoderm (*)



Aerenchyma spaces in the root mesoderm (*)

CHAPTER VII. ECO-ANATOMİCAL ANALYSİS OF THE STRUCTURAL-CONFİGURATİONAL ADAPTATİONS OF MEDİCİNAL PLANTS WİTH BİOREMEDİATİON POTENTİAL

Bioremediation is a process that utilizes microorganisms, fungi, and plants to eliminate environmental pollutants[43,44]. This method helps restore the natural balance of ecosystems by degrading or neutralizing contaminants in soil and water while exerting minimal impact on the environment due to the use of natural resources. It is particularly effective in the removal of organic pollutants[45]. Phytoremediation, a plant-based form of bioremediation, relies on the principle of plants absorbing and detoxifying contaminants from soil, water, and air (Conc. 13). This approach provides a basis for studying the ecological-anatomical traits of plants, including root, stem, and leaf structures, in response to interactions with pollutants.

7.1. *Salix alba* L.

Stem. The stem stele exhibits a non-bundle structure, composed of thick-walled xylem and exarch-type phloem elements. Vacuolization of ergastic substances was observed in phloem, cambial, and xylem cells. Moving from the phloem toward the cortex, groups of intensely sclerified sclerenchyma were identified, surrounded by prismatic oxalate crystals. Medullary rays formed parenchyma regions in the perimedullary zone rich in anomalous accumulations, where druse crystals were also detected. Epidermal cells were partially collenchymatous, with thickened periclinal walls, and anomalous inclusions were observed in some cells (Fig. 46).

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[44] Gür, N. *Lemna* cinsine ait bazı bitki türlerinin bor (B)'a karşı oluşturdukları morfolojik ve enzimatik tepkilerinin belirlenmesi ve biyoremediasyon potansiyellerinin araştırılması: / Biyoloji Anabilim Dalı Yüksek Lisans Tezi. / - Anadolu, 2016. - 60 s.

[45] Aybar, M., Bilgin, A., Sağlam, B. Fitoremediasyon yöntemi ile topraktaki ağır metallerin giderimi // Doğal Afetler ve Çevre Dergisi, - 2015, 1 (1-2), - s. 59-65.

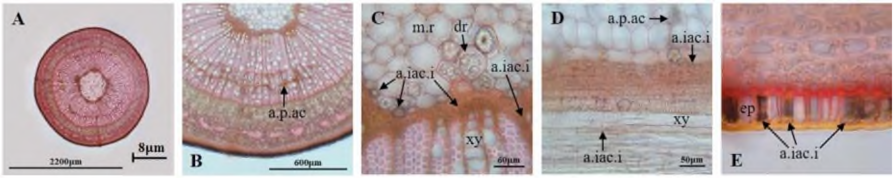


Figure 46. ***Salix alba*** **(Ganja city, Ganjachay area). Transverse and median longitudinal structure of the stem.** A - general structure (4×16), B - a part (µm - xylem) (10×), C - perimedullary zone (µm - parenchyma cell), D - perimedullary zone in median longitudinal section (40×), E - peripheral zone (100×). a.p.ac - anomik parenchymatic accumulation, m.r - medullary region, dr - druse, a.iac.i - anomik intrasellular inclusions, xy - xylem, ep - epidermis

7.2. *Typha latifolia* L.

Leaf. In transverse section, the leaf lamina of *T. latifolia* tapers toward the edges, terminating in acute tips. The central region is thickened due to large air spaces. In the xylem, large modified protoxylem and metaxylem elements were observed, while the phloem contained modified sieve tubes (Fig. 47). Small vascular bundles were present in the peripheral zones, and in the subepidermal layer, sclerenchyma and 2-3 layers of palisade parenchyma were recorded; stomata were observed in the epidermis. The accumulation of pigmented anomalous inclusions in the epidermis, phloem, modified protoxylem, and parenchyma cells represents an anatomical diagnostic adaptation structure, indicating the bioremediation potential of *T. latifolia*.

