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AN EVALUATION OF THE BIOECOLOGICAL CHARACTERISTICS OF OAK SPECIES WITHIN THE REPUBLIC OF AZERBAIJAN

Mammadova R.
PhD in biology, Associate Professor, Faculty of Biology, Baku State University
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Abstract

This study demonstrates that oak species exhibit species-specific anatomical, morphological, and physiological responses to environmental stress, making them valuable tools in ecological monitoring. The observed increase in stomata density, particularly in *Q. longipes* and *Q. ilex*, reflects an adaptive mechanism to maintain gas exchange under pollution pressure. Morphometric evaluation revealed that fluctuating asymmetry in specific leaf traits can effectively detect early signs of developmental instability. Chlorophyll measurements confirmed the higher photosynthetic capacity of *Q. longipes* under optimal conditions, but also its greater vulnerability to pollution-induced pigment loss compared to *Q. ilex*, which maintained greater chlorophyll stability. The elemental analysis further confirmed the phytoremediative and bioindicator potential of *Q. suber* and *Q. ilex*, although none of the studied species function as hyperaccumulators.

Keywords: *Quercus* L., phyto-indicator, environmental pollution

Introduction. Environmental pollution remains one of the most critical global challenges of the modern era, significantly affecting the balance between human development and nature. As industrial activities expand and urbanization accelerates, natural ecosystems are increasingly overwhelmed, often leading to irreversible damage [3]. Ironically, by disrupting ecological systems, human society ultimately undermines its own well-being. In response to these threats, Azerbaijan has adopted a progressive environmental policy centered on minimizing pollution and promoting sustainable development. A key element of this policy is the continuous assessment and management of environmental quality through systematic monitoring. Within this framework, ecological monitoring plays a crucial role, particularly in identifying early signs of environmental stress and facilitating informed decision-making for the future [6; 15; 16].

While technological methods offer various tools for assessing environmental conditions, biomonitoring stands out as a particularly effective approach. Unlike purely instrumental techniques, biomonitoring evaluates the cumulative effects of multiple environmental factors on living organisms. Since ecosystems are rarely affected by a single stressor, studying how organisms respond to complex interactions provides more accurate and meaningful insights into environmental health [4; 7; 12].

Among biomonitoring methods, the use of plants as bioindicators has proven especially valuable. Plants are stationary and continuously exposed to atmospheric and soil conditions, making them ideal for registering environmental changes. Through physiological and morphological responses, they reflect the presence of pollutants and can serve both as indicators of degradation and as agents of remediation [2; 5; 8; 14].

Phytomonitoring, in particular, meets two key criteria of environmental assessment: reliability and cost-effectiveness. Certain plant species, due to their varying tolerance to pollutants, can be selectively used to monitor air and soil quality. Those that are less tolerant to contamination often exhibit clear and measurable signs of stress, making them sensitive indicators of environmental conditions. Others, with higher resilience, play a dual role - improving environmental quality by absorbing and neutralizing pollutants, acting as natural filters [9; 11].

In this context, studying the biological characteristics of valuable tree species under diverse environmental conditions - especially within Azerbaijan's varied ecological zones - has gained increasing importance. The genus *Quercus* L., known globally for its ecological and economic value, has become a focus of interest due to its declining distribution across both global and national landscapes. Identifying species within this genus that demonstrate resilience to anthropogenic stressors is crucial, not only for conservation but also for their integration into ecological monitoring and greening programs [13; 17].

Our comparative studies have explored the eco-biological traits of several *Quercus* L. species native to Azerbaijan, including *Q. macranthera* (Oriental oak), *Q. castaneifolia* (chestnut-leaved oak), *Q. longipes* (long-stalked oak), *Q. iberica* (Georgian oak), *Q. pubescens* (downy oak), *Q. ilex* (holm oak), and *Q. suber* (cork oak). These investigations aim to evaluate their potential as indicator species and their adaptability to environmental stress. The goal is to identify oak species that not only withstand urban and industrial pollutants but also contribute to environmental remediation and sustainable land management.

