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ARTICLE 1

Role of Halophytes in Regulating Ecosystem Stability in Saline Coastal Systems: Insights from the Caspian Coast of Azerbaijan

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ABSTRACT

Saline coastal ecosystems arise from interacting marine and terrestrial processes, in which soil salinization, sea-level fluctuations, and anthropogenic disturbances jointly constrain ecological stability. Halophytes — salt-tolerant vascular plants comprising approximately one percent of global flora — play a significant functional role in these environments, frequently dominating vegetation associations in semi-desert, coastal plain, and saline meadow systems.

This review synthesizes current knowledge of halophyte functional ecology in saline coastal systems, with particular reference to the Caspian coastline of Azerbaijan. The Azerbaijani Caspian coast spans approximately 800 km and encompasses six phytogeographical regions, supporting a documented flora of approximately 1,054 vascular plant species. Halophytes meeting the ≥ 200 mM NaCl life-cycle criterion (Flowers & Colmer, 2008) constitute an estimated 8–9% of this flora.

Based on published global literature and regional floristic surveys, five ecosystem stability functions are described: topsoil ion redistribution, sediment modification, succession facilitation, biodiversity structuring, and carbon storage. The physiological mechanisms associated with these functions — including vacuolar ion compartmentalization, salt gland secretion, osmotic adjustment, and antioxidant defence — are well documented in the global literature but remain unmeasured in Caspian coastal populations.

No original experimental data are presented. All quantitative values are derived from published sources, and their applicability to the non-tidal, petroleum-affected, and irrigation-salinized Caspian system is explicitly discussed. The review provides a structured synthesis of existing knowledge, distinguishing between globally established mechanisms and region-specific observations, and outlines directions for future empirical research.

Keywords: halophytes; ecosystem stability; saline soils; Caspian coast; topsoil ion redistribution; spatial floristic zonation; ion homeostasis; Azerbaijan

1. INTRODUCTION

1.1. Halophytes: definition and ecological significance

Halophytes are vascular plants capable of completing their life cycle at salinity levels ≥ 200 mM NaCl, conditions that are lethal to glycophytes (Flowers & Colmer, 2008). Salt tolerance has evolved independently across multiple angiosperm lineages, with Chenopodiaceae (Amaranthaceae sensu lato), Tamaricaceae, Plumbaginaceae, and Poaceae among the most

prominently represented families. Despite accounting for less than 2% of global vascular plant diversity, halophytes dominate the most physiologically extreme saline environments.

Phragmites australis is excluded from this category. Although it tolerates moderate salinity through avoidance mechanisms, it does not complete its life cycle under ≥ 200 mM NaCl conditions and is therefore classified as a euryhaline glycophyte.

Halophytes are associated with modification

of soil chemical properties through ion accumulation, secretion, and exclusion, and with sediment stabilization via biomass structure. The magnitude and spatial variability of these processes remain insufficiently documented for the Caspian coastal system. The ecosystem engineering framework (Jones et al., 1994) provides an interpretive basis for understanding organism–environment interactions in such systems.

1.2. The Caspian coastal zone: a physically distinct system

The Caspian Sea — the world’s largest enclosed water body — represents a coastal system fundamentally different from tidal salt marsh environments that dominate the halophyte ecology literature. The absence of oceanic tides results in sea-level fluctuations operating

on interannual to decadal timescales, driven by the precipitation–evaporation balance and Volga River discharge. These fluctuations can reach several metres in amplitude.

Inundation regimes are therefore less frequent, longer in duration, and more spatially variable than in tidal systems. Sediment inputs are primarily aeolian and fluvial rather than tidal-current-driven. These differences limit the direct transferability of quantitative estimates (e.g., desalinization rates, sediment accretion, carbon storage) derived from tidal systems.

The Azerbaijani Caspian coast extends approximately 800 km and includes six distinct phytogeographical regions (Table 1).

Table 1. Phytogeographical regions of the Azerbaijani Caspian coast: key ecological parameters

Region	Area (km ²)	Altitude (m)	Precipitation (mm yr ⁻¹)	Dominant soil types	Salinization regime
Samur–Shabran	~1,200	–3 to +120	280–380	Alluvial meadow–forest soils	Primary (partial)
Caspian coastal plain	~850	–28 to +15	200–280	Solonchaks, grey-brown soils	Primary (intense)
Absheron Peninsula	~2,100	–25 to +100	230–320	Grey soils with petroleum influence	Primary, anthropogenic
Gobustan	~1,700	+5 to +200	250–350	Grey-brown soils, solonchaks	Primary (moderate)
Lankaran–Mugan	~3,100	–20 to +60	280–380	Irrigated meadow-brown soils	Secondary (irrigation-induced)
Lankaran lowland	~1,850	–5 to +150	1,200–1,600	Forest-yellow and alluvial soils	Weak, localized

**Approximate area of coastal zone only; indicative figures from regional geographic descriptions — precise GIS-measured values not reproduced here. †Salinization categories follow descriptive field classifications from regional surveys; formal alignment with FAO or USDA salinity classification has not been applied.*

1.3. Objectives

This review has four primary objectives: (1) to characterize the floristic composition of halophyte assemblages along the Azerbaijani Caspian coast; (2) to synthesize established

knowledge of halophyte physiological mechanisms from the global literature; (3) to examine ecosystem-level roles of these species within the regional context; and (4) to identify research priorities for improving the empirical

basis of coastal ecosystem assessment and management.

1.4. Scope and evidential framework

The review distinguishes between mechanisms established in the global literature, patterns documented in regional vegetation studies, and aspects of ecosystem functioning that remain insufficiently investigated under Caspian coastal conditions. In the absence of region-specific experimental data, the study provides a structured synthesis of existing knowledge and outlines directions for future empirical research.

2. MATERIALS AND METHODS

2.1. Study approach and definitions

This study is a conceptual and observational review and presents no original experimental data. The synthesis integrates: (1) long-term floristic and geobotanical survey data from the Azerbaijani Caspian coastal zone, collected using Braun-Blanquet relevé methods across more than 500 plot descriptions and verified against a herbarium collection exceeding 2,000 specimens; (2) international peer-reviewed literature on halophyte ecophysiology and ecosystem processes; and (3) the ecosystem engineering framework.

Operational definitions.

‘Halophyte’: vascular plant completing its life cycle in soils with NaCl concentrations ≥ 200 mM (Flowers & Colmer, 2008). ‘Ecosystem stability’: a composite concept including resistance (maintenance of system properties under disturbance) and resilience (rate of recovery following disturbance) (Donohue et al., 2013). ‘Topsoil ion redistribution’: localized and temporary reduction in surface soil salinity associated with vegetation cover, not permanent salt removal from the system. ‘Functional interpretation’: description of potential ecological roles derived from established ecophysiological knowledge and comparative literature.

2.2. Species classification criteria

Species are classified as halophytes only where published ecophysiological evidence supports completion of the life cycle under ≥ 200 mM NaCl conditions. *Phragmites australis* does not meet this criterion and is treated separately

as a euryhaline glycophyte.

Estimated halophyte proportions are based on this threshold and should be considered approximate, pending comprehensive species-level evaluation using consistent criteria.

2.3. Comparative analytical framework and literature scope

In the absence of region-specific experimental data, this review applies a structured comparative analytical framework. For each ecosystem stability function, four analytical steps are followed:

(1) Mechanism identification — identification of physiological or biophysical processes associated with observed ecological patterns;

(2) Global evidence assessment — evaluation of empirical evidence from other geographic systems;

(3) Contextual comparison — assessment of the compatibility between conditions in studied systems and those of the Caspian coastal environment;

(4) Research needs identification — specification of variables and measurements required for future empirical investigation.

This framework enables systematic comparison between globally documented processes and region-specific environmental conditions. Each function discussed in Section 3.2 follows this analytical structure, allowing transparent evaluation of evidential support.

Global studies are applied to the Caspian context only where physical system characteristics are comparable or where limitations are explicitly acknowledged. All quantitative values are derived from peer-reviewed, DOI-verified sources.

2.4. Application to management context

The review also considers practical implications for coastal ecosystem management. Section 3.6 translates the identified ecosystem functions into preliminary management considerations, structured according to the current level of available evidence. This approach supports the use of existing knowledge while clearly distinguishing areas where additional empirical data are required. Despite this relatively limited numerical representation, halophytes form the dominant vegetation component across saline

habitats, including coastal plains, semi-desert landscapes, and salt-affected meadow systems.

3. RESULTS

3.1. Floristic composition

Regional floristic and geobotanical surveys conducted systematically across the 800 km Azerbaijani Caspian coastline document a remarkably diverse vascular flora comprising 1,054 species distributed across 124 families and organized into 179 distinct vegetation associations. This comprehensive phytosociological baseline

represents one of the most thoroughly characterized coastal floras in the Caspian region, derived from Braun-Blanquet relevé methodology applied across all six phytogeographical zones.

Halophytes—strictly defined according to the internationally accepted criterion of life-cycle completion at salinity levels ≥ 200 mM NaCl (Flowers & Colmer, 2008)—constitute approximately 8–9% of total species richness, corresponding to an estimated 88–100 species.

Figure 1. Family-level composition of halophytes in the Caspian coastal flora

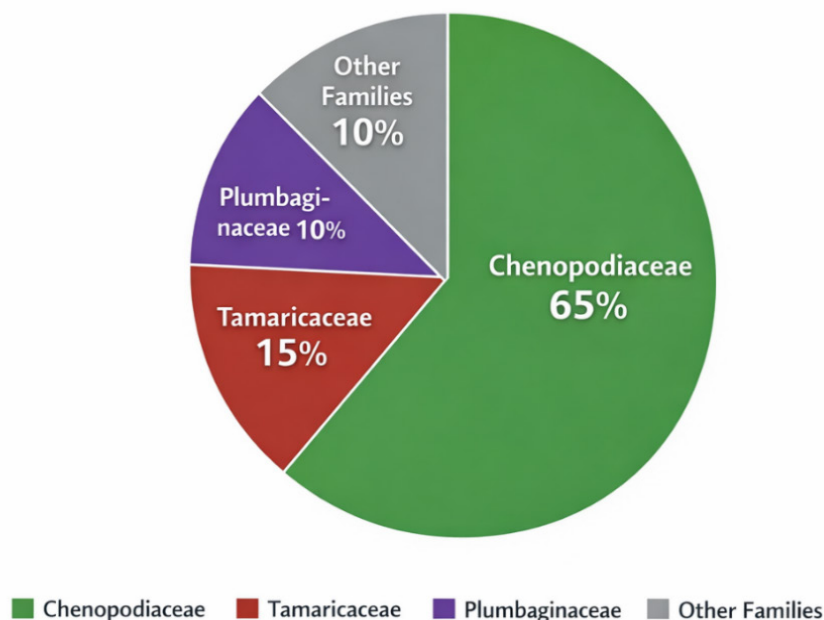


Table 2. Caspian coastal flora summary

Parameter	Total	Halophytes
Vascular plant species	1,054	~88–100 (8–9%)
Families	124	Chenopodiaceae dominant
Vegetation associations	179	Predominantly saline environments
Red Book species	69	5+ halophyte taxa (e.g. <i>Limonium gmelinii</i> CR, <i>Tamarix</i> spp. VU)

Table 3. Representative Caspian halophytes

Species	Family	Salt tolerance mechanism	Ecological context
<i>Halocnemum strobilaceum</i>	Chenopodiaceae	Vacuolar ion compartmentalization	Dominant in highly saline solonchaks
<i>Salicornia europaea</i>	Chenopodiaceae	Extreme ion accumulation	Hypersaline environments
<i>Tamarix ramosissima</i>	Tamaricaceae	Salt gland secretion	Woody coastal vegetation
<i>Suaeda</i> spp.	Chenopodiaceae	Ion accumulation with compatible solutes	Early-stage saline habitats
<i>Limonium gmelinii</i>	Plumbaginaceae	Salt gland secretion	Saline meadow systems

Table 4. Halophyte family-level dominance

Family	% of halophytes	Key genera/species	Primary habitat
Chenopodiaceae	65%	<i>Halocnemum</i> , <i>Salicornia</i> , <i>Suaeda</i>	Hypersaline pioneer zones
Tamaricaceae	15%	<i>Tamarix ramosissima</i>	Woody coastal thickets
Plumbaginaceae	10%	<i>Limonium gmelinii</i>	Saline meadow communities
Poaceae	7%	<i>Puccinellia</i> spp.	Brackish–saline transitions
Other families	3%	<i>Halogeton</i> , <i>Petrosimonia</i>	Specialized habitats

Figure 1. Family-level composition of halophytes in the Azerbaijani Caspian coastal flora. Relative proportions are based on compiled floristic data (Chenopodiaceae 65%, Tamaricaceae 15%, Plumbaginaceae 10%, Poaceae 7%, other families 3%).

3.2. Ecosystem observations

No quantitative measurements of ecosystem processes have been reported for halophyte-dominated communities in the Azerbaijani Caspian coastal zone. Existing regional literature contains no empirical data on soil electrical conductivity under vegetation compared to bare soil, sediment properties, carbon storage, or plant–soil ion exchange processes. Available knowledge is therefore limited to descriptive vegetation patterns associated with environmental gradients.

3.3. Physiological data

No published studies provide quantitative physiological measurements for halophyte populations in the Caspian coastal region. Data are lacking for ion homeostasis, osmotic adjustment, antioxidant enzyme activity, and salt secretion rates under natural environmental conditions.

4. DISCUSSION

4.1. Caspian versus global saline coastal systems

The Caspian coastal system differs fundamentally from tidal salt marsh environments due to the absence of oceanic tidal influence. Sea-level fluctuations occur over interannual to decadal timescales rather than daily tidal cycles, while sediment dynamics derive primarily from aeolian and fluvial processes rather than tidal currents. These physical differences limit the direct transferability of quantitative findings from tidal systems.

Despite their relatively modest numerical representation within the overall flora (8–9%), halophytes form the dominant structural component of vegetation across saline habitats including coastal solonchaks, semi-desert landscapes, and salt-affected meadow systems.

4.2. Data limitations

The principal finding of this review is the

complete absence of region-specific experimental data quantifying halophyte-mediated ecological processes. No measurements exist for soil salinity dynamics, sediment processes, temporal vegetation change, population ecophysiology, or carbon storage. This systematic data deficiency precludes quantitative ecological assessment.

4.3. Research priorities

Future research should prioritize field-based measurements of soil salinity dynamics, sediment processes, plant physiological responses, and long-term vegetation change. Coordinated monitoring across representative coastal regions is required to generate region-specific quantitative data for ecological assessment.

4.4. Management considerations

Floristic data indicate that halophyte communities represent a major structural component of saline coastal vegetation while supporting 69 Red Book species, including several nationally protected halophyte taxa. Management efforts should prioritize protection of existing halophyte vegetation, while restoration initiatives and quantitative desalinization targets remain dependent on the availability of empirical ecological data.

5. CONCLUSION

This review characterizes halophyte assemblages along the Azerbaijani Caspian coast, demonstrating that they constitute approximately 8–9% (approximately 88–100 species) of the 1,054 documented vascular plant species

while forming the dominant vegetation component of saline coastal habitats.

Although the physiological mechanisms underlying salt tolerance are well established in the global literature, no region-specific experimental data are currently available to quantify ecosystem-level processes under Caspian coastal conditions.

This absence of empirical evidence represents a major limitation for ecological assessment and management. The study therefore identifies key directions for future research aimed at developing a quantitative understanding of saline coastal ecosystems in the Caspian region.

5.1. Conclusion

This review characterizes halophyte assemblages along the Azerbaijani Caspian coast, demonstrating that they constitute approximately 8–9% of total plant diversity while dominating saline vegetation systems.

Although physiological mechanisms of salt tolerance are well established in the global literature, no region-specific experimental data are available to quantify ecosystem-level processes under Caspian coastal conditions.

This absence of empirical evidence represents a major limitation for ecological assessment and management. The study therefore identifies key directions for future research aimed at developing a quantitative understanding of saline coastal ecosystems in the Caspian region.

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ARTICLE 2

Ethnomedicinal Significance of Selected Riparian Plant Species: An Assessment of Life Form Diversity and Therapeutic Potential

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ABSTRACT

Riparian ecosystems are ecologically dynamic landscape mosaics that sustain high plant diversity with substantial ethnomedicinal importance. Owing to their constant water availability, fertile alluvial soils, and microhabitat heterogeneity, riparian habitats serve as centers of both ecological and medicinal richness (Riis et al., 2020; Khan et al., 2025). This paper presents a comprehensive synthesis of the reported ethnomedicinal uses of riparian plant species, emphasizing the diversity of life forms and their therapeutic implications. Forty taxa were selected based on the frequency of citation in ethnobotanical-pharmacological literature and their confirmed occurrence in riparian or moisture-influenced zones. Species verification was achieved through The World Flora Online and The International Plant Names Index (Addoun et al., 2021). Among the collected data, herbaceous taxa represented 50%, shrubs 22.5%, trees 20%, and climbers 7.5%. This dominance of herbaceous life forms highlights the ecological flexibility and harvesting convenience typical of moisture-rich environments (Elujoba et al., 2005). Riparian medicinal plants were recorded for a wide range of traditional applications—gastrointestinal, inflammatory, respiratory, metabolic, and microbial disorders—demonstrating their integrated role in local healthcare. The review underscores that these ecosystems act as “natural pharmacies,” combining cultural heritage with biochemical diversity.

Keywords: ethnomedicine; riparian ecosystems; life-form diversity; traditional medicine; medicinal biodiversity; phytochemistry

1. INTRODUCTION

Medicinal plants constitute a cornerstone of human cultural heritage and remain essential to primary healthcare in both rural and urban societies. Their importance is particularly pronounced in developing regions where access to modern pharmaceutical infrastructure is scarce (Elujoba et al., 2005). Over centuries, empirical observation and experimentation have fostered a vast corpus of ethnomedicinal knowledge linking specific plant species to therapeutic functions. This cumulative wisdom continues to inform modern pharmacognosy and medicinal

chemistry, serving as a foundation for the isolation, characterization, and standardization of bioactive compounds (Dar et al., 2023).

Riparian vegetation—located at the transitional interface between terrestrial and aquatic ecosystems—constitutes an ecotone characterized by exceptional productivity and biodiversity (Riis et al., 2020). Dynamic hydrological regimes, periodic flooding, alluvial deposition, and continuous nutrient renewal create fertile substrates that support dense and structurally diverse plant communities (Khan et al., 2025). Within these zones, numerous species hold

long-standing medicinal and cultural significance. Traditionally, riparian plants are used to alleviate gastrointestinal disorders, skin infections, fever, respiratory ailments, and inflammatory conditions, attesting to their central role in indigenous healthcare systems (Tesfaye & Ravichandran, 2018; Khouchlaa et al., 2023).

Phytochemical and pharmacological investigations indicate that riparian species are rich in secondary metabolites such as alkaloids, glycosides, flavonoids, terpenoids, and phenolic acids, which likely underpin their curative efficacy (Baig et al., 2021; Albeshri et al., 2021). Nevertheless, ethnomedicinal documentation for this ecological group remains highly fragmented, often restricted to localized surveys without broader synthesis. This fragmentation underscores the need for a comprehensive assessment that correlates life form diversity with ethnotherapeutic potentials.

Accordingly, the present study was designed to:

- (i) collect and validate published information on the ethnomedicinal uses of riparian plant species;
- (ii) classify recorded taxa according to ecological life forms using morphological growth-form categories; and
- (iii) analyze the distribution and extent of therapeutic applications to identify recurring pharmacological patterns.

2. MATERIALS AND METHODS

This study was carried out through a systematic literature review and meta-synthesis of available ethnobotanical and pharmacological information. Scientific data were retrieved from major academic databases, including Google Scholar, ScienceDirect, and PubMed, covering publications from 2000 to 2025. Search terms included: “riparian medicinal plants,” “ethnomedicinal applications,” “traditional healthcare,” “life-form classification,” and “medicinal flora.”

All plant species were taxonomically verified using The World Flora Online (WFO) and the International Plant Names Index (IPNI) to ensure correct nomenclature and resolve synonyms. Only peer-reviewed articles, ethnobotanical

surveys, and official botanical records were included to guarantee data authenticity (Figure 1).

Species were selected based on their confirmed affinity to riparian or moisture-influenced habitats and well-documented medicinal uses. Data on botanical identity, vernacular names, growth forms, and therapeutic applications were systematically extracted and organized into a structured dataset. For comparative purposes, life forms were classified as herbs, shrubs, trees, and climbers—a morphological growth-form typology widely applied in ethnobotanical surveys. This system groups plants by their general vegetative architecture and is distinct from the Raunkiaer (1934) classification, which categorizes species based on the position of regenerating buds during unfavorable seasons.

The study emphasized the qualitative synthesis of existing information rather than experimental validation. All primary sources are cited in the results and discussion sections (Figure 2; Table 1).

3. RESULTS AND DISCUSSION

The interpretation of ethnomedicinal records collected for the sampled riparian plant species revealed specific trends in the composition of life forms. The predominant growth form recorded among the taxa included herbaceous species (20 species, 50%), which represented the highest percentage of medicinal plants. Shrubs were the second most abundant life form (9 species, 22.5%), with trees (8 species, 20%) and climbers (3 species, 7.5%) being less represented (Figure 2). This distribution of life forms demonstrates how short-lived and persistent herbaceous vegetation are common in riparian habitats, where the abundance of moisture and nutrient enrichment maximize their growth and regeneration. Furthermore, the presence of woody shrubs and trees also indicates the structural complexity of plant communities along river basins, providing a stable source of medicinal biomass throughout different seasons.