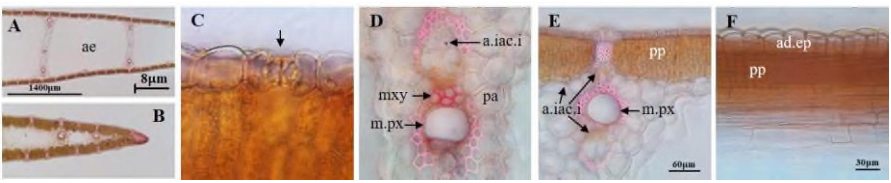


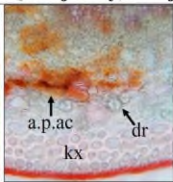
Figure 47. ***Typha latifolia*** **(Ganja city, Ganjachay area). Transverse and lateral longitudinal structure of the leaf.** A - mesophyll (4×16), B - marginal part (10×), C - stoma (indicated by arrow), D - vascular bundle, E - dorsal part (µm - protoxylem) (40×), F - dorsal part in lateral longitudinal section (µm - epidermis cell) (60×). ae - aerenchyma, a.iac.i - anomik intrasellular inclusions, m.px - modified protoxylem, mxy - metaxylem, pa - parenchyma, pp - palisade parenchyma, ad.ep - adaxial epidermis

CONCEPT 13. ECOLOGICAL-ANATOMICAL CONCEPTUAL PRINCIPLES OF TOLERANCE IN MEDICINAL PLANTS WITH BIOREMEDIATION POTENTIAL

Salix alba L. (Ganja city, Ganjachay area)

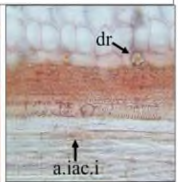
Development of sclerenchyma (sc) and collenchyma (cl) tissues in the leaf mesophyll and accumulated crystal structures (cr)

Palisade parenchyma in the leaf (*)



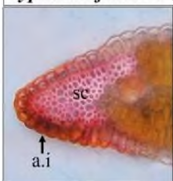
Intensity of collenchyma (cl) in the petiole, accumulated druse crystals (dr), and parenchymatic accumulation (a.p.ac)

Druse crystals (dr) and parenchymatic accumulation (a.iac.i) in the perimedullary region of the stem, pi-pith

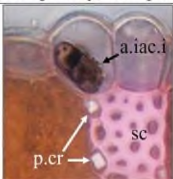


Druse crystals (dr) and parenchymatic accumulation (a.iac.i) in the perimedullary region of the stem in a median longitudinal section, pi-pith

Typha latifolia L. (Ganja city, Ganjachay are)



Sclerenchyma (sc) in the leaf margin and accumulated anomalous inclusions (a.i) in the epidermis



Anomalous intracellular inclusions (a.iac.i) in the leaf epidermis and prismatic crystal structures (p.cr) in the sclerenchyma (sc)

Palisade parenchyma (pp) in the lateral longitudinal section of the leaf

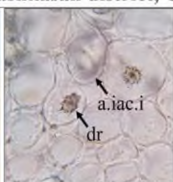
Aerenchyma spaces in the root mesoderm (*)

Protoxylem-derived aerenchyma in the root stele (*)

Portulaca oleracea L. (Dashkasan district, Chovdar Gold Mine area)

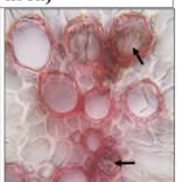

Anomalous inclusion in the sepal

Raphide crystals (rp) and anomalous inclusions (a.i) in the leaf



Druse crystals (dr) and anomalous intracellular inclusions (a.iac.i) in the petiole parenchyma


Raphide crystals (rp) in the stem parenchyma


Accumulated anomalous intracellular inclusions in some xylem elements of the root

7.3. *Portulaca oleracea* L. (Dashkasan District, Chovdar Gold Mine Area)

Petiole. In the petiole of *Portulaca oleracea*, various structurally distinct anomalous intercellular and intracellular inclusions were observed in the epidermis, vascular elements, and parenchyma tissue, along with pigmented druse crystals in the parenchyma cells (Fig. 48). Based on ecological-anatomical investigations and visual observations, these structures have been interpreted as indicators of the plant's bioremediation potential.