Thus, selecting plant species that combine ecological resilience with clear indicator traits is essential for both environmental assessment and landscape planning. Such species contribute not only to monitoring but also to the long-term improvement and stabilization of urban and industrial ecosystems.

Materials and methods. The study involved a comparative morphometric analysis of leaves from seven oak (*Quercus* L.) species: *Quercus macranthera Fish. et C. A. ex Hohen., Quercus. castaneifolia C. A. Mey., Quercus longipes Stev., Quercus iberica Stev.,* *Quercus pubescens Willd., Quercus ilex L., Quercus suber L.* Research was conducted across two types of sites: (1) control areas representing ecologically stable environments and (2) risk zones with higher levels of anthropogenic disturbance [10].

Control sites were located in protected natural ecosystems of Azerbaijan, including State Reserves, National Parks, and Botanical Gardens, where human impact is minimal. In contrast, risk zones included urban areas, roadside environments with intense traffic, and sites near industrial and production facilities.

The research aimed to assess how the stability of individual plant development varies depending on environmental quality, using fluctuating asymmetry (FA) indices as key indicators [19]. In addition, the impact of environmental conditions on the morphological and anatomical structure of leaves, their physiological status, and elemental composition was evaluated. These investigations allowed for the identification of informative parameters suitable for rapid diagnosis of environmental quality based on plant response.

Chloroplast isolation was carried out using the differential centrifugation technique [1]. Chlorophyll was extracted with 96% ethanol, and its concentration was measured spectrophotometrically using a Jenway 7300 device (Jenway, UK) [20].

Stomatal characteristics, including size and density, were assessed from leaf surface micrographs captured at 200× magnification. Measurements were performed within a standardized area of 0.1832 mm² using the Carl Zeiss Axio Imager A2m microscope (Carl Zeiss MicroImaging GmbH, Germany) [20].

The levels of heavy metals in soil and leaf samples were determined using X-ray fluorescence (XRF) spectrometry, a fast and effective technique for multi-element detection. Measurements were conducted using the Rigaku NEX QC+ spectrometer (Applied Rigaku Technologies, Japan) [18].

Results and discussion.

Exposure to urban and industrial pollution induced notable anatomical modifications in the leaves of the studied *Quercus* species. One of the most prominent changes was observed in stomatal density, a key anatomical feature regulating transpiration and gas exchange. Under control (ecologically optimal) conditions, stomatal numbers followed a specific order of increasing density:

Q. iberica < *Q. longipes* < *Q. macranthera* < *Q. suber* < *Q. pubescens* < *Q. castaneifolia* < *Q. ilex*. This gradient implies that *Q. ilex*, even under unpolluted conditions, maintains a high stomatal density, which may reflect its adaptation to arid, open habitats with high light exposure. Conversely, *Q. iberica* shows a more conservative stomatal strategy, likely suited to mesic environments.

However, in ecologically stressed (polluted) environments, the stomatal distribution pattern shifted: *Q. iberica* < *Q. pubescens* < *Q. suber* < *Q. macranthera* < *Q. castaneifolia* < *Q. longipes* < *Q. ilex*. The altered order reflects species-specific plasticity in response to environmental stress. For example, *Q. longipes* increased its stomatal density significantly, suggesting an adaptive strategy to maintain gas exchange under suboptimal conditions. *Q. ilex* remained the species with the highest stomatal density in both conditions, confirming its robust tolerance and ecological adaptability. These changes underscore the importance of anatomical traits in evaluating environmental resilience and indicate that stomatal response may serve as a useful proxy in pollution impact assessments.

In addition to anatomical shifts, morphometric traits - particularly bilateral leaf symmetry - were used as sensitive bioindicators of environmental disturbance. Among five measured morphometric traits, only one showed consistent and measurable fluctuations in response to pollution across all species: the distance from the central main vein to the leaf edge on either side at the broadest part of the lamina.