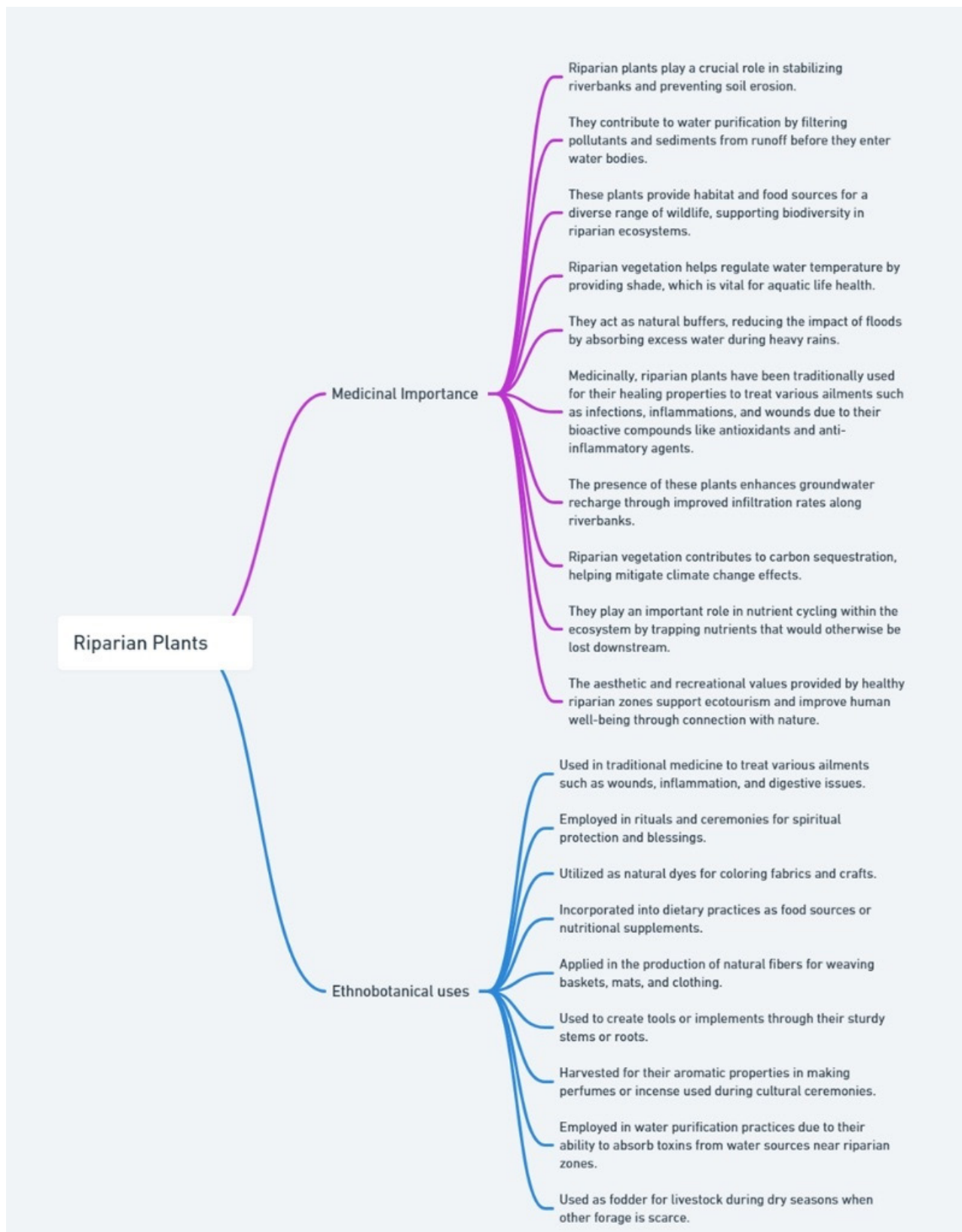


Figure 1. Overview of the ethnomedicinal and ethnobotanical significance of riparian flora. A conceptual mind map summarizing the principal categories of medicinal importance (including anti-inflammatory, antimicrobial, and wound-healing properties) and ethnobotanical uses documented for riparian plant species (Khouchlaa et al., 2023; Pham et al., 2018; Asgarpanah & Ramezanloo, 2012).

Life Form Distribution of Selected Medicinal Plants

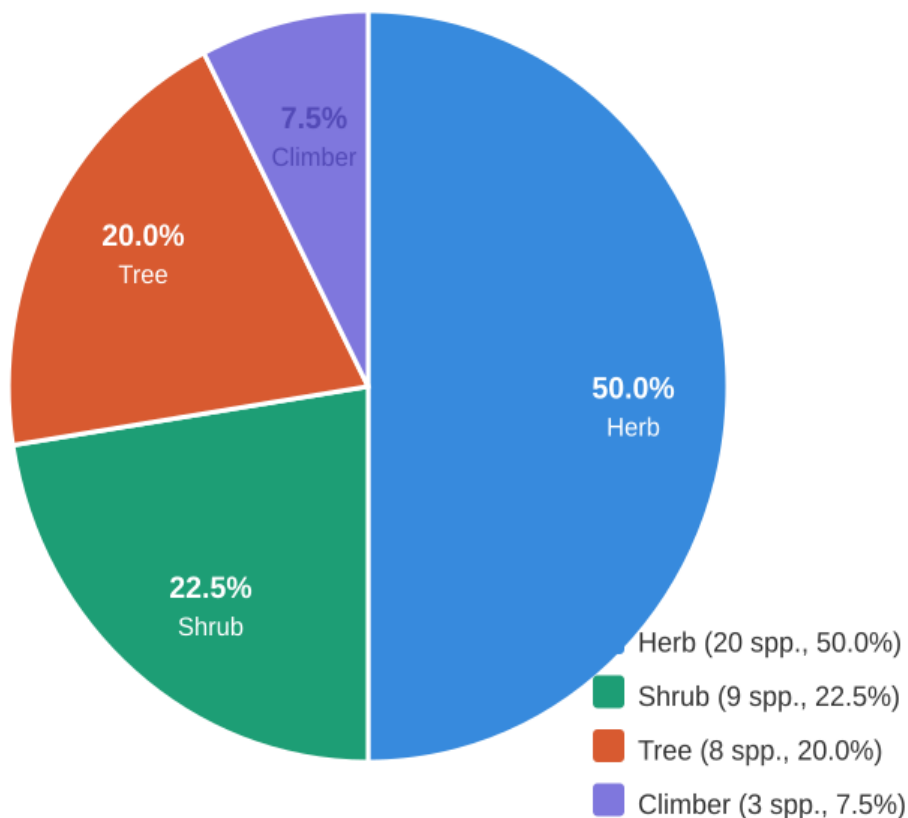


Figure 2. Distribution of life forms among selected species. Pie diagram showing the proportion of herbs (20 species; 50%), shrubs (9; 22.5%), trees (8; 20%), and climbers (3; 7.5%) recorded among the forty riparian taxa, demonstrating the dominance of herbaceous forms (Riis et al., 2020; Baliga, 2012; Rehman & Rao, 2023).

Table 1. Ethnomedicinal uses and life-form classification of selected riparian plant species.

No.	Scientific Name	Common Name	Life Form	Major Medicinal Uses	Citations
1	<i>Abutilon indicum</i> (L.) Sweet	Indian Mallow	Herb	Anti-inflammatory, diuretic, treatment of cough, asthma	(Rajeshwari et al., 2018)
2	<i>Vachellia nilotica</i> (L.) P.J.H. Hurter & Mabb.	Babul, Gum Arabic Tree	Tree	Antimicrobial, astringent, diarrhea, wound healing	(Ali et al., 2012)
3	<i>Alcea rosea</i> L.	Hollyhock	Herb	Demulcent, anti-inflammatory, respiratory ailments	(Azadeh et al., 2023)

No.	Scientific Name	Common Name	Life Form	Major Medicinal Uses	Citations
4	<i>Alstonia scholaris</i> (L.) R.Br.	Devil's Tree	Tree	Antimalarial, antipyretic, respiratory disorders	(Baliga et al., 2012)
5	<i>Althaea officinalis</i> L.	Marshmallow	Herb	Soothing agent, cough, gastrointestinal irritation	(Turgumbayeva et al., 2025)
6	<i>Asclepias curassavica</i> L.	Tropical Milkweed	Herb	Cardiotonic, expectorant, skin diseases	(Al-Snafi et al., 2015)
7	<i>Bombax ceiba</i> L.	Silk Cotton Tree	Tree	Astringent, anti-diarrheal, wound healing	(Taher et al., 2024)
8	<i>Calendula arvensis</i> L.	Field Marigold	Herb	Antiseptic, wound healing, skin inflammation	(Khouchlaa et al., 2023)
9	<i>Calotropis procera</i> (Aiton) Dryand.	Apple of Sodom	Shrub	Analgesic, anti-inflammatory, skin diseases	(Mossa et al., 1991)
10	<i>Caralluma tuberculata</i> N.E.Br.	Bitter Cucumber (Wild)	Herb	Antidiabetic, appetite suppressant	(Baig et al., 2021)
11	<i>Carissa carandas</i> Lour.	Karonda	Shrub	Antioxidant, digestive disorders, anemia	(Tesfaye et al., 2018)
12	<i>Catharanthus roseus</i> (L.) G.Don	Madagascar Periwinkle	Herb	Anticancer, antidiabetic, antihypertensive	(Pham et al., 2018)
13	<i>Centaurium pulchellum</i> (Sw.) Hayek	Lesser Centaury	Herb	Digestive tonic, liver disorders	(Krstić et al., 2003)
14	<i>Chenopodium murale</i> L.	Nettleleaf Goosefoot	Herb	Anthelmintic, digestive stimulant	(Rehman et al., 2023)
15	<i>Cleome viscosa</i> L.	Wild Mustard	Herb	Analgesic, antimicrobial, fever treatment	(Singh et al., 2015)
16	<i>Corchorus olitorius</i> L.	Jute Mallow	Herb	Anti-inflammatory, laxative, nutritional tonic	(Abdel-Razek et al., 2022)
17	<i>Cryptolepis dubia</i> (Burm.f.) M.R.Almeida	Indian Sarsaparilla	Climber	Antipyretic, antimalarial	(Hegde et al., 2023)
18	<i>Datura metel</i> L.	Thorn Apple	Shrub	Analgesic, antispasmodic (toxic—used carefully)	(Chouhan et al., 2024)
19	<i>Ficus religiosa</i> L.	Peepal Tree	Tree	Anti-asthmatic, anti-diabetic, wound healing	(Murugesu et al., 2021)
20	<i>Ficus carica</i> L.	Fig	Tree	Digestive aid, laxative, antioxidant	(Mawa et al., 2013)
21	<i>Fumaria vaillantii</i> Loisel.	Fumitory	Herb	Liver tonic, blood purifier	(Lamba et al., 1977)
22	<i>Grewia asiatica</i> L.	Phalsa	Shrub	Cooling agent, antioxidant, digestive	(Jariwala et al., 2024)

No.	Scientific Name	Common Name	Life Form	Major Medicinal Uses	Citations
23	<i>Hibiscus rosa-sinensis</i> L.	China Rose	Shrub	Hair growth, anti-inflammatory, menstrual disorders	(Missoum et al., 2018)
24	<i>Leptadenia pyrotechnica</i> (Forssk.) Decne.	Khimp	Shrub	Lactagogue, tonic, digestive	(Idrees et al., 2016)
25	<i>Morus alba</i> L.	White Mulberry	Tree	Antidiabetic, antioxidant, lipid-lowering	(Hussain et al., 2017)
26	<i>Nerium oleander</i> L.	Oleander	Shrub	Cardiotonic (toxic—medicinal in controlled doses)	(Hase et al., 2017)
27	<i>Oxystelma esculentum</i> (L.f.) Sm.	Rosy Milkweed Vine	Climber	Anti-ulcer, anti-inflammatory	(Pandya et al., 2011)
28	<i>Peganum harmala</i> L.	Syrian Rue	Herb	Antimicrobial, nervous disorders	(Asgarpanah et al., 2012)
29	<i>Pergularia daemia</i> (Forssk.) Chiov.	Veliparuthi	Climber	Anti-rheumatic, antidiabetic	(Chandak et al., 2019)
30	<i>Plantago ciliata</i> Desf.	Plantain	Herb	Wound healing, digestive disorders	(Addoun et al., 2021)
31	<i>Plumeria rubra</i> L.	Frangipani	Shrub	Anti-inflammatory, skin infections	(Khan et al., 2021)
32	<i>Rhazya stricta</i> Decne.	Harmal Bush	Herb	Anticancer, antihypertensive	(Albeshri et al., 2021)
33	<i>Sida rhombifolia</i> L.	Arrowleaf Sida	Herb	Analgesic, anti-inflammatory	(Mah et al., 2017)
34	<i>Solanum virginianum</i> L.	Yellow-berried Nightshade	Herb	Respiratory disorders, anti-asthmatic	(Saraswathi et al., 2021)
35	<i>Stellaria media</i> (L.) Vill.	Chickweed	Herb	Anti-inflammatory, skin ailments	(Miere et al., 2023)
36	<i>Tabernaemontana divaricata</i> (L.) R.Br.	Crape Jasmine	Shrub	Analgesic, sedative	(Ghosh et al., 2021)
37	<i>Tecomella undulata</i> (Sm.) Seem.	Rohida	Tree	Hepatoprotective, anti-inflammatory	(Vats et al., 2025)
38	<i>Tribulus terrestris</i> L.	Puncture Vine	Herb	Aphrodisiac, diuretic, kidney disorders	(Saeed et al., 2024)
39	<i>Vinca major</i> L.	Greater Periwinkle	Herb	Antihypertensive, wound healing	(Javaid et al., 2021)
40	<i>Woodfordia fruticosa</i> (L.) Kurz	Fire-Flame Bush	Tree	Astringent, antimicrobial, gynecological disorders	(Giri et al., 2023)

The medicinal applications of the selected species showed a high degree of diversity in their uses. A significant proportion of the plants (e.g., *Althaea officinalis*, *Ficus carica*) were found to be integral in the management of gastrointestinal ailments, such as gut upsets, diarrhea, constipation, and liver-related conditions. Riparian medicinal plants were also frequently employed to treat respiratory diseases like cough, asthma, bronchitis, and throat infections, highlighting the importance of these ecosystems in addressing common community health issues. Furthermore, some species were reported to have potent anti-inflammatory, analgesic, and antipyretic effects, implying their widespread use in treating pain, fever, and inflammation in traditional healthcare systems.

Further analysis of the ethnomedicine data revealed that the species in use possessed numerous therapeutic properties beyond single applications. Many plants were believed to have broad-spectrum antimicrobial, antidiabetic, wound-healing, and antioxidant effects, with many being used to treat both internal and external disorders. For instance, species such as *Catharanthus roseus* and *Vachellia nilotica* exhibit multipurpose pharmacological profiles. Some species were also used to treat metabolic conditions, heart ailments, and skin diseases. The prevalence of such multipurpose medicinal plants across various life forms underscores the extensive ethnomedicinal value of riparian vegetation and indicates the long history of traditional knowledge associated with these ecosystems.

From a conservation perspective, the reliance on these plants suggests that riparian

zones act as “natural pharmacies.” However, the fragmented nature of current documentation poses a risk to the preservation of this indigenous heritage. The findings suggest that integrating traditional knowledge associated with these ecosystems into modern conservation strategies is essential for the sustainable utilization of medicinal biodiversity and the potential discovery of new bioactive compounds for pharmaceutical development.

4. Conclusion

The present literature-based analysis highlights the significant ethnomedicinal relevance of riparian vegetation species and their important role in conventional medical practices. The predominance of herbaceous and shrubby taxa can be attributed to their ecological adaptability as well as their extensive utilization by local communities in riparian environments. The wide spectrum of reported therapeutic applications—including digestive and respiratory treatments, along with antimicrobial and anti-inflammatory uses—demonstrates the considerable pharmaceutical potential and diversity of riparian flora. These findings emphasize that riparian ecosystems represent landscapes of profound biological and cultural importance, underscoring the urgent need for their conservation. Protecting these habitats is essential not only for maintaining ecological integrity but also for preserving traditional medicinal knowledge. Future research and sustainable utilization of riparian medicinal plants should integrate phytochemical profiling, pharmacological validation, and conservation assessments to fully explore and safeguard their therapeutic potential.

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ARTICLE 3

Phytosociological Investigation of Aquatic Halophytic Plant Communities of Azerbaijan

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ABSTRACT

This study was carried out to determine the plant associations distributed in the saltwater-swamp vegetation of Azerbaijan, between 2007 and 2018. A total of 95 plant associations belonging to five types were determined according to their habitat and phytosociological characteristics. Of these, pure in-water units constitute 33, coastal swamp associations amount to 24, wet grass associations account for 13, aquatic forest associations number eight, and hydrohalophytes add up to 16 plant associations. As a result of the investigation of the phytosociological characteristics of plant associations found in the halophytic aquatic habitats of Azerbaijan, the following associations have been introduced for the first time as new to region: *Halimione verrucifera-Juncetum littoralisae* ass. nova, *Limonieta meyeri-Juncetum littoralisae* ass. nova, *Junco marittimi-Tamaricetum ramosissimae* ass. nova, *Juncetum acutusae* Musayev & Atamov 2013, *Tamaricetum ramosissimae* Grosheim 2029, *Halocnemetum strobilacei* Oberd 1957, *Carici extenso-Salicornietea europaeae* Tx. in Tx. & Oberd, 1958) Juvre, *Alopocuretum verticosae* Musayev & Atamov 2013, *Franketum hirsutae* Musayev & Atamov 2013, *Juncetum acutusae* Musayev & Atamov 2013, *Juncetum gerardiae* MM & VA 2013., *Juncetum littoralisae* Musayev & Atamov 2013, *Salicotnio europeo-Halocnemetum strobiloceae* Musayev & Atamov 2013, *Spergulario-Halimionetum verruciferae* Musayev & Atamov 2013.

Keywords: halophytic habitat; plant associations; phytosociology; water-swamp vegetation; Azerbaijan;

1. INTRODUCTION

Azerbaijan differs noticeably from many surrounding countries with its temperate zone and plant diversity. The factors revealing the different vegetation types and rich flora of Azerbaijan are geographical location, geological structure, topographic diversity, different soil types, macro- and microclimate events and, most importantly, the Caucasus plant geography. Considering the fact that Azerbaijan is located between the Europe and Asia, two-way plant migrations between the two continents further increase diversity and endemism (Avcı 2005).

As a result of the floristic studies carried out in recent years, the number of taxa (species,

subspecies and varieties) added to the Azerbaijani flora has reached 6000, and the number of endemic species is 460 which accounts for 7.7%. Of these taxa, a total of 449 taxa were included in the latest edition of the Red Book of Azerbaijan (Hebibbeyli, Huseynova, İbadullayeva et al. 2024).

The species diversity of habitats within the rich floristic structure of Azerbaijan is due to the different geographical structures of plants growth, microclimatic changes in the climate structure and various soil types (Avcı 2005).

Water-swamp vegetation has been studied in many regions of the world. In Turkey, some wetlands (Behçet 1994a, b; Seçmen & Leblebiçi

1996), saline wetlands (Aydoğdu & al. 2002; Hamzaoglu & Aksoy 2006; Korkmaz & Mumcu 2014) have been explored. Some phytosociological studies have been carried out too.

In Turkey's wetlands, 23 in-water plant associations have been identified, 31 in coastal meadows, seven in wet meadows, one in wetland forest habitat, and 21 in saline habitat (Seçmen and Leblebici 1996).

Gecheva & al. (2013) investigated the aquatic macrophytes in the streams of Bulgaria and stated in their floristic study that they were composed of hydrophytes, halophytes and amphiphytes in the aquatic ecosystems of the region.

Some of these associations can be found in the water marsh plant communities of the high mountainous regions of Azerbaijan.

The water-swamp vegetation of Azerbaijan was investigated according to the Braun-Blanquet (1964) method and phytosociology of the common plant associations found in the terrestrial halophytic aquatic habitats was determined. Research and syntaxonomic classifications conducted in the present study have shown that the water-swamp vegetation of Azerbaijan totals 95 plant associations, including 12 classes, 16 orders, 26 alliances (Table 1).

Water-swamp plant associations have been found everywhere in Azerbaijan, starting from

the sea level and up to the high-mountain areas (Grossheym 1946, 1948; Gulusashvili & al. 1975; Prilipko 1970; Prilipko & al. 1961; Prilipko, Agacanov, 1972; Hacıyev 1970, 1992; Aliyev & Halilov 1976; Hacıyev & al. 1979, 1990, 1991; Shaksuvarov, 1994;; Sultanov 2000; Ibrahimov 2005; Talibov & Ibrahimov 2008; Mamedov 2011, Gurbanov, Huseynova, 2019).

In the research conducted by Korkmaz & al. (2012) in the Golardi Wildlife Protection Area in the Samsun Province, the authors evaluated syntaxonomically the dune, saline and forest type vegetation.

Atamov (2008) showed that hydrohalophytes were common in the coastal areas of the Caspian Sea. In the water-marsh vegetation, cryptophytes, hemicryptophytes and therophytes dominated in number and were characteristic for that vegetation. These plant types easily adapted to the water-swamp environment and could reproduce promptly in that environment. Some of the aquatic plants with rhizomes and perennial herbaceous stems grew readily in salty lakes and swamps, while others preferred freshwater lakes and swamps. The distinctive and dominant species of these plant types occasionally form pure and occasionally mixed associations.

Table 1. Comparison of water-swamp vegetation in the different regions of Azerbaijan.

Systematic categories and habitats	On the territory of Azerbaijan (Aliyev 1969)	On the territory of Azerbaijan (Aliyev 1969)	Absheron Peninsula (Efendiyeva 1989)	Kur-Araz Plain (Musayev 2010)	According to this study
	Number/%				
Type	1	1	1	1	1
Formation class/Class	2	2	2	2	12
Formation group/Ordo	12	8	9	8	16
Formation subgroup	-	8	2	4	-
Formation	46	33	18	13	26
Association	94	62	37	30	95
Coastal water-swamp	-	-	-	-	24
Wet grass	-	-	-	-	10

Systematic categories and habitats	On the territory of Azerbaijan (Aliyev 1969)	On the territory of Azerbaijan (Aliyev 1969)	Absheron Peninsula (Efendiyeva 1989)	Kur-Araz Plain (Musayev 2010)	According to this study
<i>Water-swamp forest</i>	-	-	-	-	9
<i>Salt lake and marsh</i>	-	-	-	-	17
<i>In water</i>	20	22	11	12	33
<i>In water and on land</i>	31	73	30	20	68

In his study on the water-swamp vegetation of Azerbaijan, Aliyev (1969) found a total of 94 plant associations: 20 in water and 46 both in water and on land. Babayev (1974) identified 51 associations altogether in the water-swamp vegetation of the high-mountainous regions of the Minor Caucasus: 20 in water and 31 both in water and on land.

2. MATERIALS AND METHODS

In the investigation and classification of phytosociological properties of vegetation of aquatic halophytic habitats, classifications based on the dominance principle were used by Katanskaya (1956, 1981) and Aliyev (1966, 1967, 1969, 1971). In this research, for the first time, phytosociological properties of plant associations found in halophytic aquatic-marsh habitats were investigated within the borders of Azerbaijan based on the Braun-Blanquet (1964) method. In the classification of aquatic plant communities in the world (Rivaz-Martinez et al. (2001; Mucina et al. 2016), primary sources were also used

to reveal the diversity of aquatic vegetation in Azerbaijan. Between 2007 and 2018, studies were conducted in lakes and marshes located in the plains of Azerbaijan, on the seashore, especially in the Lenkeran Plain (Great and Small Kizilagach Bay), Samur Devechi Plain (Devechi Port), Candar Lake and Batabat Lake of Nakhchivan, Araz Valley, Kur Araz Plain (Hajigabul, Sarisu) and Absheron Peninsula (Masazir salt lake, Lokbatan and Kanligol). Plant samples were collected at different vegetation periods. The identification of the samples was based on the Flora of Azerbaijan (Karyagin, 1950-1961). Samples were collected from the Institute of Botany of the National Academy of Sciences of Azerbaijan Presented to the herbarium, Baku. Life forms of plants were given according to Raunkier (1934) and vegetation tables were compiled according to the principle of “minimum area” according to Braun-Blanquet (1964). Syntaxonomic nomenclature of units followed Weber et al. (2000).