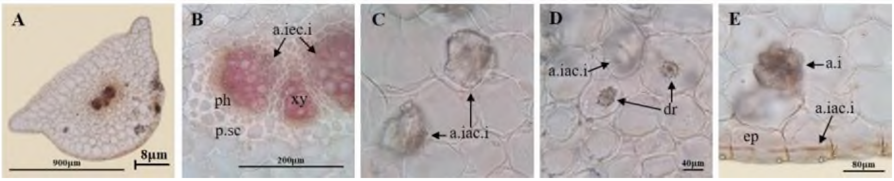


Figure 48. *Portulaca oleracea* (Dashkasan district, Chovdar Gold Mine area). Transverse structure of the stem. A - general view (4×16); B - central vascular system (μm - bundle), C, D - anomalous inclusions in parenchyma (μm - druse), E - anomalous inclusions in epidermis and parenchyma (μm - inclusion) (40×). ph - phloem, p.sc - primary sclerenchyma, xy - xylem, a.iec.i - anomalous intercellular inclusions, a.iac.i - anomalous intrasellular inclusions, a.i - anomalous inclusion, dr - druse, ep - epidermis

CONCLUSIONS

1. The first ex situ and in situ eco-anatomical study conducted in the flora of Azerbaijan demonstrated that structural adaptations of medicinal plants in mountainous ecosystems were more actively differentiated under in situ conditions. In *Fragaria vesca*, the rhizome polyderm consisted of 13-14 layers in situ and 4-5 layers ex situ, while the root polyderm comprised 8-9 layers in situ and 6-7 layers ex situ. Capitate trichomes on the petiole were observed only under in situ conditions. In *Salvia nemorosa*, protoxylem in the root was tetraarch in situ and hexaarch ex situ. Additionally, intensive sclerenchyma formation in the in situ specimens was recorded as an indicator of ecotypic adaptation.

2. In *Vinca herbacea*, under in situ (a) conditions, as compared to ex situ (b) conditions, the structural-functional activity of the cuticle

(a: 2.99 ± 0.51; b: 2.11 ± 0.25) and the lysigenous cavity (a: 38.69 ± 2.35; b: 34.96 ± 2.15) was recorded to be higher. In *Matricaria chamomilla*, under in situ conditions, the central cylinder (a: 1404 ± 209.54; b: 1786 ± 231.48) and periderm (a: 99.78 ± 26.55; b: 84.81 ± 19.69) in the root, as well as the vascular system in the leaf (a: 78.31 ± 16.84; b: 71.56 ± 14.51), were recorded as more intensively developed based on quantitative statistical analysis. Under ex situ conditions, the cortex (a: 96.52 ± 22.39; b: 156.69 ± 28.95) and palisade parenchyma (a: 77.82 ± 15.84; b: 99.78 ± 20.33) showed greater development according to quantitative biometric data. In *Fragaria vesca*, cryptostomatal structure was recorded in the sepal under in situ conditions, while in *Papaver orientale*, this structure was observed in the leaf. In the in situ samples of *Persicaria hydropiper*, *Armoracia rusticana*, and *Vinca herbacea*, intercellular spaces involved in the apoplastic transport process were identified in the stem.

3. In the *Mentha longifolia* in situ (a) sample, parenchymatic accumulations in the stem's perimedullary zone and cells with bordered-pit structures in the medullary region of the rhizome were identified through microscopic analysis. As an adaptive anatomical modification, under ex situ (b) conditions, the exoderm functioned as a temporary protective tissue in the root, whereas in situ, the epiblem's functionality as a defense mechanism was confirmed through micrographic evidence. Hyperplasia of the main parenchyma cells was observed in the vegetative organs of the in situ sample, while hypertrophy was recorded in the ex situ sample (a: 31.51 ± 2.27; b: 37.53 ± 2.46). Conservatism of the vascular tissue and thickening of the xylem vessel walls (a: 3.98 ± 0.48; b: 3.37 ± 0.34), as well as the intensity of tectorial, conical, and capitate trichomes in the leaf, were notably higher in the in situ sample.