This parameter's fluctuating asymmetry (FA) was used to calculate the developmental stability of each species. Results indicated that under pollution stress, FA values increased significantly, with higher bilateral variation observed in species growing in environmentally degraded zones. The comparative sensitivity of this parameter allows it to function as a reliable indicator of morphological stress at the organ level.

A ranking of species based on the sensitivity of their FA values led to the following order, from most to least responsive: *Q. iberica* > *Q. castaneifolia* ≥ *Q. longipes* > *Q. ilex* > *Q. suber* > *Q. macranthera* > *Q. pubescens.* Species at the top of this list, such as *Q. iberica* and *Q. castaneifolia*, demonstrated higher morphological sensitivity and are thus more suited for use in early-warning ecological assessments. Meanwhile, species like *Q. pubescens*, which showed minimal FA variation, are likely more stable under moderate stress levels.

In addition to morpho-anatomical l characteristics, chlorophyll content was examined as a physiological marker of environmental stress. Across both the control and polluted sites, the leaves of *Q. longipes* exhibited higher absolute concentrations of chlorophyll a, chlorophyll b, and total chlorophyll compared to those of *Q. ilex*. This suggests that *Q. longipes* possesses a greater photosynthetic capacity under optimal conditions.

However, under pollution stress, a greater decline in total chlorophyll content was recorded in *Q. longipes* than in *Q. ilex*. While both species responded to environmental degradation with reduced pigment levels, the more pronounced decrease in *Q. longipes* suggests that it is more physiologically sensitive to pollution. In contrast, *Q. ilex* maintained relatively stable chlorophyll levels, indicating greater pigment resilience and possibly enhanced tolerance to atmospheric and soil contamination.

These findings further support the classification of *Q. ilex* as an ecologically robust species, suitable for use in urban greening, long-term monitoring, and stress-tolerant landscaping. The chlorophyll-based response adds another layer of diagnostic value to the bioindicator traits of these oak species and underscores the importance of integrating anatomical, morphological, biochemical, and physiological data in ecological monitoring frameworks.

Heavy metal content in the leaf tissues of *Quercus* species was analyzed to determine their capacity for element uptake and accumulation. This "limiting analysis" aimed to identify species with potential for phytoremediation or those that reflect environmental contamination through their elemental profiles.

The findings revealed distinct accumulation patterns. *Q. ilex* leaves contained two heavy metals: Cu and Hg. *Q. suber*, in contrast, accumulated four metals in descending order: Co > Ni > Pb > Sr. Hg was detected in all species except *Q. macranthera* and *Q. suber*

These patterns distinguish *Q. suber* as the most chemically responsive species, particularly in relation to multi-metal uptake. Meanwhile, *Q. ilex* and *Q. castaneifolia* absorbed Hg—a toxic metal often linked to industrial emissions—indicating their environmental sensitivity.

Notably, while several species demonstrated phytoremediative or bioindicator potential, none of the studied oaks exhibited hyperaccumulator characteristics based on standard threshold concentrations. This suggests that while *Q. ilex* and *Q. suber* may be valuable for long-term monitoring and low-intensity remediation, they are not suitable for intensive decontamination applications.

Taken together, these results demonstrate the layered response of *Quercus* species to environmental stress: anatomical (stomatal density), morphological (fluctuating asymmetry), and biochemical (metal accumulation) all of which provide integrative tools for evaluating the health of urban ecosystems.

Conclusion. Integrating all levels of plant response - from anatomical changes to biochemical accumulation—provides a robust framework for assessing ecological health. Among the studied species, *Q. ilex* and *Q. suber* emerged as the most ecologically tolerant and suitable for long-term biomonitoring and urban greening initiatives. These findings support the strategic use of selected *Quercus* species in environmental planning, pollution assessment, and sustainable landscape restoration in regions undergoing anthropogenic stress.

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