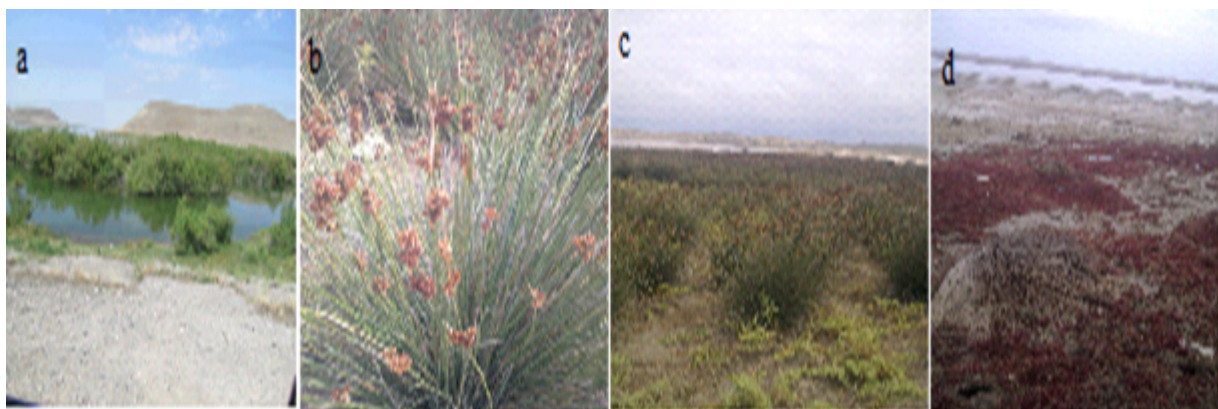


Figure 1. Some taxa distributed in halophytic aquatic habitats: a) *Tamarix ramosissima*, b) *Juncus maritimum*, c) *Juncus litoralis*, d) *Salicornia europaea*

3. RESULTS AND DISCUSSION

As a result of the present research, the water-swamp vegetation of Azerbaijan has been investigated according to the Braun-Blanquet (1964) method and the syntaxonomic evaluation results are given below.

In this study, the vegetation of the marsh ecosystems of Azerbaijan is investigated for the first time according to the Braun-Blanquet method, and the plant associations are identified and classified as follows:

Hydrohalophyte plant associations

These are associations formed by halophyte plants growing in swamps near salt lakes or the sea coast (Fig. 1).

1. *Halocnemetum strobilacei* Oberd. 1957

Halimione portulacoides and Hordeum

marinum var. marinum, along with the distinctive taxa, were found on the plains near Lokbatan and in places close to the sea. *Limonium angustifolium* was identified in the flora and phytocenological structure of the association (Table 2).

Fig. 2a illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. The observations showed that in the phytocenological structure of that association, with the participations of therophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered in the sample areas, which is due to the chemical composition of the soil and water environment in which the association spreads.

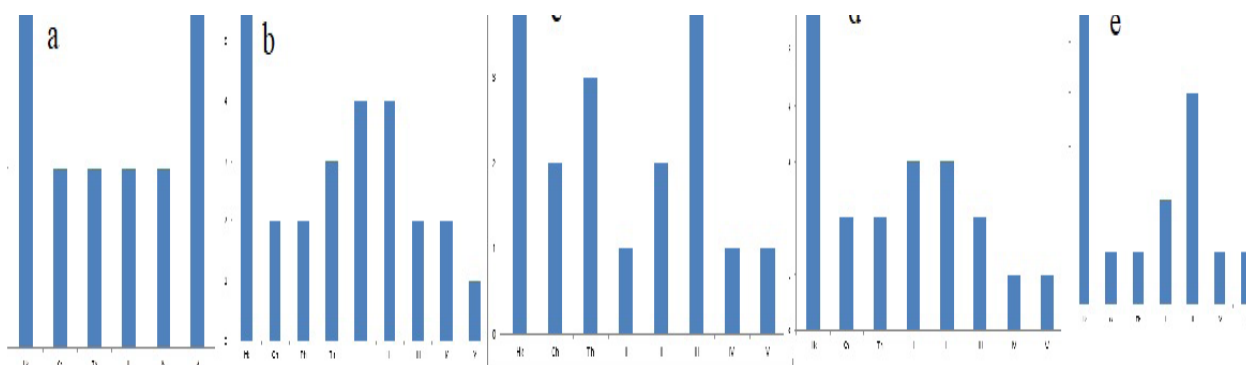


Figure 2. Ranking of the taxa participating in the glandular plant associations in the halophytic aquatic habitats according to life forms and occurrence: a, *Halocnemetum strobilacei*; b, *Junco-Tamarici ramassissimae*; c, *Spergulario-Halimionetum verruciferae*; d, *Halimione verrucifera-Juncetum littoralis*; e, *Limonio meyeri-Juncetum littoralis*.

Table 2. Phytocenological characteristics of the plant associations* in the halophytic aquatic habitats of Azerbaijan.

Sample area No	762	763	764	765	766	767	768	769	770	771	Life form	Random income
Area size (m²)	16	16	16	16	16	25	25	25	16	16		
Altitude (m)	45	45	45	60	70	70	60	60	120	130		
Inclination (%)	1	2	2	2	3	3	2	1	1	2		
Weed height (cm)	15	20	15	20	15	10	10	12	12	15		
Soil type	Ş*	Ş*	Ş*	Ş*	Ş*	Ş*	Ş*	Ş*	Ş*	Ş*		
Number of species	3	3	4	3	3	4	3	4	3	3		
Vegetation cover %	30	40	50	40	40	40	45	45	30	40		
Characteristic taxa of the association:												
<i>Halocnemum strobilaceum</i>	33	33	23	22	33	33	34	32	33	22	Ch	V
Sample area No	772	773	774	775	776	777	778	779	780	781		
<i>Tamarix parviflora</i>	22	11	+1	11	11	22	33	23	33	11	Ph	V

<i>Tamarix ramosissima</i>	+1	-	11	-	-	-	-	-	-	+1	Ph	II
<i>Juncus littoralis</i>	11	22	+1	11	+1	11	+1	+1	-	-	Ch	IV
Sample area No	782	783	784	785	786	787	788	789	790	791		
<i>Limonium meyeri</i>	-	-	-	+1	-	+1	+1	+1	+1	-	Hk	III
<i>Petrosimonia brachiata</i>	+	+	11	-	-	+1	+1	+1	-	+1	Th	IV
Sample area No	792	793	794	795	796	797	798	799	800	801		
<i>Halimione verrucifera</i>	33	22	11	23	23	32	34	33	23	22	Hk	V
<i>Spergularia marina</i>	+1	11	+	-	-	+1	-	-	-	+1	Hk	III
Sample area No	802	803	804	805	806	807	808	809	810	811		
<i>Juncus littoralis</i>	33	34	44	33	32	11	23	+1	33	22	Ch	V
<i>Halimione verrucifera</i>	11	+1	11	+1	+	22	+1	-	+1	-	Hk	IV
Sample area No	812	813	814	815	816	817	818	819	820	821		
<i>Juncus littoralis</i>	33	11	+1	-	33	23	33	34	22	+1	Ch	V
<i>Limonium gmelinii</i>	11	11	22	33	+1	-	-	+1	+1	22	Hk	IV
Sample area No	822	823	824	825	826	827	828	829	830	831		
<i>Tamarix ramosissima</i>	33	22	34	44	33	22	33	34	32	33	Ph	V
<i>Aeluropus littoralis</i>	11	+1	+	-	+1	11	+1	+1	-	+1	Ch	IV
Sample area No	832	833	834	835	836	837	838	839	840	841		
<i>Carex extensa</i>	22	33	+1	-	22	33	44	22	11	+1	Hk	V
<i>Salicornia europaea</i>	-	+1	11	22	+1	-	+	+1	12	22	Th	IV
Sample area No	842	843	844	845	846	847	848	849	850	851		
<i>Juncus maritimus</i>	33	34	23	33	34	34	22	11	23	33	Ch	V
<i>Atropis gigantea</i>	+1	+1	+1	+1	+1	-	-	-	+1	-	Hk	III
Sample area No	852	853	854	855	856	857	858	859	860	861		
<i>Phragmites australis</i>	44	34	33	33	44	34	33	33	22	33	Hk	V
<i>Juncus maritimus</i>	+1	+1	+1	+	-	+1	+1	+	11	11	Ch	V
Sample area No	862	863	864	865	866	867	868	869	870	871		
<i>Carex extensa</i>	+1	+1	11	33	33	22	11	23	22	+1	Hk	IV
<i>Halocnemum strobilaceum</i>	11	22	11	+1	+1	+1	+1	-	-	22	Ch	III
Sample area No	872	873	874	875	876	877	878	879	880	881		
<i>Alopecurus ventricosus</i>	33	44	34	33	34	23	+1	+1	34	44	Hk	V
<i>Asrostis distans</i>	+1	+1	-	+1	11	+1	+1	11	-	-	Hk	IV
Sample area No	882	883	884	885	886	887	888	889	890	891		
<i>Juncus littoralis</i>	33	+1	11	23	22	33	11	+1	+1	44	Ch	V
<i>Aeluropus littoralis</i>	+1	22	11	-	+1	-	11	11	11	+1	Hk	IV
Sample area No	892	893	894	895	896	897	898	899	900	901		
<i>Juncus acutus</i>	22	23	+1	11	23	11	34	22	23	33	Ch	V

<i>Phragmites communis</i>	+1	-	11	11	-	+1	-	+1	+1	-	Hk	III
Sample area No	902	903	904	905	906	907	908	909	910	911		
<i>Juncus gerardi</i>	11	+1	+1	33	33	22	22	34	11	23	Ch	V
<i>Juncus acutus</i>	11	22	23	-	-	11	-	-	+1	+1	Ch	III
Sample area No	912	913	914	915	916	917	918	919	920	921		
<i>Frankenia hirsuta</i>	33	33	33	32	33	33	+1	12	11	22	Hk	V
<i>Salsola crassa</i>	+	+	+1	-	+1	+	+	+	-	+	Th	IV
<i>Salicornia europaea</i>	-	+	-	+	-	-	-	+	+	+	Th	III
<i>Hordeum hytrix</i>	+	-	-	-	+	-	+	+	-	-	Th	II
Accompanying taxa												
<i>Halimione portulacoides</i>	11	11	+	22	+	11	11	+1	+	11	Hk	V
<i>Hordeum hytrix</i>	11	+1	22	-	11	11	+1	+	-	-	Th	IV
<i>Limonium angusifolium</i>	-	-	+1	+	-	+	-	+1	+	+	Hk	III
<i>Crypsis aculeata</i>				+					+		Th	I
<i>Lycium ruthenicum</i>	-	-	+	-	-	-	+	-	-	-	Ch	I
<i>Salsola soda</i>	-	-	-	-	-	+	-	-	+1	+	Th	I
<i>Oenanthe fistulosa</i>	-	-	-	+1	-	-	+1	-	-	+1	Hk	II
<i>Inula viscosa</i>	-	+1	+1	-	-	-	-	-	-	-	Hk	I
<i>Polypogon monspeliensis</i>	-	-	-	+	+1	-	11	-	+1	+	Hk	III
<i>Artemisia santonicum</i>	+1	-	+1	-	-	-	-	+1	-	-	Hk	II

*Phytocenological characteristics of the *Halocnemum strobilacei* Oberd 1957, *Spergulario-Halimionetum verruciferae* Musayev & Atamov 2013, *Juncus maritimi-Tamaricetum ramosissimae* Musayev & Atamov 2013, *Halimione verrucifera-Juncetum littoralisae* MM & VA 2024, *Limonium meyeri-Juncetum littoralisae* MM & VA 2024, *Tamaricetum ramosissimae* Grossheim 1929, *Carici extenso-Salicornietea europaeae* (Tx. in Tx. & Oberd. 1958) Julve 1993, *Juncetum maritimum* (Rubel 1930) Pignatti 1953, *Phragmito-Juncetum maritimi* Korzh. et Kljukin 1990, *Carici extenso-Halocnemum strobilacei* Vural, Duman & al. 1994, *Alopecuretum ventricosa* Musayev & Atamov 2013, *Juncetum littoralisae* Musayev & Atamov 2013, *Juncetum acutusae* Musayev & Atamov 2013, *Juncetum gerardiae* Musayev & Atamov 2013, *Salicornio europeo-Halocnemum strobilacei* Musayev & Atamov 2013, *Franketum hirsutae* Musayev & Atamov 2013 associations.

2. *Juncus maritimi-Tamaricetum ramosissimae* Musayev & Atamov 2024 ass.nova.

In the Shirvan Plain, Kur-Araz Plain and around the salty lakes in the Samur-Davachi Plain, the vegetation cover amounted to 40-90% and the vegetation cover varied between 20-150 cm. The accompanying species were: *Tamarix ramosissima*, *Juncus littoralis*, *Limonium meyeri*, *Petrosimonia brachiata*, *Aster tripolium*, *Hordeum hystris*, *Polypogon monspeliensis*, *Imperata cylindrica*, *Halocnemum strobilaceum*,

Halimione portulacoides, *Juncus maritimus*, and *Elymus elongatus* (Table 2).

Fig. 2b illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participations of phanerophytes, xamophytes, therophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered in the sample areas, which is due to the

chemical composition of the soil and water environment in which the association spreads.

3. *Spergulario-Halimionetum verruciferae* Musayev & Atamov 2013

In the moist, fertile forests and swamps of the Khazar Plain, Absheron Peninsula, Qobustan, Kur-Araz Plain, Bozdag, and Nakchivan, the vegetation cover of that association was 60-70%, while the varied between 5-30 cm. The accompanying species were: *Halimione verrucifera*, *Spergularia marina*, *Halocnemum strobilaceum*, *Aeluropus littoralis*, *Salicornia europaea*, *Juncus maritimus*, *Limonium gmelini*, *Hordeum hystrix*, and *Crypsis aculeata* (Table 2).

Fig. 2c illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participations of trophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is due to the chemical composition of the soil and water environment in which the association spreads.

4. *Halimione verrucifera-Juncetum littoralisae* Musayev & Atamov 2024 ass.nova

In the Absheron Peninsula and around Lake Masazır, in the swampy areas around Lake Hacıqabul and Acınohur, the vegetation cover was 60-90% and the varied between 60-100 cm. The following species participated in that association: *Juncus littoralis*, *Halimione verrucifera*, *Limonium suffruticosum*, *L. caspium*, *L. meyeri*, *Petrosimonia brachiata*, *Aeluropus littoralis*, *Frankenia hirsuta*, *Lycium ruthenicum*, *Salsola soda* (Table 2).

Fig. 2d illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of thero-phytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is due to the chemical composition of the soil and water environment in which the association spreads.

5. *Limonio meyeri-Juncetum littoralisae* Musayev & Atamov 2024 ass.nova

In the Absheron Peninsula, Kur-Araz, Hazar and Samur-Devachi plains, lakeside salt marsh areas, the degree of plant cover varies between 60-90% and plant height varies between 80-100 cm. The flora of the union includes: *Limonium meyeri*, *Limonium gmelinii*, *Atriplex hastata*, *Aeluropus littoralis*, *Juncus littoralis*, *Oenanthe fustulosa*, *Inula viscosa*, *Petrosimonia brachiata* etc. taxa (Table 2).

Fig. 2e illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of thero-phytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is due to the chemical composition of the soil and water environment in which the association spreads.

6. *Tamaricetum ramosissimae* Grossheim 1929

That association occurred in Samur- Davaci, Khazar Plain, Absheron Pninsula, Bozdağ Range, Kür-Araz Plain, Alazan- Ayriçay, Minor Caucasus, and Lankaran Plain, on humid and inundated coasts and around irrigation channels. The vegetation cover in the coastal sands was 40- 100%, the projection cover 100-200 (350) cm, and the most common taxa were: *Tamarix ramosissima*, *Aeluropus littoralis*, *Polypogon monspeliensis*, *Atropis gigantea* (Table 2, Fig. 3a).

Fig. 3a illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of phanerophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sampe areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

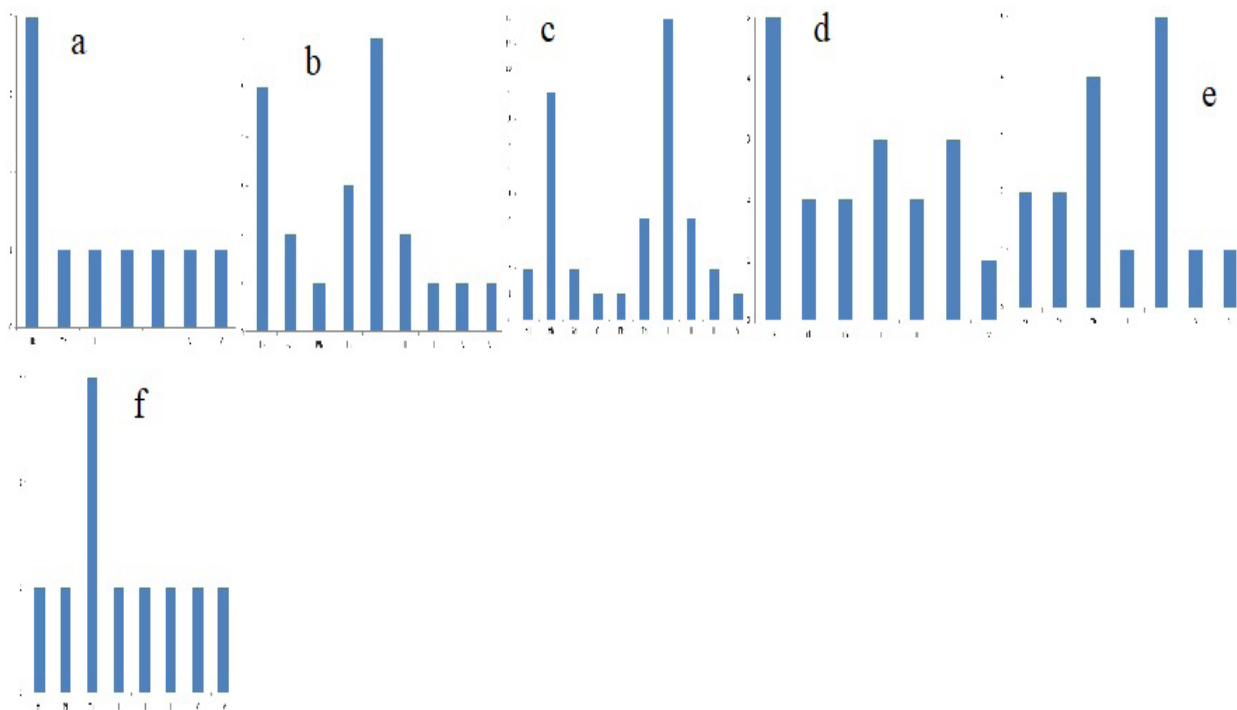


Figure 3. Ranking of the taxa participating in the glandular plant associations in the halophytic aquatic habitats according to life forms and occurrence: a, *Tamaricetum ramosissimae*; b, *Carici extenso-Salicornietum europae*; c, *Juncetum maritimum*; d, *Phragmito-Juncetum maritimi*; e, *Carici extenso-Halocnemum strobilacei*.

7. *Carici extenso-Salicornietum europaea* (Tx. in Tx. & Oberd. 1958) Julve 1993

That association was found in the Absheron Peninsula, Qobustan, around Hacıkabul Lake, Kur-Araz Plain, and Acinohur Lake's salt marshes. It consisted of the following taxa: *Atropis gigantea*, *A. bulbosa*, *Hordeum hystris*, *Suaeda altissima*, *Suaeda prostrata*, *Artemisia santonicum*, *Frankenia hirsuta*, *Halocnemum strobilaceum* (Table 2).

Fig. 3b illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participations of therophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

8. *Juncetum maritimi* (Rubel 1930) Pignatti 1953

It has been observed that it spreads in swampy areas on the shores of halophytic lakes, the vegetation cover is between 70-80%, the

plant height is between 100-120 cm and the number of taxa varies between 2 and 9. It has been determined that *Juncus maritimus*, *Atropis gigantea*, *Carex divisa*, *Limonium meyeri*, *Aeluropus littoralis*, *Elymus repens*, *Paspalum paspaloides*, *Typha domingensis*, *Schoenoplectus lacustris* and other taxa participate in its flora (Table 2, Fig. 3b).

Fig. 3c illustrates the life forms of this union that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of hydrophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

9. *Phragmito-Juncetum maritimae* Korzh. et Kljukin 1990

That association was widespread along the coast of the Caspian Sea of Birli, especially in the coastal swamps close to Shirvan, Masali and Lankaran districts. Vegetation cover was 100%. Along with *Phragmites australis* and *Juncus*

maritimus which dominated in the association, such taxa as *Carex extensa*, *Halimione verrucifera*, *Juncus littoralis* also participated in the phytocenological structure of the association (Table 2).

Fig. 3d illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of chamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

10. *Carici extenso-Halocnemum strobilacei* Vural, Duman & al. 1994

That association was found on the edges of salt lakes. The vegetation cover varied between 50-80% and the projection cover between 10-60 cm. the association included such taxa as *Halocnemum strobilaceum*, *Carex extensa*, *Halimione verrucifera*, *Limonium meyeri*, *Juncus maritimus*, *Aster tripolium*, *Phragmites australis*, and

Tamarix ramosissima (Table 2).

Fig. 3e illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes, phanerophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

11. *Alopecuretum ventricosae* Musayev & Atamov 2013

The vegetation cover of that association was 60-90%, the vegetation cover was 60-80 cm, and the number of taxa encountered within the association varied between 2-5. That association spread in the Khazar Plain, Absheron Peninsula, Kür-Araz Plain, Qobustan, Bozdağ, Kür-Araz and Naxçıvan plains. It grew in moist and salty areas. Its composition included the following taxa: *Agrostis distans*, *Hordeum hystris*, *Eleocharis uniglumis*, *Bolboschoenus maritimus* (Table 2).

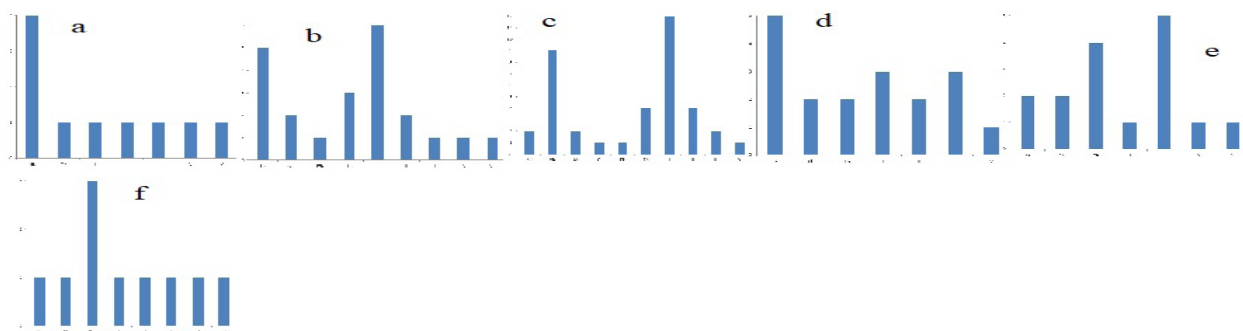


Figure 4. Ranking of the taxa participating in the glandular plant associations in the halophytic aquatic habitats according to life forms and occurrence: a, *Alopecuretum ventricosae*; b, *Juncetum littoralisae*; c, *Juncetum acutusaee*; d, *Juncetum gerardiae*; e, *Salicornia europaeo-Halocnemum strobilacei*; f, *Franketum hirsutae*.