4. For the first time, differentiation of the subexodermal complex and mesodermal heteromorphism were recorded in the root of *Convallaria majalis* under ex situ conditions, with anisocytic variations interpreted as an adaptive structural strategy. In in situ (a) samples, the epiblem covered with root hairs was observed, whereas under ex situ (b) conditions, the destruction of the epiblem resulted in

the exoderm functioning as a temporary protective tissue. Local accumulation of photosynthetic products in the leaf subepidermal parenchyma was more intensive under in situ conditions. In the phloem, in situ conditions were characterized by lignification and accumulation of callose and ergastic substances, whereas under ex situ conditions, lumen expansion was observed in the phloem (a: 10.98 ± 1.12; b: 11.48 ± 1.54) and xylem elements (a: 20.14 ± 5.93; b: 23.97 ± 6.29). In both conditions, xylem elements exhibited atypical trihedral-polygonal structures; however, lignification intensity was higher under in situ conditions (a: 1.42 ± 0.14; b: 1.12 ± 0.08).

5. The pseudoizolateral leaf structure of *Tragopogon pratensis*, recorded for the first time in the flora of Azerbaijan, reflects its eco-physiological plasticity and capacity for adaptive anatomical restructuring. Under in situ (a) conditions, the palisade-like cells exhibited active development (a: 45.11 ± 4.64; b: 30.07 ± 3.87), whereas under ex situ (b) conditions, spongy parenchyma was dominant (a: 135.33 ± 21.98; b: 198.49 ± 33.84). Trichomes on the abaxial epidermis of the sepal were observed only under in situ conditions, along with radial endodermal organization in the roots and the presence of sclereids near the periderm. In *Papaver orientale*, the laticifer cells exhibited a more functionally active state under in situ conditions (a: 31.57 ± 4.65; b: 25.89 ± 3.54). In *Persicaria hydropiper*, the localization of ergastic and constitutional substances was more intensive under in situ conditions, and the lysigenous structures showed higher functional activity (a: 31.64 ± 2.08; b: 28.92 ± 2.17).

6. Under in situ (a) conditions, *Quercus iberica* leaves exhibited actively developed bifacial palisade parenchyma (a: 88.93 ± 7.77; b: 46.97 ± 3.31), thick spongy parenchyma (a: 102.46 ± 7.26; b: 34.13 ± 2.18), trichomes (a: 6.07 ± 0.27; b: 3.62 ± 0.13), and sclerenchyma (a: 86.16 ± 4.18; b: 60.31 ± 2.31). In *Armoracia rusticana*, in situ samples were characterized by a structurally functional multilayered periderm (a: 5-6; b: 3-4), the leaf vascular system (a: 374.42 ± 34.98; b: 343.21 ± 26.84), root collenchyma (a: 11.76 ± 0.93; b: 7.56 ± 0.75), and lysigenous cavities in the petiole (a: 20.05 ± 1.64; b: 19.17 ± 1.36). Sclereids in the cortex were recorded exclusively in the in situ samples. Under ex situ (b) conditions, destructuring of supportive

structures and compensatory modifications were observed. In the in situ sample of *Althaea officinalis*, the active development of stellate and bifurcated trichomes in the stem, as well as capitate secretory trichomes in generative and vegetative organs (a: 41.97 ± 3.45; b: 38.94 ± 3.29), was recorded for the first time. In situ, the central vascular bundle of the flower petals was present in two units, compared to one unit in ex situ conditions. Additionally, in situ samples exhibited intensive accumulation of osmophores and other ergastic substances in the stem, leaves, and sepals.

7. For the first time in the flora of Azerbaijan, eco-anatomical research under urbanization conditions has demonstrated that medicinal plants are affected by anthropogenic ecological pressure, resulting in structural deformation and stomatal anomalies. In *Taraxacum officinale*, epidermal hypertrophy and the presence of anomalous inclusions in spongy and palisade parenchyma were confirmed through micrographic evidence. In *Laurus nobilis*, anomalous intracellular inclusions were observed in vascular elements, fundamental tissue cells, epidermis, and mechanical cells, while in *Plantago lanceolata*, anomalous accumulations were detected in the peripheral vascular system, parenchyma cells, and sieve and companion cells of the phloem.

8. For the first time, functional structural adaptations in medicinal plants involved in phytoremediation processes of the local flora (*Typha latifolia, Portulaca oleracea, Salix alba*, etc.) have been identified through microscopic analyses. As a unique finding in the evolution of ecological anatomy, the modified protoxylem in the root of *T. latifolia* was documented for the first time. The intensive development of aerenchyma, responsible for phytofiltration and phytostabilization functions, was micrographically studied for the first time. In the bioremediation-potential species *S. alba*, anomalous intracellular inclusions were recorded in leaf parenchyma, vascular tissues, stem medullary parenchyma, and epidermal cells. Osmoregulatory compounds were identified in the cortex and medullary region of the stem as an adaptive response to ecological pressure.

9. For the first time, an anatomical diagnostic analysis of medicinal plants at the ecological group level has been conducted in the flora of

Azerbaijan. In the xerophyte *Thymus serpyllum*, a thick cuticle and bicellular palisade tissue were observed, while in the xeromesophyte *Xanthium strumarium*, a conservative spongy parenchyma and sclerenchyma in the stem were identified. In hygrophytes and hydrophytes (*Persicaria hydropiper, Mentha longifolia, Equisetum arvense, Nymphaea alba*), aerenchyma structures were noted. In the mesophyte *Viola odorata*, deactivated mechanical structures, dispersive functionality of the vascular system and palisade parenchyma, as well as functionally open and hypostomatic stomata were observed. During the study, various wreath-type anatomical structures were identified, including salsoloid (*Salsola nodulosa*), continuous crown ring (*Tribulus terrestris*), crown-like (*Peganum harmala*), and atriplicoid (*Portulaca oleracea*).

10. At the international scientific level, for the first time, the presence of tectorial trichomes on the leaves of *Laurus nobilis* (Toghanali ecotype) has been confirmed through microscopic studies. As indicators of different ecosystems, distinct adaptive structures were identified in the Toghanali (a) and Ganja (b) ecotypes. In the Toghanali ecotype, a more compact bicate palisade tissue (a: 82.28 ± 2.85; b: 95.08 ± 3.84), active schizogenous cavities (a: 67.34 ± 2.04; b: 47.14 ± 2.85), intensive development of the epidermis and sclerenchyma (a: 146.88 ± 7.65; b: 125.54 ± 7.03), and functional structural activity of the vascular system (a: 684.61 ± 56.89; b: 611.58 ± 49.62) were observed. In the Ganja ecotype, sclerenchyma was weak, while the main parenchyma (a: 71.65 ± 10.29; b: 79.97 ± 12.53) showed active development. In both ecotypes, the xylem vessels in vegetative organs exhibited predominantly atypical polygonal structures, although the Toghanali ecotype showed more intensive lignification (a: 6.54 ± 0.86; b: 4.79 ± 0.71). In *Xanthium spinosum*, subepidermal aerenchyma and schizogenous cavities were observed only in the Toghanali (a) specimen. In the Aghdam specimen (c), the sclerenchyma (a: 5.12 ± 1.01; c: 3.41 ± 0.73) and main parenchyma (a: 74.94 ± 7.18; c: 49.39 ± 6.28) showed reduced structural functional activity, as determined by microscopic analysis.

11. In *Tribulus terrestris* subjected to phytocontamination, a modified dorsoventral and wreath-like leaf structure was identified. As

part of the anatomical adaptations to ecotoxic stress, collenchymatous subepidermal cells in the petiole, lignification-induced transformation of collenchyma into sclerenchyma at the boundaries of the vascular system, raphide and anomalous inclusions in crown cells, and pigmented callose in the phloem were observed. Under phytocontamination conditions, for the first time, the formation of stress-induced idioblasts based on localized detoxification and phytoprotective compensation was recorded in the leaves of *Peganum harmala*. Hypertrophied palisade cells in the abaxial parenchyma, stomatal anomalies, and structural modifications were noted as adaptive changes. Additionally, an isobilateral leaf structure was identified for the first time in the flora of Azerbaijan. The formation of a supernumerary periderm on the root periderm was evaluated as a key anatomical indicator confirming the species' restructuring potential.