Fig. 4a illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

12. *Juncetum littoralisae* Musayev & Atamov 2013

That association was mostly found in the substantial salty sands along the Khazar coast, seldom on the Bozqir Plateau and the Kur-Araz Plain. Its vegetation cover varied between 50-80% and the projection cover was between 60-100 cm. Along with the dominant species, the most common taxa were: *Aeluropus littoralis*, *Hordeum hystris*, *Cyperus longus*, *Cirsium italicum*, *Spergularia media*, *Atropis gigantea*,

Artemisia santonicum, *Tamarix ramosissima*, *Bolboschoenus maritimus* var. *maritimus*, *Atriplex hastata* (Table 2).

Fig. 4.b illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes, phanerophytes, xamophytes, and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

13. *Juncetum acutusae* Musayev & Atamov 2013

In the Samur-Deveçi, Abşeron Peninsula, Kur-Araz and Lankaran plains, and especially along the Khazar coast, in humid flat sandy areas and water places 0-10 (20) cm deep, the vegetation cover of that association reached 40- 70(90) %, and its projection cover 100-120. *Phragmites communis*, *Tamarix ramosissima*, *Schoenoplectus lacustris*, *Iris pseudacorus*, *Veronica anagallis-aquatica*, *Sparganium erectum*, *Juncus gerardi*, *Triglochin palustre*, *Zannichellia palustris*, *Plantago maritima*, *Salicornia europaea*, *Carex distans*, *Eragrostis collina*, *Falcaria falcarioides*, *Ruppia maritima*, *Frankenia hirsuta*, *Suaeda altissima*, and *Scirpoides holoschoenus* were the participating taxa in that association (Table 2, Fig. 4b).

Fig. 4c illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes, xamophytes, hydrophytes, geophytes, and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

14. *Juncetum gerardiae* Musayev & Atamov 2013

Along the lakes, streams, canals and flat humid, sandy and swampy meadows of Azerbaijan,

from the plains to the central mountain range, the vegetation cover of that association was between 40-70 (100) cm and the taxa *Juncus acutus*, *Plantago maritima*, *Phragmites australis*, *Cynodon dactylon*, *Bolboschoenus maritimus*, and *Schoenoplectus lacustris* participated in the phytocenological structure, along with the characteristic species of the association.

Juncetum associations are most typical and widely distributed in the swamps. They thrive there in the form of small islands in the Abşeron Peninsula, the Kur-Araz and Khazar plains. *Juncus gerardi*, one of the characteristic species of the association, adds dark hues to the general appearance of the association when it start flowering from mid-July. When the species *Inula aspera* and *Taraxacum confusum* are in bloom, the association becomes more visible in the swamps and places with quickly drying water. *Cynodon dactylon* mostly predominates the association. Since these lands are used as grazing areas for various species of cattle and sheep, such as *Juncus maritimus*, in spring, forms small, green, coma-shaped patches (Table 2).

Fig. 4d illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

15. *Salicornio europaea-Halocnemum strobilacei* Musayev & Atamov 2013

That association is found on the edges of swamps in the Abşeron Peninsula, Samur-Davaçhi, Kur-Araz and Khazar plains, and within the swamps, where the amount of salt increases in spring.

Halocnemum strobilaceum and *Suaeda microphylla* are the characteristic species of the association. Most of these plants appear in places where they grow well on dry soil. In literary sources, these association have also been shown as spreading over wide areas, starting from the December. Sea to Central Asia (Yurdakulol 1974;

Yurdakulol & Ercopkun 1990).

The vegetation cover of the association varies between 30-50%. As the amount of salt increases in the upper soil layers in spring, the areas between some plants, such as *Holocnemum strobilaceum* and *Suaeda mycrophylla*, which are the characteristic species of the association, become bare and the species spread. They thrive in places where the amount of salt is the highest. As the soil dries out, the salt left by the evaporating water coming from the lower to the upper soil layers hardens completely the upper soil layers and amounts to more than 3%. Typical examples of such patches could be seen around Böyük Şor, Masazır (Absheron Peninsula), Hacıkabul, and Acınohur Lake (Table 2, Fig.4c).

Fig. 4e illustrates the life form of the association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes, xamophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical composition of the soil and water environment in which the association spreads.

16. *Franketum hirsutae* Musayev & Atamov 2013

That association could be found locally around the Absheron Peninsula, Kür-Araz, Samur-Deveci and the salty lakes of the Khazar Plain. It was encountered in swamps, between halophyte units and *Artemisietum* associations.

After drying up of the swamp, the association emerges where the water level is not very deep. Its vegetation cover varies between 30-50(60)%. In July, the characteristic forms of that associatin bloom and it looks more lively and attractive (Table 2).

Fig. 4f illustrates the life forms of that association and the frequency of occurrence of the species in the sample areas. Observations have shown that in the phytocenological structure of that association, with the participation of therophytes, phanerophytes and hemicryptophytes, species with very different frequency of occurrence have been encountered within the sample areas, which is related to the chemical

composition of the soil and water environment in which the association spreads.

4. CONCLUSION

Five hundred and two taxa belonging to 62 families and 208 genus were found in the water-swamp flora of Azerbaijan. Taxa belonging to the families of *Poaceae*, *Cyperaceae*, *Ranunculaceae*, *Fabaceae*, *Potamogetonaceae*, *Juncaceae*, and *Salicaceae* were widestrepresented. The genus *Carex*, *Ranunculus*, *Juncus*, *Potamogeton*, *Schoenoplectus*, *Cyperus* and *Salix* contained the greatest number of taxa.

The *Poaceae* family manifested 47 genus, followed by *Cyperaceae* with 18, *Cenopodiaceae* and *Fabaceae* with nine each, *Lamiaceae* and *Asteraceae* with seven each, *Brassicaceae* and *Apiaceae* with five each, and *Potamogetonaceae* and *Scrophulariaceae* families represented by four each. A total of 68 genus with three or fewer species were encountered.

Syntaxonomic classifications made by the authors of this study have shown that the aquatic communities of Azerbaijan total 95 plant associations: 12 classes, 16 orders, 26 alliances (Musayev, Atamov et al, 2015; Atamov, 2022). During the vegetation studies of the region, the water-swamp ecosystems seemed to have been investigated extensively, but the world-wide applied methods were not used in the classification of the vegetation, which was based only on the dominance principle, without taking into account the habitat types, phytosociological structure and ecological conditions. A further detailed research of the large lakes and aquatic communities within the borders of Azerbaijan will undoubtedly provide new floristic records and reveal new plant associations.

According to the obtained results, the water-swamp ecosystems have been extensively investigated in the earlier studies, but without using the world-wide applied methods in the classification of vegetation. The earlier studies have been only based on the principle of dominance, without taking into consideration the habitats, phytocenological structure of the vegetation and ecological conditions.

A further detailed investigation of the large lake and water-swamp ecosystems

within Azerbaijan would certainly reveal new plant associations to supplement the former flora records.

In the study area, the widest spread and most characteristic were: *Halocnemum strobilacei* Oberd 1957, *Junco maritimi-Tamaricetum ramosissimae* Musayev & Atamov 2024, *Spergulario-Halimionetum verruciferae* Musayev & Atamov 2013, *Halimione verrucifera-Juncetum littoralisae* Musayev & Atamov 2024, *Limonio meyeri-Juncetum littoralisae* Musayev & Atamov 2024, *Tamaricetum ramosissimae* Grosheimi 1929, *Juncetum acutusaе* Musayev & Atamov 2013, *Carici extenso-Salicornietea europaeae* (Tx. in Tx. & Oberd. 1958) Julve 1993, *Juncetum maritimum* Pignatti 1953, *Phragmito-Juncetum maritime* Korzh. et Kljukin 1990, *Carici extenso-Halocnemum strobilacei* Vural, Duman & al. 1994, *Alopecuretum ventricosa* Musayev & Atamov 2013, *Juncetum littoralis* Musayev & Atamov 2013, *Juncetum acutusaе* Musayev & Atamov 2013, *Juncetum gerardiae* Musayev & Atamov 2013, *Salicornio europea-Halocnemum strobilacei* Musayev & Atamov 2013, and *Franketum hirsutae* Musayev & Atamov 2013. In conclusion, the water-swamp communities were divided into five types according to habitat diversity:

1) in-water habitats (33); 2) coast marsh (31); 3) wet grass (13); 4) aquatic forest (8), 5) hydrohalophytes (16 plant associations).

As a result of the study of phytosociological properties of plant associations in halophytic wetlands of Azerbaijan, the phytosociological properties of the following associations of the region were identified:

Halimione verrucifera-Juncetum littoralisae Musayev & Atamov 2024 ass.nova, *Limonio meyeri-Juncetum littoralisae* Musayev & Atamov 2024 ass.nova, *Tamaricetum ramosissimae* Grosheimi 1929, *Juncetum acutusaе* Musayev & Atamov 2013, *Halocnemum strobilacei* Oberd 1957, *Junco maritimi-Tamaricetum ramosissimae* Musayev & Atamov 2013, *Carici extenso-Salicornietum europaeae* (Tx. in Tx. & Oberd, 1958) Julve, *Alopecuretum verticosae* Musayev & Atamov 2013, *Franketum hirsutae* MM & VA 2013, *Juncetum acutusaе* Musayev & Atamov 2013, *Juncetum gerardiae* Musayev & Atamov 2013, *Juncetum littoralisae* Musayev & Atamov 2013, *Salicornio europeo-Halocnemum strobilacei* Musayev & Atamov 2013, *Spergulario-Halimionetum verruciferae* Musayev & Atamov 2013.

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ARTICLE 4

Biodiversity and Areas of Distribution of Di-, Tetra- and Hexaploid Wheat (*Triticum* L.) Species in Azerbaijan

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ABSTRACT

This study presents the results of an investigation into the biodiversity and distributional areas of diploid, tetraploid, and hexaploid wheat (*Triticum* spp.) species in Azerbaijan. The contrasting soil and climatic conditions, vertical zonality, and abundant solar radiation of the region have formed rich biodiversity, confirming Azerbaijan as one of the primary centres of wheat origin and diversification. A total of 14 wheat species have been identified in Azerbaijan: three diploid hulled species (*Triticum urartu*, *T. boeoticum*, and *T. monococcum*); seven tetraploid species including two hulled forms — one wild (*T. araraticum*) and one cultivated (*T. dicoccum*) — and five free-threshing naked-grain species (*T. durum*, *T. turgidum*, *T. turanicum*, *T. polonicum*, and *T. carthlicum*); and four hexaploid species comprising two hulled forms (*T. spelta* and *T. vavilovii*) and two free-threshing forms (*T. aestivum* and *T. compactum*). Botanical variety data from field collections spanning all major agro-ecological zones are presented. Given the ongoing threat of genetic erosion, urgent collection, comprehensive study, and ex situ conservation of all endangered wheat species in Azerbaijan is strongly recommended.

Keywords: *diploid wheat; tetraploid wheat; hexaploid wheat; Triticum; genetic resources; biodiversity; centre of origin; Azerbaijan*

1. INTRODUCTION

One of the primary centers of origin for cultivated plants, Western Asia is also distinguished by its richness in wheat species. Nine botanical species of the wheat genus are considered endemic to this center. In Azerbaijan, which is one of the key zones of the Western Asian center, the contrasting soil and climate conditions, vertical zonality, and abundant natural solar radiation have contributed to the formation of rich biodiversity. The intensity of speciation, the abundance of wild and rare species, subspecies,

varieties, and forms confirm that this region is one of the original centers of origin for wheats (*Triticum* L.).

As a result of archaeological excavations and paleontological research, numerous cereal plant remains (straw, grain, and flour) have been discovered in layers dating back to the 4th–2nd centuries BCE in the areas of Binagadi, Mingachevir, the Nakhchivan Autonomous Republic (Kultepe), Goygol, and Asgaran (Khojaly). In addition, stone sickles used for grain cultivation, threshing tools, and stone hand mills for grinding

grain have been found. Charred seeds of various types of wheat, barley, and emmer, dating back to the mid-3rd millennium B.C., were discovered during excavations at the Kultepe mound in Nakhchivan. These findings prove that in the territory of the Nakhchivan ASSR during that period, durum, bread, and club wheats, emmer, different types of barley, and other crops were cultivated. Boat-shaped stone grain grinders and flint inserts for wooden sickles were also found at the site (1-7).

2. MATERIALS AND METHODS

Among the genera distinguished by their biodiversity within the Poaceae Barnh. family, the genus *Triticum* (wheat) is particularly notable. The genus comprises 19 natural species (both widespread and endemic), along with numerous natural mutants and synthetic species of hybrid origin. Based on ploidy level, the genus *Triticum* is classified into three groups: (1)

diploid wheats (monococcum group), (2) tetraploid wheats (dicoccoides group), and (3) hexaploid wheats (spelta group).

Among wheat species, the most important and widely cultivated is bread wheat (*Triticum aestivum* L.), followed by durum wheat (*T. durum* Desf.), which is an indispensable raw material for pasta and confectionery industries. The cultivated emmer (*T. dicoccum* (Schrank) Schuebl.) was historically grown on different continents for groat production. Other tetraploid species such as *T. turgidum* L., *T. turanicum* Jakubz., *T. polonicum* L., *T. carthlicum* Nevski (= *T. persicum* Vav.), and hexaploid species such as *T. compactum* Host., *T. spelta* L., and *T. sphaerococcum* Perciv. had limited practical significance. The remaining species are found either in the wild or as biological intermediates among the aforementioned species. In Azerbaijan, a total of 14 wheat species have been identified (Table).

Table1. Wild, rare and cultivated wheat species of Azerbaijan (Dorofeev et al, 1979)

Subgenus	Section	Species groups	Species	Ploidy, 2n	Genomes
<i>Triticum</i>	<i>Urartu</i> Dorof. et Filat.	Monococcion	<i>T.urartu</i> Thum. ex Gandil.	14	A ^u
	<i>Dicoccoides</i> Flaksb.	Emmers	<i>T. dicoccum</i> (Schrank) Schuebl.	28	A ^u B
		Tetraploids with light threshing	<i>T. turgidum</i> L.	28	A ^u B
			<i>T. durum</i> Desf.	28	A ^u B
			<i>T. turanicum</i> Jakubz.	28	A ^u B
			<i>T. polonicum</i> L.	28	A ^u B
			<i>T. carthlicum</i> Nevski (<i>T. persicum</i> Vav.)	28	A ^u B
	<i>Triticum</i>	Spelt	<i>T. spelta</i> L. <i>T. vavilovii</i> Jakubz.	42 42	A ^u BD A ^u BD
		Hexaploids with light threshing	<i>T. compactum</i> Host. <i>T. aestivum</i> L.	42 42	A ^u BD A ^u BD
<i>Boeoticum</i> Mig. et Dor.	<i>Monococcon</i> Dum.	Monococcion	<i>T. boeoticum</i> Boiss. <i>T. monococcum</i> L.	14 14	A ^b --"--
	<i>Timopheevii</i> A.Filat. et Dorof.	Emmers	<i>T. araraticum</i> Jakubz.	28	G ^b

3. RESULTS AND DISCUSSION

I. Among the wild diploid wheats, *T. urartu* Thum. ex Gandil., *T. boeoticum* Boiss., and *T. monococcum* L. have been collected in Azerbaijan (1–6).

T. urartu Thum. ex Gandil. – A wild, hulled species (the grain is difficult to separate from the husk) with the Au genome. In the Zangilan region, the botanical varieties var. *spontaneorum* and var. *albonigricans* have been found.

T. boeoticum Boiss. – A wild, hulled species with the A^b genome. From the regions of Jabrayil (630–750 m above sea level), Nakhchivan AR (Babek district, Chalkhangala village, 1230–1270 m a.s.l.), Shabran, Zangilan (630 m a.s.l.), Shamakhi (720–1270 m a.s.l.), and Hadrut, 19 botanical varieties belonging to 2 subspecies have been collected (1–6):

–subsp. *boeoticum* – in Azerbaijan var. *aznaburticum*, var. *baydaricum*, var. *boeoticum*, var. *pseudoboeticum*, var. *viridiboeticum*, var. *symboloenense*, var. *viridisymboloenense*, var. *pseudozuccarinii*, var. *mayssuriani*, var. *pubescentinigrum*, var. *helenae* botanical varieties were found.

–subsp. *thaoudar* – in Azerbaijan var. *thaoudar*, var. *azerbajdjanicum*, var. *nigrireuteri*, var. *balansae*, var. *balaclavicum*, var. *fuscum*, var. *luteinigrum*, var. *mazzettii* botanical varieties were found.

T. monococcum L. – A cultivated, hulled species with the A^b genome – 10 botanical varieties have been collected from the regions of Shusha, Khankendi (1000–1230 m above sea level), Lachin, Ismayilli (600–1300 m a.s.l.), and Yardimli (1000 m a.s.l.): var. *monococcum*, var. *macedonicum*, var. *flavescens*, var. *pseudoflavescens*, var. *macedonicum*, var. *pseudomacedonicum*, var. *hohensteinii*, var. *hornemannii*, var. *pseudohornemannii*, var. *vulgare* (1–6).

II. Wild tetraploid wheats (A^bG genomes). Only one species is found in Azerbaijan – *T. araraticum* Jakubz. 1947. In various classifications, it has been referred to under different names: *T. dicoccoides* subsp. *armeniaceum* Jakubz., 1932; *T. armeniaceum* (Jakubz.) Makush., 1938; *T. montanum* Makush., 1948; *T. chaldicum* Menabde, 1948; *T. turgidum* subsp. *armeniaceum* (Jakubz.) A. et De Löve, 1961; *T. timopheevii*

subsp. *armeniaceum* (Jakubz.) J. Mac Key, 1966 (1–6).

From the Nakhchivan AR (Babek district, Chalkhangala village, 1230–1270 m a.s.l.), Agsu (290–700 m a.s.l.), Shamakhi (290–700 m a.s.l.), and Nagorno-Karabakh (410 m a.s.l.), 8 botanical varieties belonging to the subspecies *araraticum* have been collected: var. *araraticum*, var. *nachitschevanicum*, var. *araxicum*, var. *thumaniani*, var. *pseudostraussianum*, var. *pseudoarmeniaceum*, var. *pseudoaaronsohnii*, var. *nigrum* (1–6).

III. Cultivated tetraploid wheats (A^uB genomes). In Azerbaijan, the following species are found: *T. dicoccum* (Schrank) Schuebl., *T. turgidum* L., *T. durum* Desf., *T. turanicum* Jakubz., *T. polonicum* L., *T. cartlicum* Nevski (= *T. persicum* Vav.) (1–7).

T. dicoccum (Schrank) Schuebl. – Cultivated emmer wheat. From the Nakhchivan AR (Babek and Sharur, 1230–1270 m a.s.l.), Karabakh (Shusha, Khankendi, Aghdara, 800–1400 m a.s.l.), Lachin (1300–1400 m a.s.l.), Lerik and Ismayilli (600–1300 m a.s.l.), 12 botanical varieties belonging to 2 subspecies have been found:

–Subsp. *dicoccum* convar. *dicoccum* –var. *dicoccum*, var. *rufum*, var. *pseudorufum*, var. *semicanum*, var. *macratherum*, var. *atratum*, var. *hybridum*; var. *pseudoerythrurum* belonged to the European group of the European subspecies.

–Subsp. *asiaticum* Vav. convar. *transcaasicum* Flaksb. – var. *uniluteotinctum*, var. *uniaeruginosum*, var. *haussknechtianum*, var. *jakubzineri*, var. *aeruginosum*, var. *chevsuricum*, var. *flaksbergerii* belonged to the Southern Caucasus botanical variety of the Asian subspecies.

In recent years, new hybrid-origin emmer wheat accessions have been developed. The new hybrids do not differ in spike shape from emmer, and include forms that combine traits of durum wheat (naked grain, vitreousness, grain shape, and color) and emmer (grain shape and color). Accessions have been identified with red and white grain, with elongated and oval grain shapes.

In addition, constant low-growing forms have been identified with false (as in *T. vavilovii*) and true (as in *T. turgidum*) branching. Some

hybrids are phenotypically indistinguishable from emmer, but have easy threshing; the naked-grain types thresh easily regardless of the type of thresher used.

Constant forms of cultivated emmer have been identified: short (35.0–60.0 cm), medium (65.0–95.0 cm), and tall (over 125 cm), with early and late heading (May 1–13), hulled and naked-grain types — all with easy threshing, with normal spikes, flat, inflated, and turgidoid spike forms. Compared to short and medium-height forms, tall samples show higher resistance to fungal diseases (6).

***T. turgidum* L.** — Turgidum wheat has been collected from almost all regions of Azerbaijan — from lowland, foothill, and mid-mountain areas (48 botanical varieties) (1-3). In Azerbaijan, var. *turgidum*, var. *melanatherum*, var. *nigroglumarum*, var. *musciabile*, var. *dreischianum*, var. *speciosissimum*, var. *ferespeciosissimum*, var. *herreriae*, var. *rubroherreriae*, var. *gentile*, var. *nigrobarbatum*, var. *striatum*, var. *speciosum*, var. *martensii*, var. *nigromartensii*, var. *albofumidum*, var. *megalopolitanum*, var. *salomonis*, var. *pseudomirabile*, var. *rubroalbum*, var. *nigropseudomirabile*, var. *albojodurum*, var. *pseudosalomonis*, var. *rubroatrum*, var. *falsejodurum*, var. *jodurum*, var. *muticospeciosum*, var. *muticospeciosum* botanical varieties of convar. *turgidum* — the group with simple, unbranched spikes have been found.

Convar. *compositum* Filat. — belongs to the group with branched spike. The following varieties have been found in Azerbaijan: var. *ramosolusitanicum*, var. *nachitschevanicum*, var. *pseudocervinum*, var. *plinianum*, var. *columbinum*, var. *cubinum*, var. *pavoninum*, var. *ramosostriatum*, var. *levipavoninum*, var. *leviramosostriatum*, var. *schemachanicum*, var. *mirabile*, var. *felsemirabile*, var. *lencoranicum*, var. *giganteum*, var. *centrigranium*, var. *pseudocentrigranium*, var. *compositum*, var. *pseudolinnaeum*, var. *caucasicum*

Out of the 420 *Triticum turgidum* specimens stored in the VIR world collection, 90 (21.4%) were collected from the territory of Azerbaijan during the Soviet era, up until the 1970s–80s. Of the 71 known varieties, 47 (66.0%) have been found in Azerbaijan. This once again proves that

Azerbaijan is one of the main centers of formation and polymorphism of *T. turgidum* wheat forms.

***T. durum* Desf.** — Durum wheat is found in all ecological and geographical conditions of Azerbaijan. However, its botanical varieties are not evenly distributed. Botanically, the richest region is Shirvan, where the composition varies sharply depending on altitude (–16 to 1200 m), with 19 botanical varieties recorded. The number of botanical varieties decreases in the following regions: Mugan-Salyan (16), Mil-Karabakh and Lankaran (11), Shaki-Zagatala (10), Guba-Khachmaz (8), Ganja-Gazakh, Nakhchivan AR, and Nagorno-Karabakh (7), the mountainous zone of the Lesser Caucasus (6), Aras lowlands (5), and Absheron (3) (1-3).