12. In the flora of Azerbaijan, the vegetative organs of *Zygophyllum fabago* collected from arid and saline regions exhibited structural and functional activity of the vascular system, bifacial palisade parenchyma, cuticle, and sclerenchyma. Water-storing cells were identified in the medullary region of the stem. In *Salsola nodulosa*, which grows under the same conditions, specific adaptive structures indicative of halophytism and xerophytism were revealed through microscopic analysis, including succulence and radial-anatomical modifications of the leaf. In the central part of the leaf, large-volume succulent parenchyma cells responsible for hydroaccumulation and epidermal salt glands were confirmed by microscopic examination. Osmoprotectants were microscopically identified as adaptive structures in response to ecological stress.

RECOMMENDATİON

- **Scientific-research significance**

1. The database for ecological-anatomical diagnostics should be expanded for the flora of Azerbaijan and applied to other medicinal and endemic plants. Newly recorded anatomical structures in the flora of Azerbaijan - pseudoizolateral and isobilateral leaf mesophyll - should be incorporated into national botanical education standards to support the preservation of the country's botanical heritage. The

obtained results should also be considered in evaluating the resistance of medicinal plants to ecological risks and in determining the quality parameters of raw materials used in phytotherapy. A more in-depth investigation of the Kranz-type anatomical structures, identified for the first time in the flora of Azerbaijan, is warranted to elucidate their relationship with plant photosynthetic activity and ecophysiological adaptation mechanisms.

2. The study revealed, for the first time, the presence of tectorial trichomes in the leaf epidermis of the *Laurus nobilis* Toghanali ecotype. Existing literature generally reports that trichomes are absent in this species. This finding indicates that morpho-anatomical variations at the ecotype level are more diverse and remain insufficiently studied. It is recommended that the comparative investigation of trichome presence across different ecotypes of *Laurus nobilis* be expanded, and the results should be incorporated into systematic and anatomical references for the flora of Azerbaijan. This scientific novelty is also of significant importance for enriching the methodological framework in plant anatomy research, particularly in studies focusing on "epidermal modifications of plants."

3. Under conditions of climate variability, the establishment of ecotype-based ex situ collections and the monitoring of in situ populations are recommended for the conservation of medicinal plants. Additionally, assessing the ecological-anatomical tolerance of medicinal plants under ecological pressing conditions should be prioritized in COP and other international projects.

It is also advisable to deepen autoecological approaches regarding the anatomical response reactions of medicinal plants in extreme ecosystems and to systematize comparative analyses. It is recommended that the application of quantitative statistical approaches be expanded in order to enhance the comprehensiveness of scientific results and improve the accuracy of comparative evaluations in eco-anatomical studies. In the ecosystems of the Lesser Caucasus, structural variations in medicinal plants exposed to phytocontamination and involved in bioremediation processes - particularly the identification of anomalous intercellular and intracellular inclusions through visual-anatomical analyses - should be investigated. Given that these species are medicinal plants, such studies should be integrated into pharmaceutical toxicology research to better understand their adaptive and functional responses.

4. Based on the ecological-anatomical investigation of medicinal plants with naturally occurring populations in the ex situ study area under mountainous in situ and ex situ conditions, it is recommended that flora elements native to a given region be introduced from other areas and subjected to comparative anatomical analyses with their natural populations not only during the initial years but also over a long-term period of five years or more. Such an approach will enable the determination of the stages and duration required for structural compatibility to develop between introduced specimens and natural representatives of the local population.

This strategy is of significant scientific importance for studying mechanisms of ecological-anatomical stabilization and provides a scientific foundation for the sustainable introduction and adaptation strategies of medicinal plant resources in the future. It is further recommended that future research focus on the acclimatization and naturalization processes of medicinal plants studied under ex situ conditions while simultaneously having local natural populations in the same ecosystem. This approach will allow the assessment of the adaptive potential of medicinal plants across different ecological conditions. Comprehensive ecological-anatomical studies of this nature are crucial for establishing a sustainable and effective raw material base, identifying systematic variations, and scientifically supporting the conservation of the gene pool and the direction of adaptive selection in medicinal plant resources.