Studies have shown that durum wheats of Azerbaijan exhibit high intraspecific polymorphism, with 52 botanical varieties observed. By this indicator, they are second only to bread wheat. The most commonly found hard wheat varieties in our Republic belong to the subsp. *durum*. The most widely distributed are var. *leucurum*, var. *hordeiforme*, var. *melanopus*, var. *apulicum*, var. *caerulescens*, var. *leucomelan*, var. *affine*, var. *reychenbachii*, var. *alexandrinum*, var. *provinciale*, var. *valenciae*, and var. *niloticum*. However, some breeding cultivars belong to the subsp. *horanicum*, particularly var. *horanoleucurum*. Durum wheats are distributed along a vertical zonation from below sea level (–16 m, Caspian lowland) up to 1870 m (Shusha, Kecheldag). In cultivated fields, they are mainly found in plains and foothill regions at altitudes of 800–1000 m. (1-3).

In recent years, accessions belonging to the truly branched botanical variety (subconvar. *duroramosum* Dorof.), including var. *ramosoleucurum*, var. *ramosoleucomelan*, var. *ramosohordeiforme*, var. *ramosoerythromelan*, var. *ramosoaffine*, var. *ramosocaerulescens*, var. *ramosobscurum*, var. *ramosoalbobscurum*, and var. *ramosolibycom*, have been selected and submitted to the National Gene Bank.

***T. turanicum* Jakubz.** (= *T. orientale* Persiv.) — Turan wheat is genetically related to durum wheat, forming fertile hybrids. In terms of biodiversity, Azerbaijan (11 botanical varieties)

and Turkey (10) occupy leading positions. Historically, it was mainly collected from Tartar, Khojavend, Agdam, Aghjabadi, Fizuli, Masalli, Jalilabad, and Agsu districts. In Azerbaijan, the following botanical varieties have been recorded: *var. ferghanicum*, *var. gasimustafakemalii*, *var. generosum*, *var. insigne*, *var. jalovanianum*, *var. notabile*, *var. turanaffine*, *var. turaninigrum*, *var. turanobscurum*, *var. turanmursiense*, *var. turaniprovinciale* (1-3).

***T. polonicum* L.** – Polish wheat has been found in Azerbaijan (Fizuli district) in durum wheat fields, in small quantities, as a rare biological mixture, represented by three botanical varieties: *var. polonicum*, *var. pseudolevissimum*, and *var. villosum* (2, 3). In recent years, accessions with ordinary and branched spikes belonging to *var. chrysospermum*, *var. pseudochrysospermum*, *var. skalasubovii*, *var. pisarevii*, *var. rufescens*, *var. pseudocaryopsirubrum*, *var. rubrosemineum*, *var. caryopsirubrum*, *var. heydelbergi*, *var. abyssinicum*, *var. levissimum*, and others have been selected and submitted to the National Gene Bank (7).

***T. cartlicum* Nevski = *T. persicum* Vav.** – Kartvel (Iran) wheat was first recorded in Azerbaijan by N.N. Kuleshov (1926) in Nakhchivan. Later, at altitudes of 90–1600 m, it was observed in Nakhchivan AR (Culfa, Babek, Sharur, Shahbuz), Kalbajar, Aghdara, Agdam, Yevlakh, Saatly, Sabirabad, Gazakh, Goygol, Agsu, Shamakhi, Lerik, Masalli, Jalilabad, Bilesuvar, Goranboy, Khachmaz, Shabran, Guba, Shaki, and Zagatala, with six botanical varieties recorded: *var. stramineum*, *var. pseudostramineum*, *var. rubiginosum*, *var. pseudorubiginosum*, *var. nigrorubiginosum*, and *var. fuliginosum*. The collected accessions also differ in spike density, intensity of coloration, and the length and coarseness of spikes and awns.

IV. Hexaploid wheats (A^uBD genomes). In Azerbaijan, the species *T. aestivum* L., *T. compactum* Host., *T. spelta* L., and *T. vavilovii* Jakubz. are distributed (1–7).

***T. aestivum* L.** – Bread wheat is the most widely distributed, ecologically plastic, and cosmopolitan species. It occurs on all five continents – from the Polar regions to the southern extremes of America, Africa, and Australia,

and from below sea level up to 4000 m elevation (Peru). In terms of varietal diversity and the number of collected accessions, Azerbaijan ranks first in the South Caucasus. Botanically, the richest regions (39 botanical varieties) are Nakhchivan AR and Shaki-Zagatala. These are followed by Shirvan (31 botanical varieties), Guba-Khachmaz (25), Mugan-Salyan (21), Ganja-Gazakh (20), Mil-Karabakh and Lankaran-Ashtara (19), Aras lowlands and Nagorno-Karabakh (17), and Absheron (6). The most widely distributed botanical varieties are *var. suberythrospermum*, *var. lutescens*, *var. ferrugineum*, and *var. caesium*. In addition, in cultivated fields, *var. milturum*, *var. barbarossa*, *var. pseudobarbarossa*, and *var. hostianum* occur as biological mixtures. In plains and foothill regions, genotypes with a winter growth habit predominate, whereas in mountainous and high-mountain areas, semi-winter and spring types are more common. Hairy and dark-colored forms are mainly found in high-mountain regions (1-3).

In modern classification, based on morpho-biological and ecological traits, bread wheat is divided into the subspecies *hadropyrum* (Flaksb.) Tzvel. – representing the Asian subspecies, and subsp. *aestivum* – representing the Indo-European subspecies (1).

In our Republic, the Asian subspecies is represented by the groups of convar. *rigidum* and convar. *semirigidum*, and specimens belonging to the European subspecies (subsp. *aestivum*) have also been found (1-3):

–convar. *rigidum* represented by the following botanical varieties: *var. subgraecum*, *var. suberythroleucum*, *var. suberythrospermum*, *var. subferrugineum*, *var. submeridionale*, *var. submesopotamicum*, *var. subhostianum*, *var. subpseudohostianum*, *var. subbarbarossa*

–convar. *semirigidum* represented by the following botanical varieties: *var. pseudoalbirubrum*, *var. cinereum*, *var. introitum*, *var. delfii*, *var. graecum*, *var. nigrigraecum*, *var. pseudo-graecum*, *var. erythroleucum*, *var. pseudoerythroleucum*, *var. chiovendae*, *var. caesioides*, *var. cinerosum*, *var. almaatense*, *var. indicum*, *var. melanopogon*, *var. variabile*, *var. nigricans*, *var. bengalense*, *var. meridionale*, *var. pseudo-meridionale*, *var. hamadanicum*, *var. turcicum*,

var. *pseudoturcicum*, var. *griseum*, var. *mesopotamicum*, var. *iranicum*, var. *hostianum*, var. *pseudohostianum*, var. *kazvinicum*, var. *barbarossa*, var. *pseudobarbarossa*, var. *luritanicum*, var. *rubrimurinum*, var. *renovatum*, var. *fuliginosum*.

The European subspecies is represented by the following botanical varieties: var. *aureum*, var. *albirubrum*, var. *lutescens*, var. *milturum*, var. *anglicum*, var. *villosum*, var. *aestivum*, var. *nigraristatum*, var. *ferrugineum*, var. *sardoum*, var. *caesium*.

T. compactum Host. - Dwarf, compact wheat is very close to bread wheat, differing only by its short and dense-compact spikes. It has both winter and spring growth habits. In Azerbaijan, it has had no significant agricultural importance. A total of 13 botanical varieties have been frequently found as biological mixtures in soft and hard wheat population fields in Nakhchivan AR, Nagorno-Karabakh, Kalbajar, Shamakhi, Zagatala, Guba, and Gusar. Pure plantings have been observed only in Nakhchivan AR. In our Republic, the following varietal forms have been collected: var. *fetissoyii*, var. *erinaceum*, var. *cabristanicum*, var. *rubriceps*, var. *pseudorubriceps*, var. *albiceps*, var. *kanaschii*, var. *echinoideum*, var. *kerkianum*, var. *humboldtii*, var. *wernerianum*, var. *compactum* var. *icterinum*

T. spelta L. - The winter spelta wheats of Azerbaijan are tall, with high leafiness and strong tillering; they are resistant to cold, frost, and humidity, but susceptible to drought, and are immune to yellow rust, brown rust, and powdery mildew. Spelta flour is of high quality. A total of 25 botanical varieties have been collected from the following regions: Nakhchivan AR (Babek, Sharur), Shusha, Lachin, Gabala, Goygol, Goranboy, Kalbajar, Ismayilli, Shamakhi, Zagatala, Guba, Gusar, Khachmaz, and Masalli: var. *vavilovii*, var. *asiduhamelianum*, var. *albiduhamelianum*, var. *asialbispicatum*, var. *jakubzineri*, var. *thumanianii*, var. *marinae*, var. *asiamissum*, var. *asirecens*, var. *asineglectum*, var. *subbuldojii*, var. *pseudobuldojii*, var. *mustaphaevii*, var. *karabachicum*, var. *flaksbergeri*, var. *subbaktiaricum*, var. *pseudobaktiaricum*, var. *subsharkordii*, var. *pseudosharkordii*, var. *samuricum*, var. *shemachanicum*, var. *sinakajae*,

var. *asialbivelutinum*, var. *asirubrivelutinum*, var. *asicaeruleum*.

T.vavilovii Jakubz. - Vavilov wheat is a true winter species, a xerophyte highly resistant to drought and high temperatures, and a relatively monomorphic species. In Azerbaijan, three botanical varieties have been rarely observed: var. *azericum*, var. *mirabile*, var. *vavilovii*. var. *munuru*, var. *mravianii*, var. *ruvromravianii* var. *nova*

4. CONCLUSION

Thus, in Azerbaijan, 14 wheat species belonging to the genus *Triticum* have been identified: 3 diploid hulled species – *T.urartu* Thum. ex Gandil., *T. boeoticum* Boiss., *T.monococcum* L.; 7 tetraploid species – 2 hulled, one of them wild (*T. araraticum* Jakubz.), *T. dicoccum* (Schrank) Schuebl., and 5 free-threshing (naked-grain) species – *T.durum* Desf., *T.turgidum* L., *T.turanicum* Jakubz., *T.polonicum* L., *T.cartlicum* Nevski; 4 hexaploid species – 2 hulled, *T. spelta* L., *T. vavilovii* Jakubz., and 2 free-threshing species – *T. aestivum* L., *T. compactum* Host.

Taking into account the above-mentioned, we consider that the urgent collection, comprehensive study, and utilization of endangered wheat species in Azerbaijan for obtaining donors and genetic resources is both timely and essential. For this purpose, it is necessary to collect, multiply, and restore cultivated, rare, and wild species and varieties, landraces, modern cultivars with complex biological and economic traits, advanced perspective hybrids, rare botanical forms, mutants, genetic lines, donors, and genetic resources, as well as to implement comprehensive research and conservation measures.

The rare, relict species of the genus *Triticum*, *T. karamyshevii*, has been cultivated in Azerbaijan since ancient times. Its low requirements for soil and climate conditions and its ecological plasticity have stimulated its cultivation on soils with poor fertility and weak physico-chemical properties, especially under continental climatic conditions. However, in the past century, the abolition of private farms, the establishment of collective and state farms, the transition to "planned" production, and the introduction of

more productive breeding cultivars led to the displacement and loss of local landraces, including valuable *T. karamyshevii* genotypes, which had passed through centuries of natural and artificial selection.

Emmer wheat groats are rich in easily digestible proteins and amino acids. For centuries, it has been cultivated by Turkish peoples for the purpose of obtaining groats. After primitive gatherers discovered that its grains were tastier and more nutritious, they developed local landraces through spontaneous selection and transmitted them from generation to generation.

As is known, local emmer wheat forms are semi-winter and spring types. The tillering capacity of emmer wheat is very intensive, similar to barley. When included in multi-field crop rotation, its vegetation period allows sowing after late-harvested predecessors (cotton, sugar beet, winter cabbage, and other vegetable crops) at the end of autumn, or under favorable conditions, in winter or early spring, to obtain high yields. Due to its strong tillering, emmer wheat can also be used in controlling perennial rhizomatous weeds (meadow grass, couch grass, thistle, etc.). For this purpose, barley is

usually employed; however, during one growing season, emmer wheat can also effectively suppress these dangerous weeds. Since emmer wheat grain and groats are more expensive than barley, their cultivation offers higher economic returns.

The high domestic demand for groats in our Republic is met through exports. Currently, at the Genetic Resources Institute, local emmer wheat accessions and complex wheat-emmer hybrids have been cultivated for propagation, restoration, and study. The main goal is to multiply them and preserve them for future generations. In addition, studying the morpho-biological and agronomically important traits of emmer wheat under various soil and climatic conditions provides opportunities to obtain initial breeding material, genetic resources, and donors.

By efficiently using the initial breeding material, it is possible to develop, within a short time, high-yielding and grain-quality wheat cultivars with immunity, suitable for different regions of Azerbaijan. Furthermore, previously collected accessions should be propagated in their original habitats for restoration and reconstruction.

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ARTICLE 5

Structure, Species Composition and Diversity of *Bothriochloa ischaemum* (L.) Keng Communities in Steppe Ecosystems of the South-Eastern Part of Azerbaijan

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ABSTRACT

Steppe ecosystems of the South Caucasus are among the most ecologically sensitive and economically significant vegetation types in the region, yet their phytocoenotic diversity remains insufficiently documented. This study investigates the structure, floristic composition, and current ecological status of *Bothriochloa ischaemum* (L.) Keng communities in the arid steppe zone of south-eastern Azerbaijan, encompassing the Gobustan, Salyan, Shirvan, and Saatli districts. Geobotanical surveys were conducted using the Braun-Blanquet relevé method, with species abundance estimated according to the standard cover-abundance scale. A total of 11 families, 25 genera, and 28 vascular plant species were recorded within the study communities. The families Poaceae (7 species, 25%), Fabaceae (4 species, 14%), and Asteraceae (4 species, 14%) are dominant in terms of species richness and ecological significance, while the remaining eight families are each represented by a single species. Seven principal plant associations were identified, ranging from bunchgrass–forb to wormwood–graminoid types, depending on soil salinity and edaphic conditions. The edificator *B. ischaemum* demonstrates high ecological plasticity, colonising diverse substrates including non-saline and slightly saline soils, rocky outcrops, and degraded shrublands. Productivity assessments of wormwood–yellow bluestem pastures revealed a seasonal gross dry matter yield of 16.4 c/ha, with an edible fraction of 8.0 c/ha, corresponding to a carrying capacity of approximately 2 sheep per hectare. The observed decline in species diversity in recent years, combined with increasing anthropogenic pressure and aridification, underscores the need for targeted conservation and sustainable rangeland management strategies across the south-eastern steppe belt of Azerbaijan.

Keywords: *steppe phytocoenoses; plant associations; Bothriochloa ischaemum; yellow bluestem; edificator; pasture productivity; south-eastern Azerbaijan*

1. INTRODUCTION

Steppe vegetation is one of the dominant types on Earth. Steppes are a vital link in the planet's overall bioecosystem chain, serving as a key source of forage pastures (Dengler et al., 2014). In Azerbaijan, particularly in the south-eastern part of the country, steppe vegetation is the primary forage source and is primarily represented by dry steppes. Today, these steppes are

experiencing significant anthropogenic impacts.

Steppe landscapes in the southeastern part of the republic dominate the area around the village of Gobustan, as well as the Shirvan, Salyan, Saatli, and Sabirabad districts, occupying primarily flat and foothill areas. Dry steppes, combined with patches of deserts and semi-deserts, form a complex horizontal mosaic, often observed even in the coastal zone of the Caspian

Sea.

The steppe vegetation type mainly consists of drought-resistant species (Asadova, 2008). In terms of climate, the region is characterized by a moderately warm, dry continental climate. The average temperature of the warmest month is +23 to +25°C, and of the coldest month, -2°C. In summer, the absolute maximum temperature reaches +38 to +44°C. Annual precipitation is extremely low, amounting to approximately 250–350 mm per year (Museibov, 1998). Winds are mostly weak and gusty. In winter and autumn, southern and southwestern winds predominate, while in spring and summer, eastern and northeastern ones prevail. The soils of the dry steppe zone are diverse, ranging from light chestnut soils, relatively rich in humus, to grey-brown, slightly saline, and saline soils.

2. MATERIALS AND METHODS

The study of yellow bluestem was conducted primarily in the Gobustan, Salyan, Shirvan, and

Saatli districts (Fig. 1). Perennial grasses are the dominant species in the steppe communities of these areas. In our study area, they are represented by beard grass (*Bothriochloa ischaemum* (L.) Keng), fescue (*Festuca rupicola* Heuff), wheatgrass (*Agropyron cristatum* (L.) Gaertn.), and feather grass (*Stipa caspia* C.Koch). Forb perennials and legumes (*Trifolium canescens* Willd., *Filago arvensis* L., *Calendula persica* C.A.Mey., and others) are also common (Atamov, 2002; Gurbanov, 2024).

The studies were conducted using methods generally accepted in geobotany (Pedrotti, 2013). The standard geobotanical description included compiling a species list, determining abundance and projective cover, layering, degree of palatability, and other indicators (Ponyatovskaya, 1960). Species abundance was scored using the Braun-Blanquet cover-abundance scale (Braun-Blanquet, 1932; Theurillat et al., 2021). Yield was determined according to the *Handbook of Hayfields and Pastures* (1956).

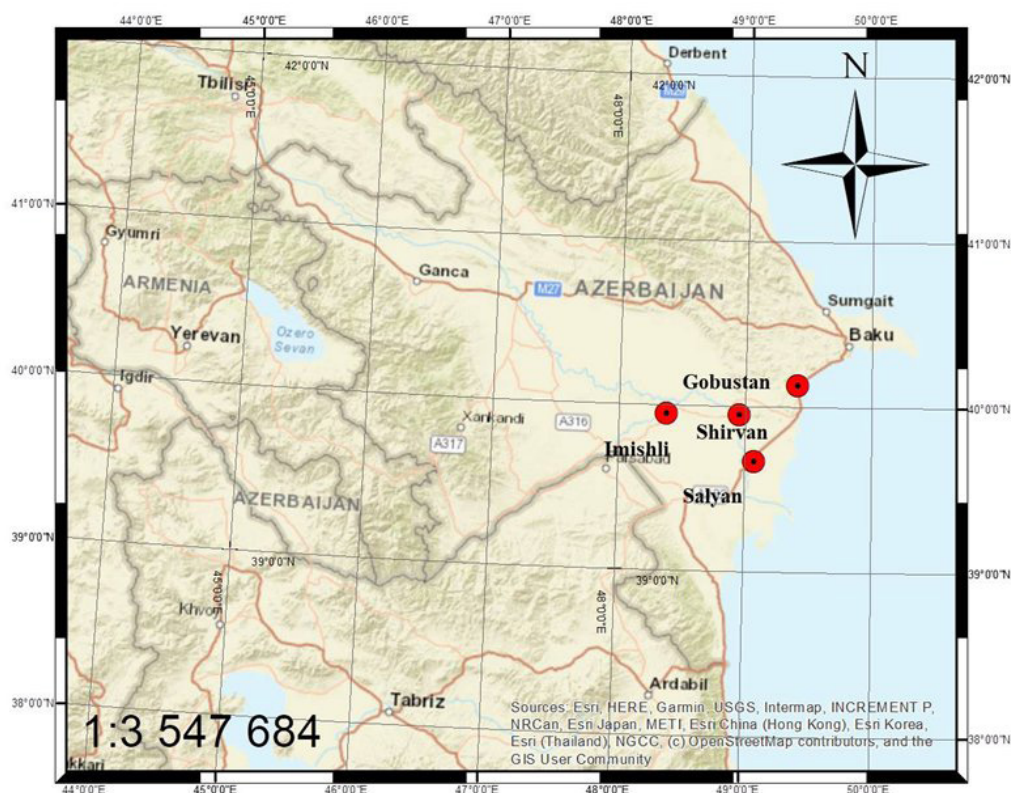


Figure 1. Map of the investigation routes in the south-eastern part of Azerbaijan, showing sampling localities in the Gobustan, Shirvan, Salyan, and Saatli districts (red dots).

3. RESULTS AND DISCUSSION

Bothriochloa communities predominate

primarily in flat areas and on gentle slopes. Here, the prevalence of this edificator is clearly evident, with a distinct dominant composition represented primarily by grasses. The species composition of yellow bluestem communities in these areas is characterized by low diversity, owing to the influence of a hot desert and semi-desert climate. The constant composition

comprises up to 30 species. Depending on climatic conditions, the range of species composition fluctuates between 20 and 56 species in different years. However, in recent years it has shown a clear trend of decline. The main vegetation consists of *Medicago coerulea* Less. ex Ledeb., *Bromus commutatus* Schrad., and other species.

Table 1. Species composition of yellow bluestem communities in the south-eastern part of Azerbaijan.

No	Family	Genus	Species	Life forms (Serebryakov, 1952)	Abundance (Braun- Blanquet, 1932)
1.	Poaceae Barnhart	<i>Agropyron</i> L.	<i>Agropyron cristatum</i> (L.) Gaertn.	Perennial	3
		<i>Bromus</i> L.	<i>Bromus commutatus</i> Schrad.	Annual	1–2
		<i>Bothriochloa</i> L.	<i>Bothriochloa ischaemum</i> (L.) Keng	Perennial	3–4
		<i>Stipa</i> L.	<i>Stipa caspia</i> C.Koch	Perennial	2–3
		<i>Setaria</i> L.	<i>Setaria viridis</i> (L.) Beauv.	Annual	1–2
		<i>Festuca</i> L.	<i>Festuca rupicola</i> Heuff	Perennial	2
		<i>Phleum</i> L.	<i>Phleum paniculatum</i> Huds.	Perennial	1–2
2.	Fabaceae Lindl.	<i>Medicago</i> L.	<i>Medicago minima</i> (L.) Bartalini	Annual	1–2
			<i>Medicago rigidula</i> (L.) All.	Annual	1–2
			<i>Medicago coerulea</i> Less. ex Ledeb.	Perennial	2–3
		<i>Onobrychis</i> Hill.	<i>Onobrychis vaginalis</i> C.A.Mey.	Perennial	1–2
		<i>Trifolium</i> L.	<i>Trifolium canescens</i> Willd.	Perennial	2–3
3.	Asteraceae Dumort.	<i>Tragopogon</i> L.	<i>Tragopogon graminifolius</i> DC.	Perennial	1–2
		<i>Carduus</i> L.	<i>Carduus arabicus</i> Jacq.	Annual	2
		<i>Inula</i> L.	<i>Inula hirta</i> L.	Perennial	1
		<i>Artemisia</i> L.	<i>Artemisia fragrans</i> Willd.	Perennial	2–3
4.	Brassicaceae Burnett	<i>Alyssum</i> L.	<i>Alyssum hirsutum</i> Bieb.	Annual	1–2
5.	Chenopodiaceae Vent.	<i>Salsola</i> L.	<i>Salsola dendroides</i> Pall.	Subshrub	1–2

No	Family	Genus	Species	Life forms (Serebryakov, 1952)	Abundance (Braun- Blanquet, 1932)
6.	Lamiaceae Lindl.	<i>Salvia</i> L.	<i>Salvia viridis</i> L.	Subshrub	1–2
		<i>Phlomis</i> L.	<i>Phlomis pungens</i> Willd.	Perennial	1–2
		<i>Stachys</i> L.	<i>Stachys pubescens</i> Ten.	Perennial	1
7.	Apiaceae Lindl.	<i>Daucus</i> L.	<i>Daucus carota</i> L.	Biennial	2
8.	Caryophyllaceae Juss.	<i>Arenaria</i> L.	<i>Arenaria serpyllifolia</i> L.	Annual	2
		<i>Melandrium</i> Roehl.	<i>Melandrium latifolium</i> Poir.	Annual	2
9.	Scrophulariaceae Juss.	<i>Euphrasia</i> L.	<i>Euphrasia caucasica</i> Juz.	Annual	2
10.	Papaveraceae Juss.	<i>Papaver</i> L.	<i>Papaver commutatum</i> Fisch. et C.A.Mey.	Annual	1–2
11.	Euphorbiaceae Juss.	<i>Euphorbia</i> L.	<i>Euphorbia falcata</i> L.	Annual	2

According to the consolidated species list, yellow bluestem communities comprise 11 families, 25 genera, and 28 species (Fig. 2, Table 1).

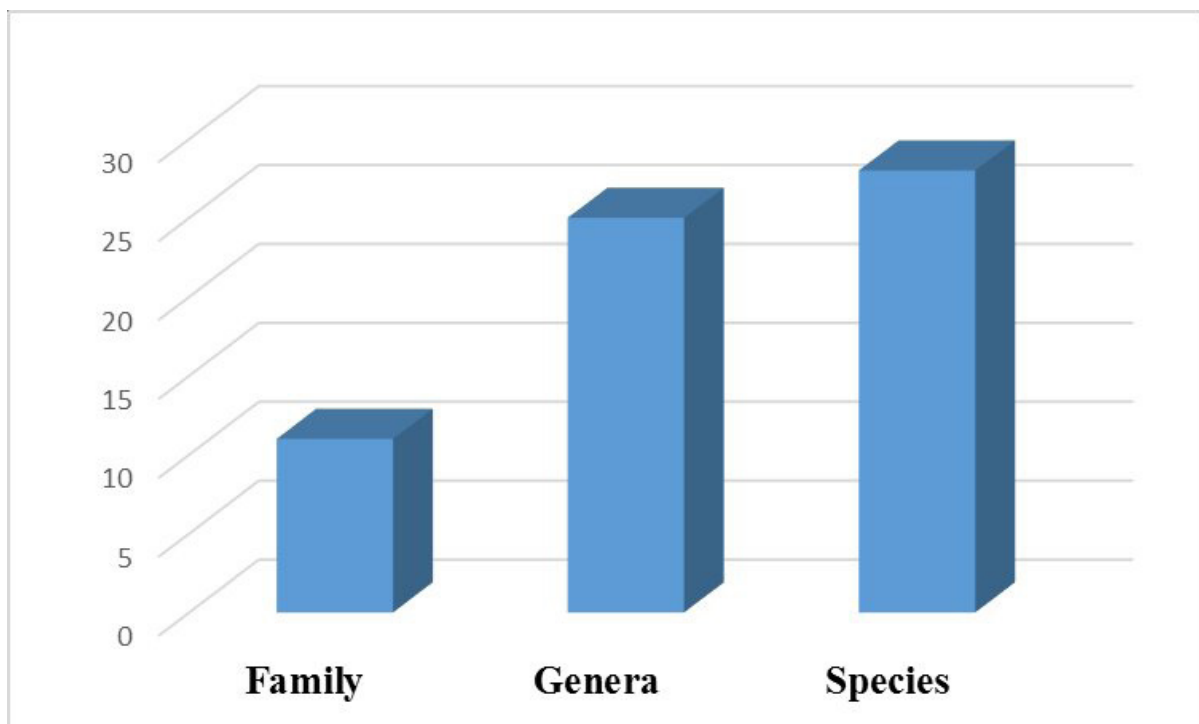


Figure. 2. Taxonomic structure of *Bothriochloa ischaemum* (L.) Keng communities in the south-eastern part of Azerbaijan (number of families, genera, and species).

In terms of species composition and abundance, the families Poaceae, Fabaceae, and Asteraceae play the primary role in determining the ecological value of these communities. The remaining families are each represented by a single species (Fig. 3).

Steppe communities are mixed in nature, including elements of semi-desert ecosystems, in particular species of the genera *Artemisia* and *Salsola* (Fig. 4). The value-forming species in such communities are *Bothriochloa ischaemum*, *Agropyron cristatum*, and *Stipa caspia*.

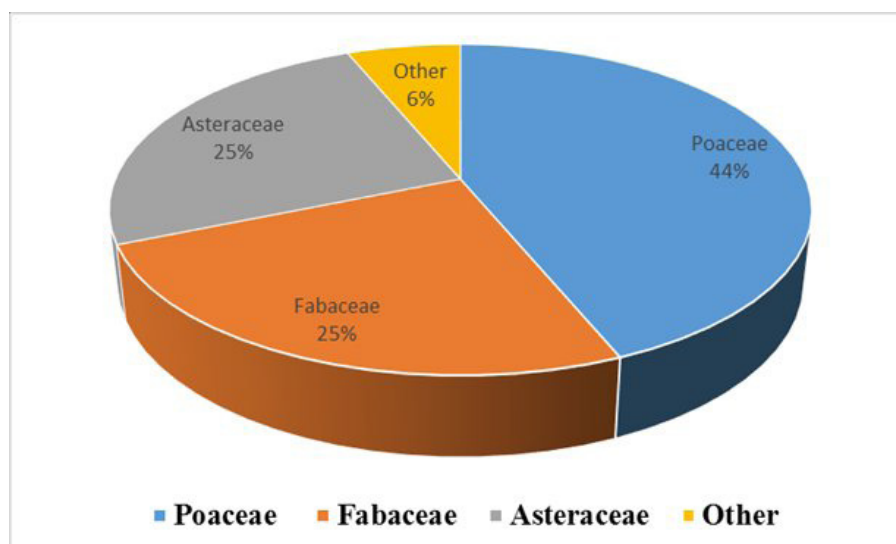


Figure. 3. Proportional contribution of dominant families to the total species composition of *Bothriochloa ischaemum* (L.) Keng communities. Poaceae – 44%; Fabaceae – 25%; Asteraceae – 25%; Other – 6%.

The xerophilous perennial edificator grass *Bothriochloa ischaemum* is a turf-forming plant in dry steppes. It forms turfs of various shapes that spread across the soil surface, with a tendency to merge. When turfs merge, they increase the projective soil cover by 20–30%. Where turfs remain separated from one another, other grasses and forbs occupy the intervening spaces.

It is worth noting that yellow bluestem is ecologically flexible. Analysis of numerous phytocoenological relevés reveals that it is found in a variety of plant communities: it penetrates shrub thickets that have replaced cleared forest areas, and also occurs on gravelly and rocky substrates (Zhang et al., 2017; Li et al., 2019). The habitats of *Bothriochloa ischaemum* frequently contain valuable forage-rich grass–forb and forb–legume communities, such as *Bothriochloa ischaemum* + *Trifolium arvense*, *Medicago coerulea* + *Tragopogon graminifolius*, etc.

The dry-steppe variant of *Bothriochloa* is represented by bunchgrass and bunchgrass–wormwood associations. Depending on edaphic conditions (degree of salinity, moisture regime, and soil type), one or another variant becomes dominant (Lazu et al., 2021). On slightly saline or non-saline soils, *Bothriochloa ischaemum*, fescue (*Festuca rupicola*), wheatgrass (*Agropyron cristatum*), and feather grass (*Stipa caspia*) typically predominate. In areas with higher salinity,

wormwood–graminoid associations prevail.

In total, seven associations were identified for dry steppes:

- 1) *Bothriochloa ischaemum* + *Herbosa*;
- 2) *Festuca rupicola* + *Herbosa*;
- 3) *Agropyron cristatum* + *Herbosa*;
- 4) *Cynodon dactylon* + *Herbosa*;
- 5) *Stipa caspia* + *Bothriochloa ischaemum*;
- 6) *Agropyron cristatum* + *Artemisia lerchiana*;
- 7) *Bothriochloa ischaemum* + *Artemisia lerchiana*.

Wormwood–beard grasslands (*Artemisia lerchiana* + *Bothriochloa ischaemum*) are located at elevations of 500–700 m above sea level and play an important role in the region's forage resources. Fragments of these grasslands were mostly recorded at elevated sites. This type of grassland forms a transitional link between wormwood desert, semi-desert, and dry yellow bluestem grassland. Some permanent dominant species include *Festuca rupicola*, *Stipa caspia*, *Poa bulbosa*, and *Catabrosella humilis*. Compared to wormwood–ephemeral grasslands, *Poa bulbosa* is less abundant here, owing to altered habitat conditions. This type of grassland predominates on slightly saline soils, resulting in a greater diversity of ephemeral vegetation.

The forage value of wormwood–yellow bluestem pastures is based not only on ephemerals but also on perennial bunchgrasses (*Agropyron cristatum*, *Stipa caspia*, *Bothriochloa*

ischaemum). These species significantly increase the stability of the grass stand under long-term grazing (Wang et al., 2024; Wu et al., 2024). The percentage of each dry yield fraction, presented in Table 2, shows that in spring, alongside the edificator (17.2%), the legume and forb fractions produce high yields (53.7% combined). A comparison of spring and autumn yield data reveals that during autumn, the percentages of legumes, grasses, and forbs decrease sharply

to negligible levels. Yellow bluestem, however, continues to persist in the pastures. Forage plants account for approximately 58.7% of the total composition of these pastures, of which grasses and legumes occupy a significant share. Among the forbs, Asteraceae plays a notable role in forage value. In spring, community productivity is based primarily on ephemerals and, to some extent, on the growing green mass of yellow bluestem (Table 2).

Table 2. Productivity of wormwood–yellow bluestem pastures on slopes.

Feed fractions	Spring					Autumn				
	Dry yield 1 m ² total (g)	Dry yield 1 m ² food (g)	Dry yield 1 ha total (c)	Dry yield 1 ha food (c)	%	Dry yield 1 m ² total (g)	Dry yield 1 m ² food (g)	Dry yield 1 ha total (c)	Dry yield 1 ha food (c)	%
Wormwood	19.9	7.3	1.99	0.73	13.9	88.2	43.9	8.82	4.39	47.7
Yellow bluestem	24.7	16.1	2.47	1.61	17.2	90.6	14.1	9.06	1.41	48.5
Cereals	21.8	19.7	2.18	1.97	15.2	3.2	2.9	0.32	0.29	1.6
Legumes	37.6	32.9	3.76	3.29	26.3	–	–	–	–	–
Mixed herbs	39.4	21.0	3.94	2.10	27.4	4.4	2.1	0.44	0.21	2.2
Total	143.4	97.0	14.34	9.7	100	186.4	63.0	18.64	6.3	100

In the combined spring–autumn period, the gross yield is 16.4 c/ha of dry matter, including 8 c/ha of edible matter, which corresponds to a carrying capacity of 2 sheep per hectare.



a



b



c

Figure 4. Steppe landscapes of south-eastern Azerbaijan. (a) *Bothriochloa ischaemum* community with sparse vegetation on sandy-loam soil, Salyan district; (b) mixed bunchgrass–wormwood steppe with *Artemisia* spp. and shrub elements, Shirvan district; (c) degraded dry steppe with *Bothriochloa ischaemum* and *Salsola* spp. under grazing pressure, Gobustan district.

4. CONCLUSION

Steppe vegetation is extensively developed in the foothill zone of the northwestern Shirvan

Plain. Based on geobotanical surveys, two principal steppe formations were distinguished: bunchgrass steppes dominated by yellow

bluestem (*Bothriochloa ischaemum*), and subshrub–bunchgrass dry steppes in which bearded grass (*Bothriochloa* spp.) and wormwood (*Artemisia* spp.) play a significant role.

The steppe belt is mainly confined to the southeastern part of the study area. Toward the north, the importance of steppe communities decreases sharply, giving way to wormwood and wormwood–saltwort (*Artemisia–Salsola*) formations. Steppe grasslands are characterized

by well-developed bunchgrass communities, with dominant taxa including feather grass (*Stipa* spp.), fescue (*Festuca* spp.), and beard grass.

The floristic spectrum of the investigated yellow bluestem communities includes 11 families, 25 genera, and 28 species. The leading families in terms of species richness and ecological significance are Poaceae, Fabaceae, and Asteraceae.

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ARTICLE 6

Characteristics of Forest Phytocoenoses Established by the Biogroup Method in the Eastern Zangezur Region

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ABSTRACT

Forest stand density and spatial distribution are fundamental determinants of ecosystem structure and productivity; however, their dynamics in artificially established biogroup plantations in the South Caucasus remain insufficiently studied. This study investigates the structural characteristics of forest phytocoenoses established using the biogroup method in the Zangilan district of the Eastern Zangezur region during the 2024–2025 field research period. Three sample plots (each 1 ha) were established, and the forest phytocoenosis was examined based on biometric indicators of trees in central rows, trees in edge rows, and ground vegetation cover. The number of biogroups per hectare ranged from 210 to 240, with maximum stand density (up to 5,000 plants/ha) recorded in 13–15-year-old stands. In the central parts of the biogroups, 25-year-old trees had a mean stem diameter of 8.7 cm and a mean height of 7.9 m. Tree mortality was most intensive during the first decade of growth. Maximum standard deviation for diameter was recorded in 25-year-old stands ($\delta = 2.9$ cm); minimum deviation was observed in 5-year-old biogroups ($\delta = 1.0$ cm). Coefficients of variation for diameter (41–43%) exceeded those for height (30–33%), indicating greater variability in radial than in vertical growth. These findings confirm that intra-specific competition is most intense in younger biogroups and provide a scientific basis for optimising stand density in sustainable forest management of the Eastern Zangezur region.

Keywords: *Eastern Zangezur; forest phytocoenosis; biogroup method; stand density; biometric indicators; intra-specific competition; Azerbaijan*

1. INTRODUCTION

Existing forest plant communities are of particular importance as sources of genetic resources ensuring natural forest regeneration. Due to the relatively limited area occupied by forest phytocoenoses, they create additional ecological niches for populations and therefore possess high biocenotic significance (Kurbanov, 2024). In this context, the research materials have been evaluated not only from an economic

perspective (as a source of timber), but also from an ecological standpoint, considering forest-protective functions, reforestation potential, food value, aesthetic importance, and other ecosystem services (Labokha, 2018; Ibrahimov, 2005).

Landscape is understood as a complex of relief elements, forest stands, shrubs, meadows, rivers, lakes, and other natural components that, in various spatial compositions and

density gradients, create scenery with definite aesthetic value. It represents a complex system in which the physical and biological characteristics of a territory interact dynamically. Forest landscapes, as structural elements of broader ecosystems, reflect both ecological processes and anthropogenic influences (Dzhandzhugakova, 2017; Snytko, 2018).

Forest ecosystems have significant sanitary, hygienic, social, and ecological importance. One of the most essential hygienic properties of green areas is their capacity to create a favorable microclimate by regulating temperature, humidity, and solar radiation. Forest stands mitigate extreme thermal effects, reduce wind velocity, and stabilize local climatic conditions, which is particularly important under current climate change scenarios (Zheldak et al., 2023).

The protective role of forests against dust, gases, wind, and noise is well documented. Forest phytocoenoses serve as natural filters: when polluted air masses encounter forest stands, airflow velocity decreases, causing suspended particles to settle under gravitational force. Dust particles accumulate on the morphological organs of trees and shrubs, especially leaves, significantly reducing airborne particulate concentration. In general, the amount of dust within forested areas is 2–3 times lower than in adjacent open areas (Ibrahimov, 2005; Mammadov et al., 2017).

It should also be noted that the dust-retention capacity of forests depends on the characteristics of the understory layer. Researchers emphasize that the absence of a well-developed herbaceous cover significantly reduces dust deposition efficiency within forest stands (Ibrahimov, 2005). Thus, the structural complexity of forest ecosystems—including canopy, shrub, and herb layers—directly influences their ecological and sanitary effectiveness.

Beyond sanitary functions, forests play a crucial role in biodiversity conservation and the maintenance of native plant communities. Studies on vegetation structure and phytosociology highlight the importance of preserving natural forest remnants as reservoirs of floristic diversity and genetic variability (Theurillat et al., 2021; Lazzaro et al., 2020). Forest ecosystems

also contribute to the stability of soils, prevention of erosion, and conservation of rare and endangered tree species (Mammadov, Iskender & Talibov, 2016; Fedorkov, 2024).

Therefore, the comprehensive ecological assessment of forest phytocoenoses—considering sanitary-hygienic conditions, soil integrity, plant resistance, and landscape aesthetics—provides a scientific basis for sustainable forest management and long-term ecosystem resilience (Cheshko, 2024; Kovtunov, 1962).

2. MATERIALS AND METHODS

In carrying out the research, both classical and modern methods of forest ecological assessment were applied (Labokha, 2018; Cheshko, 2024). The methodological approach was based on forest inventory principles, phytocoenological analysis, and landscape-ecological evaluation (Kovtunov, 1962; Shevelina et al., 2016).

Assessment of Recreational Digression of Forests

The stages of recreational digression of forests were determined according to established forestry and landscape assessment approaches (Kovtunov, 1962; Labokha, 2018):

Stage I – No observable changes in the forest environment (forest landscapes are intact, no trails or trampled areas). The understory vegetation and soil cover remain undisturbed. Tree trunks exhibit healthy growth and development indicators. No regulatory measures are required from a recreational perspective.

Stage II – Minor changes in the forest environment (slightly disturbed forest landscapes; trails and trampled areas occupy up to 5–7%). Understory vegetation and natural regeneration are relatively evenly distributed. Damaged or dried trees constitute 5–20% of the total tree number. Trees affected by diseases or pests do not exceed 20%. Certain management measures are required for recreational use.

Stage III – Moderate changes in the forest environment (moderately disturbed landscapes; trails and trampled areas account for 11–30%). Understory vegetation and shrubs are moderately dense and distributed in patches. Tree mortality ranges from 20–50%. Significant

management interventions are required for recreational purposes.

Stage IV – Significant changes in the forest phytocoenosis (heavily disturbed landscapes; trails and trampled areas exceed 35%). Between 50–70% of trees are diseased or dead. Understory vegetation is sparse, patchy, or absent. Serious restoration measures are required for recreational suitability.

Stage V – Severe degradation of the forest phytocoenosis (extensive disturbance; trails and trampled areas exceed 51%). Understory vegetation and regeneration are absent. Forest stands are sparse, and more than 70% of trees are diseased or dead. The area is considered unsuitable for recreational use.

Aesthetic Evaluation of Tree and Shrub Species

A three-point scale was used for the aesthetic evaluation of trees and shrubs (Dzhandzhugakova, 2017):

- Class I – High decorative value;
- Class II – Moderate decorative value;
- Class III – No decorative value.

Selection and Description of Sample Plots

Further work consisted of selecting representative sites (sample plots) for detailed analysis of typical phytocoenoses. To assess variability in species characteristics, at least four plots were selected for each forest type. Field studies were conducted in different parts of the research region, including Zangilan, Gubadli, and Lachin districts. In each district, four sample plots were established.

The size of each experimental plot was 500 m². Whenever possible, plots were square-shaped; however, in some cases, rectangular plots were used depending on site conditions. During plot selection, attention was given to ensuring that the site was sufficiently representative of the target forest type and that the taxa present were systematically comparable (Labokha, 2018).

Field Survey and Inventory Methods

The description of each experimental plot was carried out using the route (transect) survey method, covering all vegetation layers—primarily trees and shrubs—as well as other components of the forest biogeocoenosis (Snytko,

2018). Natural regeneration (seedlings and saplings) in the understory was recorded in each plot.

Tree stem density was characterized by the number of stems per unit area. The following density classification scale was applied (Labokha, 2018):

- Very dense – more than 1000 stems/ha;
- Dense – 1000–400 stems/ha;
- Medium density – 400–150 stems/ha;
- Low density – 150–60 stems/ha;
- Sparse (open woodland) – 60–15 stems/ha.

Architectural and Landscape Characteristics

The architectural and landscape characteristics of tree stands were determined according to established forestry assessment criteria (Shevelina et al., 2016):

The landscape type was determined according to the Kovtunov method (Kovtunov, 1962), which integrates stand structure, spatial composition, and functional characteristics in forest landscape classification.

3. RESULTS AND DISCUSSION

During the 2024–2025 field research period, experimental plots were established within the forest area of the Zangilan district. The forest phytocoenosis of the selected sites was studied based on several structural indicators: trees located in the central rows of biogroups, trees located in the edge rows, and ground vegetation cover.

The age range of plants within the experimental forest phytocoenoses varied between 5 and 49 years. Three sample plots were established for 5-year and 25-year biogroups, as the period between these age limits plays a significant role in the further development and structural differentiation of forest phytocoenoses. A biogroup is defined as a group of plants of different ages forming a localized structural unit within a forest stand.

It is well known that one of the most important characteristics of forest vegetation is stand density and spatial distribution. The issue of density in forest plantations remains one of the fundamental and debated topics in silviculture and forest biology (Saxnov et al., 2023).

In the studied sample plots, the maximum

number of biogroups per hectare reached 230 units. The maximum density of plants was determined as 5000 seedlings per hectare. The number of biogroups ranged from 210 to 240 per hectare. The highest density was observed

in stands aged 13–15 years (5000 plants per hectare). The maximum size of each sample plot was 1 hectare.

Table 1. Characteristics of Sample Plots

Plot No.	Area (ha)	Number of Biogroups per ha	Density (plants/ha)	Bonitet Class	Age (years)
1	1	230	4500	III–IV	10–15
2	1	210	5000	III–IV	6–20
3	1	240	4200	III	10–49

Analysis of age-related changes (5–49 years) allows determination of the characteristics of biogroup formation and development dynamics.

The average biometric indicators of trees located in the central rows of biogroups are presented in Table 2.

Biometric Indicators of Trees in the Central Rows.

Table 2. Main Indicators of Trees in the Central Rows of Biogroups

Plot No.	Average Diameter (cm)	Average Height (m)	Number of Trees	Forest Site Type (C3)	Age (years)
1	2.3	1.7	43	C3	5
2	6.4	6.3	31	C3	15
3	8.7	7.9	33	C3	25

In the central parts of the biogroups, 25-year-old trees had an average stem diameter of 8.7 cm and an average height of 7.9 m. Tree mortality was more intensively observed during the first decade of growth.

The statistical indicators of trees in the central rows are shown in Table 3.

Table 3. Mean Statistical Indicators of Trees in the Central Rows

Plot No.	Average Diameter (cm) ± SE	Standard Deviation (δ)	Average Height (m) ± SE	Standard Deviation (δ)
1	2.3 ± 0.2	1.0	1.7 ± 0.1	0.4
2	6.4 ± 0.7	2.1	6.3 ± 0.5	2.0
3	8.7 ± 0.5	2.9	7.9 ± 0.4	2.3

From Table 3, it is evident that the maximum standard deviation for diameter was recorded in 25-year-old plants. The minimum deviation in diameter was observed in 5-year-old biogroups (Plot 1). For height, the greatest deviation was also recorded in 25-year-old plants, while the

smallest was observed in 5-year-old trees.

To evaluate competition mechanisms and measurement reliability, the coefficient of variation (CV) was calculated (Table 4).