- **Educational and awareness significance**

5. It is advisable to offer the course “Fundamentals of Ecological Anatomy” at higher and secondary specialized education institutions. This course can serve as a practical foundation for studying the adaptive mechanisms of flora elements. The anatomical results obtained are recommended for use in the preparation of visual atlases, electronic teaching materials, and laboratory methodological guidelines. Comparative studies of in situ and ex situ adaptation capabilities of medicinal plants are particularly suitable as a priority

research direction at the master's and doctoral levels.

The results of these studies can also be utilized as instructional and research materials in plant anatomy, a fundamental branch of botany, as well as in the teaching of pharmacognosy at the master's level. Publication of these findings for educational and scientific-research purposes is therefore considered appropriate.

6. To enhance knowledge of the biodiversity of the Azerbaijani flora, it is recommended that the results obtained from ecological-anatomical studies conducted under conditions of phytocontamination, as well as in arid and saline environments, be incorporated into the teaching materials for undergraduate and master's level students in fields such as autoecology, pharmaceutical toxicology, ecological monitoring, and related disciplines. In medicinal plants with bioremediation potential, anomalous inclusions, modified protoxylem, and aerenchymal structures not only reflect ecological adaptation but also carry microbial functionality, contributing to the optimal stabilization of anaerobic conditions in the rhizosphere. The formation of these structures facilitates the strengthening of plant-microorganism interactions. Therefore, integrating these findings into plant microbiology and soil microbiology curricula with a holistic approach is highly advisable.

- **Practical application significance**

7. Diagnostic features observed in urban environments, such as epidermal hypertrophy, stomatal anomalies, and the accumulation of inclusions, can be applied as biomarkers within ecological monitoring systems. Medicinal plant species with high adaptive potential should be prioritized for use in environmental restoration and phytoremediation processes.

8. The identified anatomical restructuring mechanisms should be considered in selective breeding programs aimed at enhancing the resilience of medicinal plants under climate change conditions. Species that demonstrate successful adaptation in ex situ conditions can be incorporated into botanical garden collections and cultivation programs for pharmacopoeial purposes.

9. Permanent microscopic slides prepared from longitudinal and transverse sections of plants' vegetative and generative organs are

intended to be used as visual teaching materials in the educational and research processes for undergraduate, master's, and doctoral programs, including pharmaceutical sciences. These slides enable students to study anatomical structures based on real microscopic specimens and facilitate comparative ecological-anatomical analyses in scientific research.

The main content of the dissertation and scientific statements are reflected in the following articles and theses:

1. Sərdarova, A.S. Adi çobanyastığı (*Matricaria chamomilla* L.) növünün ex situ və in situ şəraitində eko-anatomik tədqiqi // - Bakı: Botaniki tədqiqatlarda yeni çağırışlar, - 2018. - s. 188-190.
2. Сардарова А.С., Гусейнова А.К. Морфо - анатомическая характеристика растения *Armoracia rusticana* L. // - Moskva: Modern Science, - 2020. Vol. I, No 2, - с. 12-15.
3. Sardarova, A.S. Morpho-anatomical features of the plant of *Armoracia rusticana* L. // - Bishkek: Dialogue of sciences and cultures in the modern World (The XXXIII International Scientific Symposium), - 2022, - p. 246-248.
4. Sardarova, A.S. The eco-anatomical research of the type of ordinary chamomile (*Matricaria chamomilla* L.) in ex and in situ conditions // - Bakı: The XXXII International Scientific Symposium "Turk's Victory: from Chanakkale to Karabakh", - 2022, - p. 437-440.
5. Sərdarova, A.S., Çələbiyev, K.M. Azərbaycanın müxtəlif ekoloji şəraitində yayılmış dərman bitkiliərinin morfoloji və anatomik xüsusiyyətləri // - Mingəçevir: Yeni dövrdə təhsil və tədqiqat fəaliyyəti: reallıqlar və çağırışlar, - 2022. II cild, - s. 567-570.
6. Sərdarova, A.S., Çələbiyev, K.M. Respublikamız ərazisində yayılmış müxtəlif ekoloji qrupdan olan dərman bitkilərinin morfoloji və anatomik xüsusiyyətləri // - Kars, Türkiye: International scientific symposium "Actual problems of science: in the light of national unity and solidarity", - 2022, - p. 60-64.
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