Table 4. Coefficient of Variation of Average Biometric Indicators (Central Rows)

Plot No.	Diameter CV (%)	Precision Coefficient (%)	Height CV (%)	Precision Coefficient (%)
1	41	5	32	5
2	43	6	31	6.5
3	42	4.5	30	5.0

According to statistical standards, a coefficient of variation above 20% is considered significant. In the studied plots, CV values indicate considerable variability within biogroups. However, precision coefficients did not exceed 6.5%, confirming the reliability of the experimental data.

The highest CV for diameter was recorded in 15-year-old Georgian oak stands, while the

minimum was observed in 25-year-old stands. Variation in height was generally lower than variation in diameter, indicating that height growth is more stable compared to radial growth.

Biometric Indicators of Trees in the Edge Rows

The main parameters of trees located in the edge rows of biogroups are presented in Table 5.

Table 5. Main Parameters of Trees in the Edge Rows

Plot No.	Average Diameter (cm)	Average Height (m)	Number of Trees	Forest Site Type (C3)	Age (years)
1	2.1	1.8	57	C3	5
2	6.7	7.2	33	C3	15
3	8.1	8.6	31	C3	25

In the edge rows, 25-year-old trees had an average diameter of 8.1 cm and an average height of 8.6 m. The highest number of trees was recorded in the youngest plot (Plot 1), confirming that natural thinning processes reduce

tree number over time.

The statistical indicators of edge-row trees are shown in Table 6.

Table 6. Mean Statistical Indicators of Trees in the Edge Rows

Plot No.	Diameter (cm) ± SE	Standard Deviation (δ)	Height (m) ± SE	Standard Deviation (δ)
1	2.1 ± 0.06	0.8	1.8 ± 0.06	0.5
2	7.2 ± 0.5	2.3	6.2 ± 0.52	2.3
3	8.6 ± 0.7	3.1	7.5 ± 0.6	3.2

Maximum standard deviation values for both diameter and height were recorded in 25-year-old stands, while minimum values were observed in 5-year-old trees.

The coefficients of variation for edge rows are presented in Table 7.

Table 7. Coefficient of Variation of Average Biometric Indicators (Edge Rows)

Plot No.	Diameter CV (%)	Precision Coefficient (%)	Height CV (%)	Precision Coefficient (%)
1	40	5.5	33	5.0
2	43	6.0	32	6.0
3	42	4.6	31	4.5

Comparison of Tables 4 and 7 shows that variation coefficients for diameter and height in

central and edge rows are within similar ranges. In stands younger than 15 years, variation in diameter was greater than variation in height. With increasing age, variability decreases and remains within acceptable forestry standards.

The results demonstrate that intra-specific competition is more intensive in younger biogroups. As stands mature, structural differentiation stabilizes and competition intensity decreases. Central rows showed slightly more stable variation coefficients compared to edge rows.

4. CONCLUSION

The 2024–2025 field studies conducted in the forests of the Zangilan district revealed clear age-related patterns in the structure and development of forest phytocoenoses. The number of biogroups ranged from 210 to 240 per hectare, with maximum density (up to 5000 plants/ha) observed in 13–15-year-old stands,

indicating intensive growth and competition at early stages.

Biometric analysis showed that both diameter and height increase with age; however, diameter exhibited greater variability than height. The highest coefficients of variation were recorded in younger (up to 15 years) biogroups, confirming stronger intra-specific competition during early development. With increasing age, variability decreases and stand structure becomes more stable. Comparison of central and edge rows demonstrated similar patterns of variation, although central rows showed slightly more stable indicators. Overall, younger stands are characterized by higher competition intensity and structural differentiation, while older stands display greater growth stability. These findings provide a scientific basis for optimizing stand density and improving sustainable forest management practices in the region.

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ARTICLE 7

Morphological and Productivity Trait Analysis of Soybean Genotypes

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ABSTRACT

This study provides a morphological and productivity analysis of 20 soybean (*Glycine max* L. Merr.) genotypes maintained in the Azerbaijani Genetic Resources collection (AZGR), with emphasis on the relationships between plant development characteristics and yield components. The 20 genotypes originated from Azerbaijan, Uzbekistan, Turkey, Canada, and Australia and were evaluated at the Saray Support Point, Institute of Genetic Resources, during 2024–2025. A hierarchical cluster analysis was performed using PAST v4.16 software (Hammer et al., 2001) based on predetermined morphological and yield-related criteria. Three distinct genetic clusters were identified. Cluster I (9 genotypes, including Kanata and Gen-8) was distinguished by the longest pod length and highest pod number per plant. Cluster II comprised predominantly Uzbek genotypes, further divided into two sub-clusters. Cluster III included genotypes with intermediate morphological profiles most similar to the Australian (Anjelica) and Kyota accessions in productivity metrics. The results demonstrate that genotype origin and genetic background significantly influence key yield components and provide a practical basis for targeted selection in soybean breeding programmes aimed at improving productivity under Azerbaijani agro-ecological conditions.

Keywords: soybean; *Glycine max* L. Merr.; genotype; yield components; pod length; cluster analysis; genetic resources; Azerbaijan

1. INTRODUCTION

One of the most significant crops in world agriculture, soybeans (*Glycine max* L. Merr.) are rich in protein and oil. It is extensively cultivated for its high nutritional value, valuable oils and fatty acids, animal feed high in protein, and a variety of culinary items. By dry weight, the soybean seeds contain around 36–40% protein, 18–20% oil, and 30–35% carbs. Numerous biotic and abiotic stressors have an impact on plants as they grow and develop [Alizada et al., 2024; Alizade, 2024]. As global warming increases, drought has emerged as one of the most important stressors limiting output. Soybean yields are significantly reduced by drought stress; under mild conditions, this drop might reach 40% [Amjid & Üstün, 2025]. Africa generated 1% of the

world's (350 million metric tons) production in 2019, with one-third coming from West Africa. Problems including poor seed germination, low soil nutrients, high input costs, poor agronomic techniques, insufficient rainfall, and a lack of mechanical operations in production (including harvesting) are all blamed for the low yield [Alizada & Aliyeva, 2024; Tabdeen, 2025]. With 33.3 million hectares of soybean agriculture, the USA comes in second with 113.27 million tons of seeds and 3.4 t per hectare, respectively. Next are Argentina (48.10 million metric tons), Paraguay (48.10 million metric tons), China (20.84 million metric tons), India (11.88 million metric tons), Canada (6.98 million metric tons), and Russia (6.8 million metric tons). Together, Brazil, the United States, Argentina, and Paraguay

produce 91.7% of the world's soybeans [Rashid, 2025]. Consequently, some of the most important elements influencing soybean production are included due to the high level of soybean crop cultivation worldwide, with the soil biota—which includes rhizobia and mycorrhizal fungi—playing a significant influence. Since soybeans are one of the most important crops in the world, more research is being done to understand how they are produced under different conditions, including stress. It is possible to improve soybean production and reduce factors like stressors that negatively affect soybean yield by using data on the rate of soybean production worldwide. Soil microorganisms have a major influence on soybean productivity. Thus, it is imperative that more research be done with an emphasis on sustainability and raising agricultural output. Mutualistic connections such as those involving fungi may be very beneficial for soybean growth. The application of beneficial rhizospheric microorganisms as biofertilizers in agriculture is growing, and further study is needed to understand how various inocula impact soybean physiology and growth [Hamza, 2024]. Due to its high protein and oil content, soybeans (*Glycine max* L. Merr.) an East Asian legume crop, are currently farmed all over the world. Soybeans are properly referred to as the “Golden gift of nature to mankind” due to their many uses. With a yield of 2.76 tons per hectare and a total production of 334.89 million tons, soybeans are grown on an average of 121.53

million hectares worldwide. The importance of soybeans as a staple crop that significantly contributes to addressing the nutritional needs of populations globally is highlighted by its widespread production and high yield. Soybeans are a valuable resource for agriculture and nutrition due to their economic significance and adaptability as a food and industrial crop. Soybeans are a major food crop and a major source of protein and oil worldwide [Bayramli & Akparov, 2025].

2. MATERIALS AND METHODS

The research was conducted at the Saray Support Point Institute of Genetic Resources of the Ministry of Science and Education of Azerbaijan during 2024 and 2025. A total of 20 varieties, namely Kanata, CHU-11, Ген-8, БК-98, Kyota, Л-1, Л-12, Krasnodar-68, Л-3, Alexa, CHU-10, Л-4, Л-7, Л-9, Opus, CHU-14, Л-8, Anjelica, Л-2, and Кол-6, were utilized as the material for the study. Twenty genotypes grown in five replications made up the experimental material. Twenty samples were planted in each of the three regions. Patches were spaced one meter apart, rows were 0.6 meters apart, and rows were 10 meters long. As a result, 100 samples in all were collected. These genotypes were also utilized in our earlier investigation of the storage globulin proteins employing polyacrylamide gel electrophoresis (A-PAGE) [Bayramli, 2024].

Table 1. Comprehensive catalogue of forty soybean (*Glycine max* L. Merr.) genotypes utilized in AZGR experimentation: Nomenclature and provenance

Genotypes		AZGR name	Origin
1	Kanata	13566	Canada
2	CHU-11	13898	Türkiye
3	Ген-8		Uzbekistan
4	БК-98		Uzbekistan
5	Kyota	13565	
6	Л-1		Uzbekistan
7	Л-12		Uzbekistan
8	Krasnodar-68	13902	
9	Л-3		Uzbekistan
10	Alexa	13241	Australia

Genotypes		AZGR name	Origin
11	CHU-10	13897	Turkiye
12	Л-4		Uzbekistan
13	Л-7		Uzbekistan
14	Л-9		Uzbekistan
15	Opus	13568	
16	CHU-14	13901	Turkiye
17	Л-8		Uzbekistan
18	Anjelica	13214	Australia
19	Л-2		Uzbekistan
20	Кол-6		Uzbekistan

This large dataset, which included 20 treatments, was analyzed using cluster analysis to arrange them into comparable cluster groups. Cluster analysis was used to categorize the data according to measurable attributes that show similar or equal values. The cluster analysis full linkage approach was used in this investigation. The farthest-neighbor distance—that is, the separation between the two most distant inter-cluster observations or units—is used in this approach to calculate the distance between two clusters. Compact clusters are typically produced by this method, which permits comparatively comparable observations to stay in distinct clusters until the analysis is finished. The National Genbank (AZGR), which is run by the Ministry of Science and Education of the Republic of Azerbaijan's Institute of Genetic Resources, provided the types used as research material.

3. RESULTS AND DISCUSSION

Multivariate statistical analysis was used to assess the productivity and physical characteristics of the soybean genotypes under study in order to ascertain the degree of genotype similarity and divergence. The dendrogram was created using PAST v4.16 software based on specified morphological and yield-related criteria, and a hierarchical cluster analysis was carried out. Among all the genotypes, the Gen-8 and Kanata variety was distinguished by having the highest pod length and a unique genetic profile.

Three separate clusters were formed from the genotypes based on the dendrogram. It was discovered that the majority of the genotypes

in Cluster I were Turkish. Two subclusters were created from Cluster II. In the first and second subcluster six genotypes were Uzbek. It's interesting to note that, despite being separately assigned to Cluster III subcluster, the Uzbek L-9 genotype was more similar to the Angenica and Kyota in terms of production metrics. In the meanwhile, Cluster II contained the remaining Uzbek genotypes (**Fig 1**).

4. CONCLUSION

In summary, this study shows that plant growth stage and levels have a major impact on soybean productive factors. According to the findings, cluster Cluster I had the longest pod. Additionally, genotypes in Cluster I showed a large quantity of pods per plant, according to the study. The study's conclusions have significant ramifications for soybean breeding initiatives. The findings imply that in order to increase the productive components of soybeans, breeding programs should take plant growth regulators and levels into account. The study also emphasizes how crucial it is to use a mix of plant growth regulators and dosages to get the best outcomes. Overall, this study offers insightful information on how plant growth stage and levels affect soybean productive factors. The findings of this study can be utilized to increase soybean crop yield and create more successful breeding techniques.

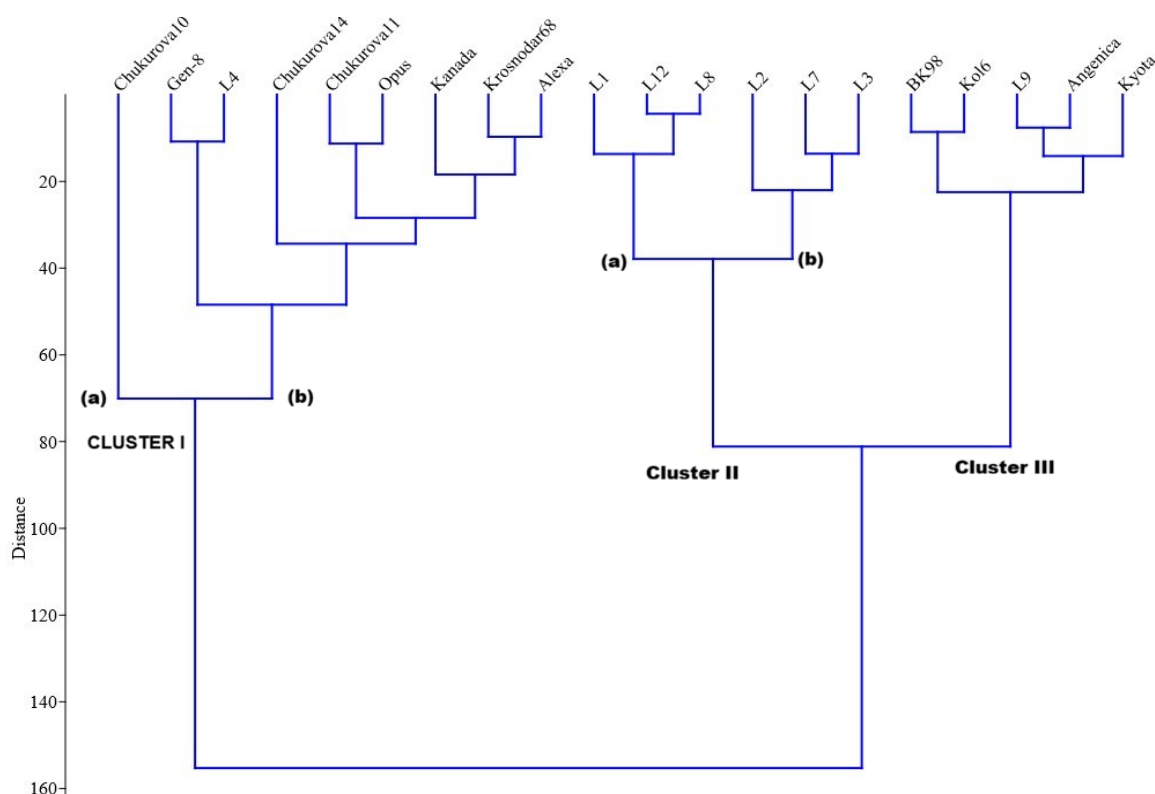


Figure 1. Analysis of the Dendrogram Using PAST v4.16 software for Clustering Soybean Samples Genetic variations across genotypes were plainly visible based on the dendrogram that was produced as a consequence of the study. It became clear at this point that several imported genotypes of soybeans were genetically distinct from one another. The genotypes were grouped into three distinct groups based on the dendrogram. It was discovered that while cluster 2 was split into two subclusters, all of the genotypes detected in cluster 1 were imported from other nations. Nine genotypes were found in Cluster 1, which was also split into two subclusters: Chukurova 10, Gen-8, L 4, Chukurova 14, Chukurova 11, Opus, Kanata, Krosnadar 68, and Alexa.

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ARTICLE 8

Synthesis and Characterization of Medicinal Silver Nanoparticles from *Melissa officinalis* Plant Extract

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ABSTRACT

Silver nanoparticles (AgNPs) were synthesised using aqueous extracts and homogenates of *Melissa officinalis* L. (Lamiaceae), a medicinally important plant species distributed across all regions of Azerbaijan. This study contributes to botanical pharmacology by characterising the phytochemical mediators in *M. officinalis* responsible for nanoparticle biosynthesis, with direct relevance to plant secondary metabolite research. The effects of infusion time, extract concentration, and stabilisation time on the size, shape, and morphology of the synthesised AgNPs were examined. UV-Vis spectroscopy confirmed AgNP formation through a surface plasmon resonance band in the 300–450 nm range. Scanning electron microscopy (SEM) revealed predominantly spherical AgNPs from aqueous extracts, with a size range of 9.5–80 nm; homogenate-derived particles were rod-shaped (15–45 nm). X-ray diffraction (XRD) analysis confirmed the crystalline nature of AgNPs, with an XRD-calculated mean crystallite size of 14 nm — this measure reflects the coherent scattering domain size, which is distinct from the physical particle size range observed by SEM. Fourier transform infrared spectroscopy (FTIR) identified the hydroxyl (OH) and carbonyl (CO) functional groups of the *M. officinalis* extract as the principal reducing and stabilising agents. The green synthesis route is rapid, low-cost, and environmentally friendly, suggesting strong potential for biomedical applications of these botanically derived nanoparticles.

Keywords: green synthesis; silver nanoparticles; *Melissa officinalis*; aqueous extract; phytochemistry; FTIR; XRD; SEM; antimicrobial; Azerbaijan

1. INTRODUCTION

Many efficient and functional technologies have been proposed for the synthesis of AgNPs from extracts obtained from the leaves of *Melissa officinalis*. These technologies are simple, economically efficient and environmentally friendly. Based on the results observed with UV-vis, Fluorescence, FT-IR spectroscopy, SEM and TEM microscopy, it can be confirmed that organic compounds such as metabolites and phenols present in *Melissa officinalis* play an important role in the reduction of Ag⁺ ion to Ag⁰. The synthesized silver nanoparticles can

be antibacterial, antibiotic and also medicinal nanoparticles with various effects. AgNPs have become a fundamental research area due to their wide range of applications in many fields such as physics, chemistry, materials science, optoelectronics, renewable energies, environmental remediation, medical practice, and biomedical devices (Jamil et al., 2015). AgNPs exhibit high chemical stability, catalytic and antibacterial activity (Hinojos-Márquez et al., 2016) and can play an important role in the preparation of new types of drug preparations that reflect the pharmacological effects of medicinal

plants. Many methods for the preparation of Ag-NPs using silver nitrate salt, synthesis in organic solvents, reduction such as thermal decomposition in microemulsions, reduction with the help of ultrasound and microwaves, and photo and electrochemical reduction methods have been proposed (Ahmed et al., 2016). However, many chemical methods are expensive and potentially environmentally hazardous due to the use of toxic chemical reagents that pose various biological risks (Palanisamy et al., 2017). Therefore, the development of green synthesis of silver nanoparticles from plant extracts, including extracts of medicinal plants, can be considered one of the main challenges of nanotechnology (Ravichandran et al., 2016). In recent years the synthesis of silver nanoparticles was conducted in extracts of plants such as *Peumus boldus*, *Eclipta prostrata*, *Nelumbo nucifera*, *Acalypha indica*, *Allium sativum*, *Aloe vera* (Sekhar et al., 2016), *Jatropha curca* (Bar et al., 2009), *Mentha piperita* (MubarakAli et al., 2011), *Murraya koenigii* (Philip et al., 2011), *Edible mushroom* (Philip, 2009), *Piper longum* (Jakop et al., 2012), *Prosopis farcta* (Miri et al., 2015), *Tea* (Sun et al., 2014), *Tephrosia purpurea* (Ajitha et al., 2014), *Ziziphus jujube* (Cavade et al., 2015), *Mangifera indica* (Philip, 2011), *Malva parviflora* (Zayed et al., 2012), *Hibiscus rosasinensis* (Philip, 2009). In these experiments, the physicochemical characteristics, antibacterial and antifungal properties of the synthesized Ag nanoparticles were studied in detail.

The aim of this research was to investigate the nucleation and growth of silver nanoparticles in relation to surface plasmon optical absorption. In this method, known as green synthesis, a leaf extract of the medicinal plant *Melissa officinalis* was used to facilitate a simple reduction process. The main advantage of the green synthesis method is that it does not involve the use of toxic chemical reagents. Silver nanoparticles produced using this method are environmentally friendly and cost-effective materials. Their potential applications in the future include their use as drug nanoparticles in medical practice

2. MATERIALS AND METHODS

***Melissa officinalis* L. plant.** *Melissa officinalis* L. is a perennial herbaceous plant of the *Lamiaceae* family. This medicinal plant is found in all regions of Azerbaijan, especially in forest, lowland and mountain zones. The composition of *Melissa officinalis* is rich in biologically active substances, and their amount varies depending on the habitat, developmental stage and species diversity. It has been determined that it contains terpenes (monoterpenes, triterpenes and sesquiterpenes), phenolic components (phenolic acid, tannins and flavonoids) (Allahverdiyev et al., 2004; Moradkhani et al., 2010). However, studies have shown that the main components of the plant are volatile compounds (geraniol, neral, citronellal and geraniol), triterpenes (urosylic acid, oleanolic acid) and phenols (cis and trans rhizomers of caffeic acid derivatives, luteolin, naringin, hesperdin) (Argyropoulos and Müller, 2014; Ibragic et al., 2014).

Preparation of an aqueous extract and homogenat from *Melissa officinalis* leaves . In the experiments for the synthesis of AgNPs, both the aqueous extract from dry leaves of the *Melissa officinalis* plant and homogenate from fresh leaves were prepared (Fig.1). Dried leaves of *Melissa officinalis* are produced by “Herba Flora” LLC in the Absheron region of the Republic of Azerbaijan and are freely sold in pharmacies. Fresh leaves of *Melissa officinalis* were collected from plants cultivated in a laboratory Plant Growth Chamber. Firstly, the dried plants were ground into a fine powder. For the preparation of the aqueous extract 100 ml of sterile double distilled water at 80°C temperature was added to 2 g of powdered samples and infused for 10 minutes. The suspension was left for 2 hours and then filtered through Whatman no.1 filter paper. The samples were centrifuged at a high speed (6000 rpm) for 10 minutes and kept at 4°C until further analysis. To prepare the homogenate, a 1 g sample of fresh lemon balm leaves is taken and crushed in a mortar. Then, 50 ml of distilled water at room temperature is added to the obtained leaf suspension. The resulting mixture is centrifuged for 10 minutes and the precipitate is cleaned. The homogenate was stored in a refrigerator at 4°C for further experiments.

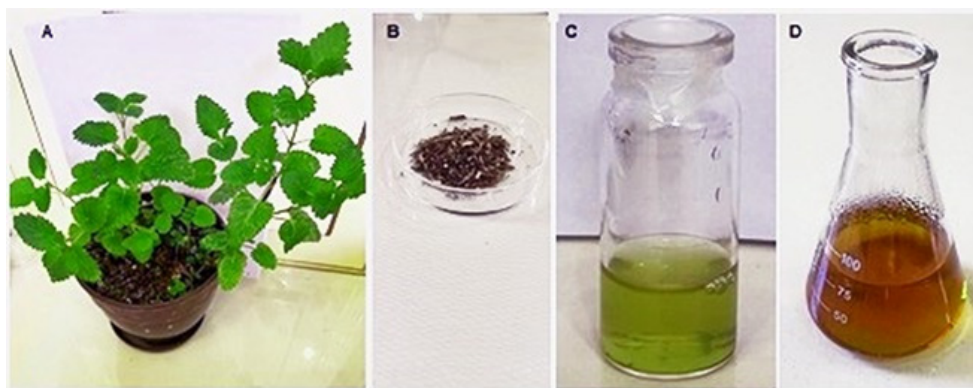


Figure 1. *Melissa officinalis* plant (A), dry leaf material (B), Homogenate (C), Agues extract (D)

Biosynthesis of silver nanoparticles. The biosynthesis of silver nanoparticles using green methods has been extensively studied. The synthesis process varies depending on the biological source, plant organs, used, concentration of silver nitrate salt, amount of extract and homogenate in the synthesis solution temperature and pH. In our experiment, we first prepared a 0.1 M solution of AgNO_3 (silver nitrate) and stored it in an amber-colored bottle. To synthesize Ag nanoparticles, a $5 \cdot 10^{-3}$ M solution was prepared. The solution was heated to 80°C in a thermal magnetic stirrer, and various amounts of extract or homogenate were added drop wise to this solution. Initially, the change in color of the solution indicates the formation of silver nanoparticles. The synthesized solution of Ag nanoparticles was analyzed after being stored at room temperature for 24 hours for standard experiments.

UV-Visible Spectroscopy. The spectral analysis of the *Melissa officinalis* extract and the solution for both the formation and stability of the nanoparticles were monitored using UV-VIS spectrometry. A SPECORD 210 Plus UV-VIS Spectrometer was used in the wavelength range of 250 - 600 nm for silver nanoparticles. UV-vis spectroscopy is a convenient method for identifying of certain classes of compounds in transparent liquids and biological mixtures. Its advantage lies in its ability to be used for quantitative analysis, as aromatic molecules are strong chromophores in the UV range. Therefore, biologically active molecules can be identified using UV-vis spectroscopy based on their absorption spectra. UV-Vis spectroscopy is also utilized to

determine the total phenolic extract (280 nm), flavones (320 nm), phenolic acids (360 nm), and total anthocyanins (520 nm) (Kemp et al., 1991; Urbano et al., 2006).

Scanning Electron Microscopy (SEM). The size and shape of Ag nanoparticles synthesized by *Melissa officinalis* were determined by scanning electron microscopy using high-performance JSM 7600F SEM machine (JEOL, Japan). In the optimal variant for SEM analysis, a drop of the Ag nanoparticles synthesized solution was added to the surface of the microscope slide. Once the solution dried in a vacuum environment on the slide, SEM images of the sample were captured, and the elements present in its composition were identified.

X-Ray Diffraction analysis. X-ray diffraction (XRD) is one of the most widely used techniques for determining the structural properties of nanoparticles. In this method, X-rays penetrate nanomaterials to obtain structural information and the resulting diffraction pattern is compared with standards (Mourdikoudis et al., 2018). The XRD analysis of synthesized AgNPs was conducted using a Rigaku SmartLab equipment, operating at 45kV and 200mA, Cu K α radiation ($1.54059\text{\AA}$), in parallel beam configuration ($2\theta/\theta$ scan mode), from 25 to 90 2θ degrees. The components were identified using the Rigaku Data Analysis Software PDXL 2, with a database provided by ICDD

Fourier Transform Infrared Spectroscopy. FTIR is a method that analyzes the vibrational changes in a molecule when exposed to infrared radiation, resulting in infrared absorption. Essentially, infrared spectroscopy is a form of vibrational spectroscopy that identifies different chemical bonds such as C–C, C=C, C $\equiv$ C, C–O, C=O,

O–H, and N–H) based on their unique vibrational frequencies. If these types of bonds are present in a biologically active molecule, they can be distinguished by the characteristic frequency absorption bands in the infrared spectrum. FTIR is a high-resolution analytical tool that helps for identify chemical constituents and reveal structural relationships. In a study analyzing composition of lemon balm extract FTIR was used to detect organic functional groups (C–C, C=C, C≡C, C–O, C=O, O–H, and N–H) and other chemical residues attached to the surface of Ag nanoparticles. The nanoparticles were examined using a Bruker Tensor 27 FTIR spectrometer (Karlsruhe, Germany) in the range of 500 to 4000 cm^{-1} utilizing the potassium bromide pellet technique on lyophilized samples.

3. RESULTS AND DISCUSSION

UV-Visible Spectroscopy of aqueous extract.

The characteristics, physical properties, and composition of the extract prepared from the leaves of *Melissa officinalis* play an important role in the size, shape, crystallinity, and optimal synthesis of AgNPs. Therefore, the analysis of Melissa extracts prepared in different solvents is important and the control of the synthesis of Ag nanoparticles depends on the results of these analyses. In preliminary experiments, aqueous extracts were prepared from Melissa leaves

using the above-mentioned methodology and samples were taken after incubating for 5, 10, 20, 30, 40 minutes, 1, 2, and 24 hours. UV-vis spectra of the samples were recorded depending on the incubating time. The results of this experiment are shown in Figure 2. It was clear from the results that there was no strict law in the intensity of the absorption spectra depending on the incubating time. The maximum intensity was observed in the extract incubating for 1 hour and decreased after 24 hours. In the UV-vis absorption spectrum, two maximum absorption peaks are observed in the wavelength range of 250 – 400 nm, like shoulders, which corresponds to different phytochemicals. The wavelength of the first of these peaks varies depending on the brewing time around 283 nm, and the second around 321 nm. It is known from the existing scientific literature in this field that the absorption spectral peaks of most flavonoids are in the wavelength range of 240 – 280 and 300 – 400 nm (Ramos et al., 2017; Sankar et al., 2020). The observed range of wavelengths of these absorption bands observed in the aqueous extract of Melissa closely follows the structure of the polyphenol molecule, including the degree of coupling, the number and position of substituents, and the OH groups (Araujo et al., 2013; Masek et al., 2017)

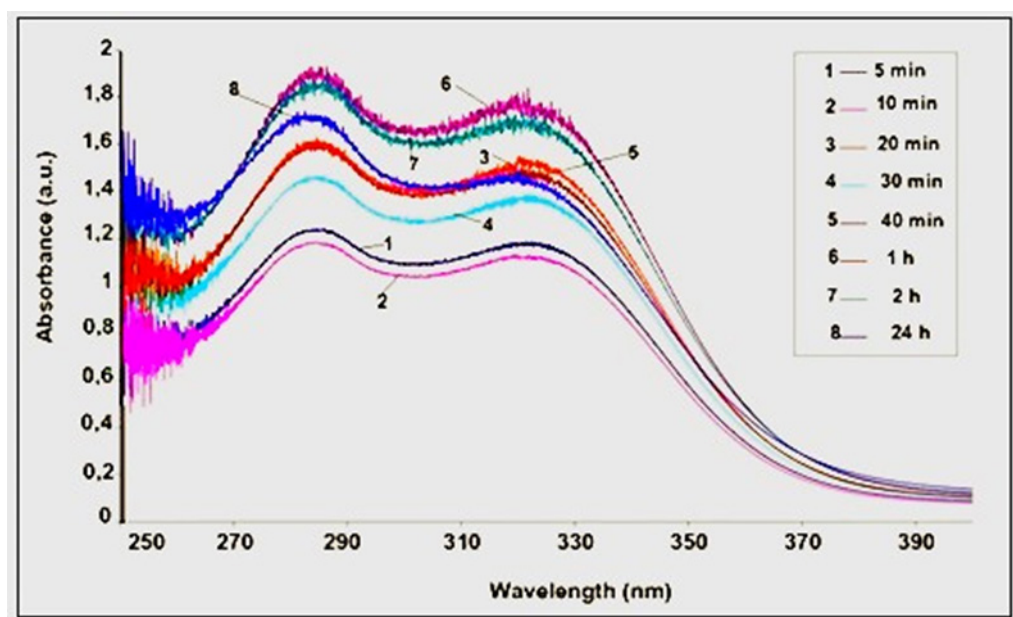


Figure 2. UV-Vis spectra of *Melissa officinalis* extract depending on the infusion time: two maximum absorption peaks (wavelength of bands 283,1 nm and 321,4 nm), like shoulders

Biosynthesis of AgNP. In the green synthesis procedure, the initial indication of the conversion of silver ions into nanoparticles is observed by adding a specific amount of extract at an optimal concentration to a silver solution resulting in a color change. Fresh extract of *Melissa officinalis*, which can vary in color depending on the infusion time, is initially light yellow. When this extract is added dropwise to an AgNO_3 solution at a temperature of 80°C on a magnetic stirrer, the color of the solution changes to pale pink within 5 minutes, light red within 10 minutes and eventually dark brown over the next 30 minutes to 2 hours. This color transformation from yellow to brown-red and dark brown serves as the first sign of nanoparticles formation and is linked to the phenomenon of Plasmon resonance (Solidum et al., 2018). However, physical methods such as UV-Vis spectrophotometry, SEM, TEM, Raman spectroscopy, XRD and FTIR are employed to analyze the synthesis of nanoparticles. These methods help determine the nanoparticles' size, shape, distribution, amount, crystalline as well as the reducing and stabilizing agents.

One of the characteristics of the aqueous extract of *Melissa officinalis* is its infusion time. In our experiment, the optimal infusion time of the extract was determined to be 2 hours.

However, to clarify the role of extracts with different infusion times (5,10,20,30,40 minutes, 1 hour and 2 hours) in controlling the nanoparticles in the synthesis of AgNPs, the synthesis of nanoparticles was carried out based on these times. The results of this experiment are presented in Figure 3. From the UV-vis spectra of the AgNPs synthesized solution, it was evident that the peak value of the absorption spectrum, the intensity of absorption and the particle size distribution do not correlate with the infusion time of the extract. Depending on the infusion time, the peak wavelength is 420.4 nm at 5 minutes, 430.4 nm at 10 minutes, 434 nm at 20 minutes, 428.5 nm at 30 minutes, 433.1 nm at 40 minutes, 435.8 nm at 1 hour, and 436.7 nm at 2 hours. The size of the nanoparticles corresponding to these absorption peak wavelengths falls in the range of 50-60 nm. There is no correlation in the intensity of the absorption spectrum either. The lowest intensity is observed in the extract with an infusion time of 20 minutes, while the highest intensity is observed in the extract with an infusion time of 2 hours. Interestingly, in the extract with an infusion time of 5 minutes, the AgNPs are both relatively smaller in size and their quantity is higher, except for the 2-hour extract.

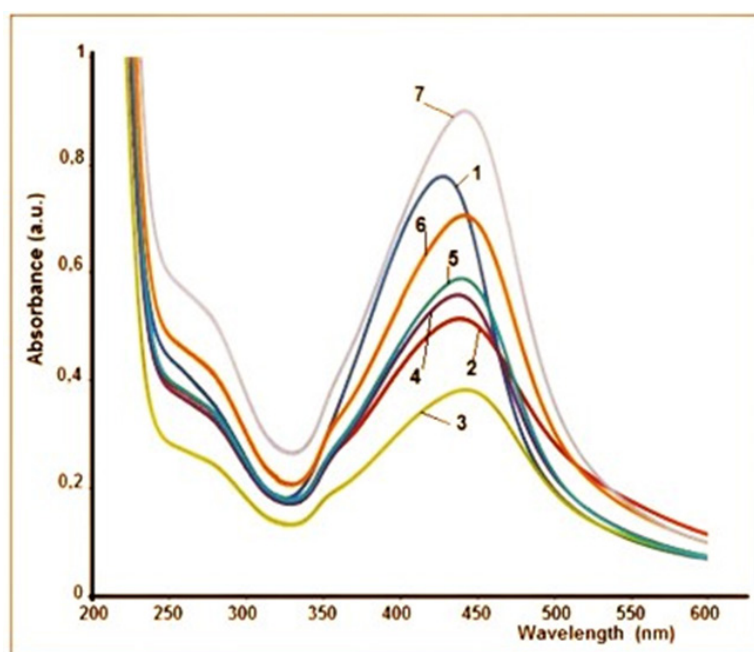


Figure 3. Synthesis of silver nanoparticles in *Melissa* extracts with different retention times: 1-5 min (420.4 nm), 2 -10 min (430.4 nm), 3 -20 min (434 nm), 4 -30 min (428.5 nm), 5 -40 min (433.1 nm), 6 – 60 min (435.8 nm), 7 – 120 min (436.7 nm)

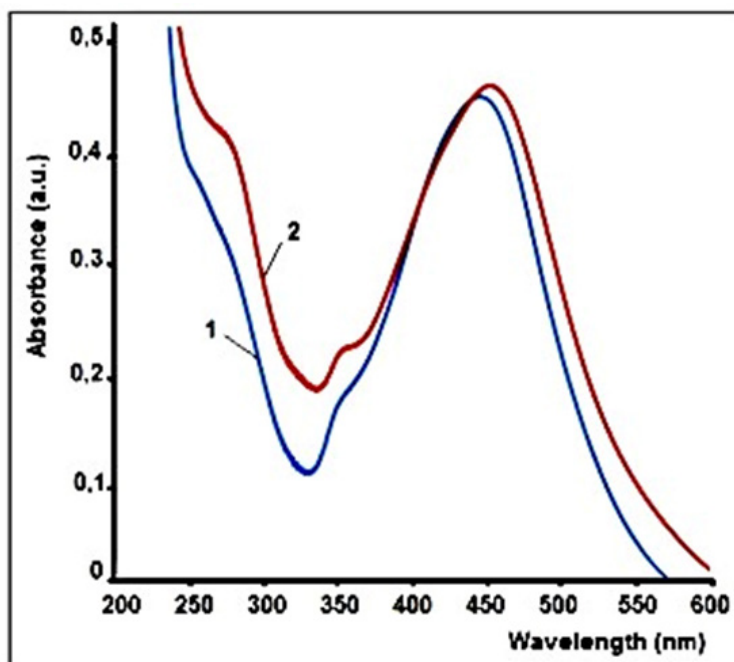


Figure 4. Synthesis of silver nanoparticles in Melissa extracts with infuse time 1-5 min (420.4 nm) and 2 – 120 min (436.7 nm)

Since there was no significant difference in the synthesis of AgNPs in extracts with different infusion times specifically between the 5 – minute and 2-hour infusion times, we decided to repeat the experiment. The results of this

experiment are displayed in Figure 4 which confirms smaller nanoparticles were indeed synthesized in the extract with a 5-minute infusion time compared to the extract with a 2-hour infusion time.

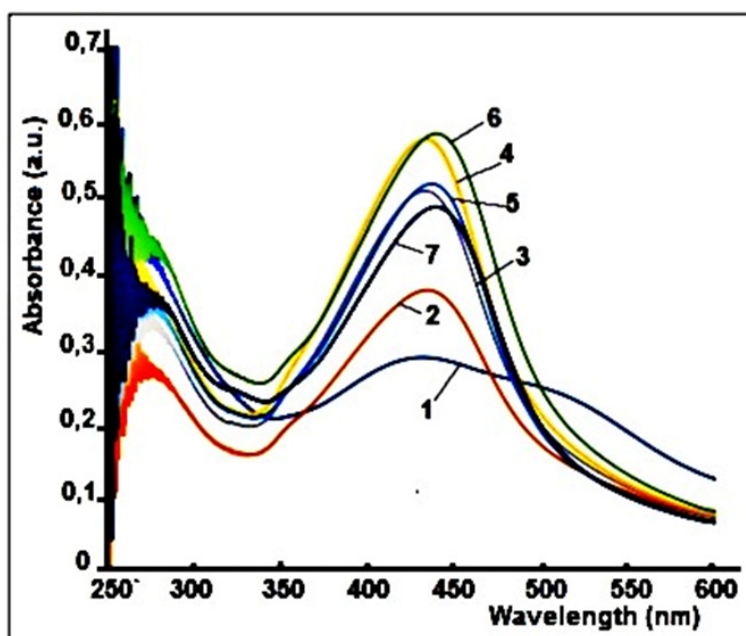


Figure 5. UV-Vis absorption spectra of silver nanoparticles stabilized in *Melissa officinalis* by varying the time from 5 to 120 min: 1 -5 min (427,12 nm), 2 -10 min (427,12 nm), 3 -20 min (425,5 nm), 4 -30 min (426,4 nm), 5 – 40 min (425,5 nm), 6 -1 hour (433,2 nm), 7 – 2 hour (432,3 nm)

In another experiment, the UV-Vis characteristics of the synthesized nanoparticles were examined based on the stabilization time of the standard AgNPs synthesis in Melissa extract. As outlined in the nanoparticle synthesis methodology, 5 ml of extract was added to a $5 \cdot 10^{-3}$ M AgNO_3 solution at 80°C in a magnetic stirrer. Samples were then collected at various time intervals (5, 10, 20, 30, 40 minutes, 1 hour and 2 hours) and UV-Vis spectra were recorded. The results of the experiment are presented in Figure 5. No significant correlation was observed in the peaks of the absorption spectrum, absorption intensity, and size distribution of the nanoparticles based on the duration of their synthesis. A slight shift to the left was noted at the peak wavelengths of the absorption spectrum (427.12 nm, 427.12 nm, 425.5 nm, 426.4 nm and 425.5 nm) for 5, 10, 20, 30 and 40 minutes respectively. However, the absorption intensity increased with time. The absorption intensity reached its maximum during the AgNPs synthesis process for 1 hour (figure 5, spectrum 6), and decreased after 2 hours, (figure 5, spectrum 7). A shift to the right (433.3 nm) was observed in the absorption peaks based on the time. Initially, the sizes of AgNPs ranged from 50-60 nm during the synthesis of nanoparticles and slightly exceeded 60 nm after 1 hour and 2 hours.

In the experiments, silver nanoparticles were synthesized using homogenate obtained from fresh leaves of *Melissa officinalis*. According to the methodology, 1 gram of fresh leaves of *Melissa* was taken and crushed in a mortar and

pestle to prepare the homogenate. Then, 50 ml of distilled water was added to the obtained leaf suspension at room temperature. The resulting mixture was centrifuged for 10 minutes and the precipitate was cleaned. The homogenate was stored in a refrigerator at 4°C for subsequent experiments. In one experiments, silver nanoparticles were synthesized by adding 2.5 ml, 5 ml and 10 ml of homogenate to an AgNO_3 solution with at a temperature of 80°C and a concentration of $5 \cdot 10^{-3}$ M in a magnetic stirrer for 10 minutes and 2 hours. The results of the experiment are shown in Figure 6. The results indicated that as the amount of homogenate increased for 10 minutes, the amount of synthesized nanoparticles increased, and the peak wavelength in the absorption spectrum shifted to the left, indicating smaller size of Ag nanoparticles (Figure 6A). During the 2-hour synthesis process, the amount of Ag nanoparticles formed in excess of homogenate increased and was twice as large as the nanoparticles synthesized in 10 minutes (Figure 6B). In another experiment, the formation of Ag nanoparticles was studied depending on the stabilization time. UV-Vis spectra of Ag nanoparticles synthesized in 5, 10, and 2 hours with 5 ml and 10 ml of homogenate added to the AgNO_3 solution were recorded. It was evident from the spectra that the amount of Ag nanoparticles synthesized within 5 and 10 minutes at both homogenate values was the same. However, during the 2 hour stabilization period the amount of nanoparticles increased sharply and their sizes became smaller (Figure 7 A and B).

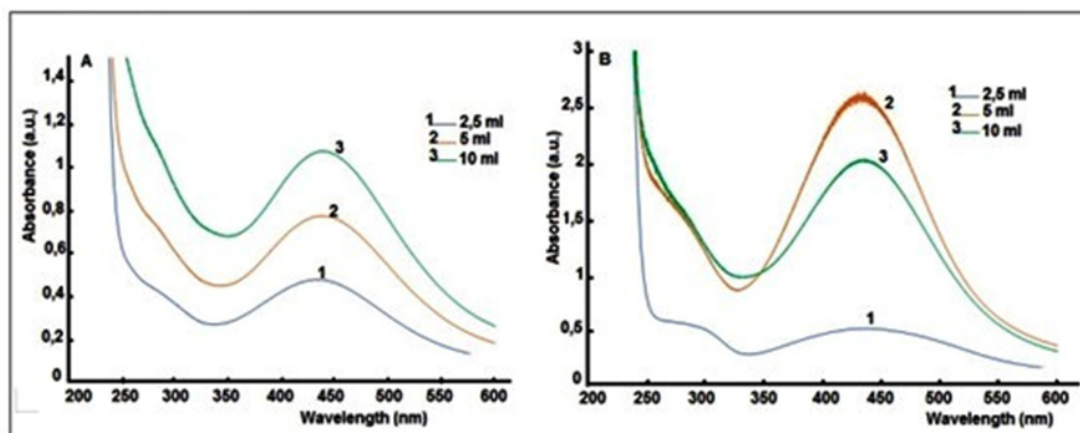


Figure 6. Dependence of the synthesis of silver nanoparticles in the homogenate obtained from the leaves of *Melissa officinalis* on the amount of homogenate: A- synthesis for 10 minutes, B synthesis for 2 hour

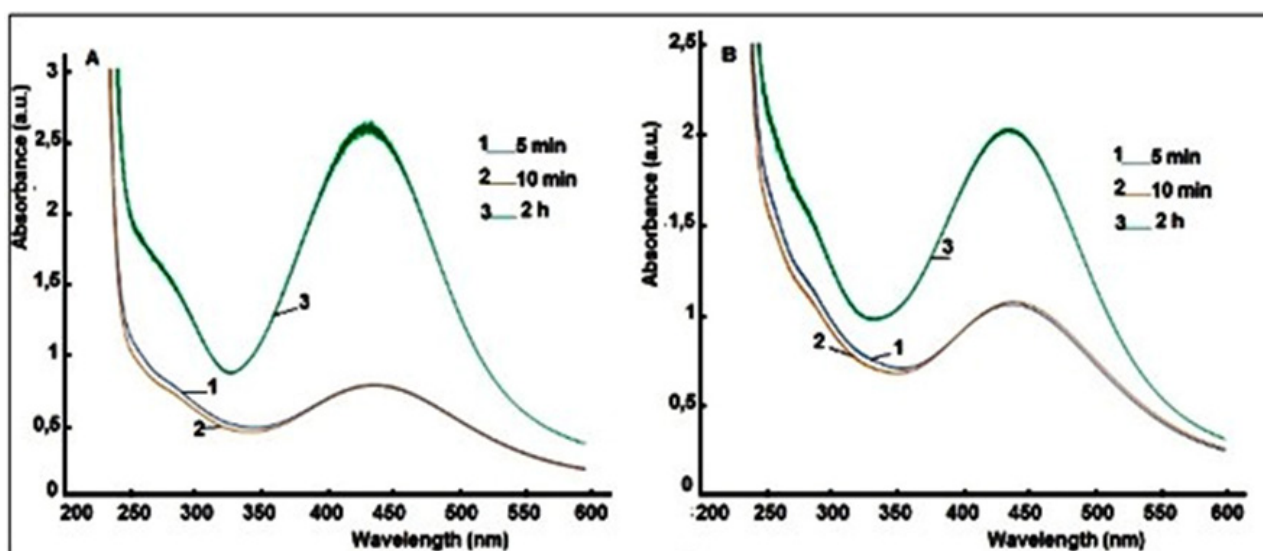


Figure 7. Dependence of the formation of silver nanoparticles in the homogenate obtained from the leaves of *Melissa officinalis* on the synthesis time: A- by adding 5 ml of homogenate, B – by adding 10 ml of homogenate.

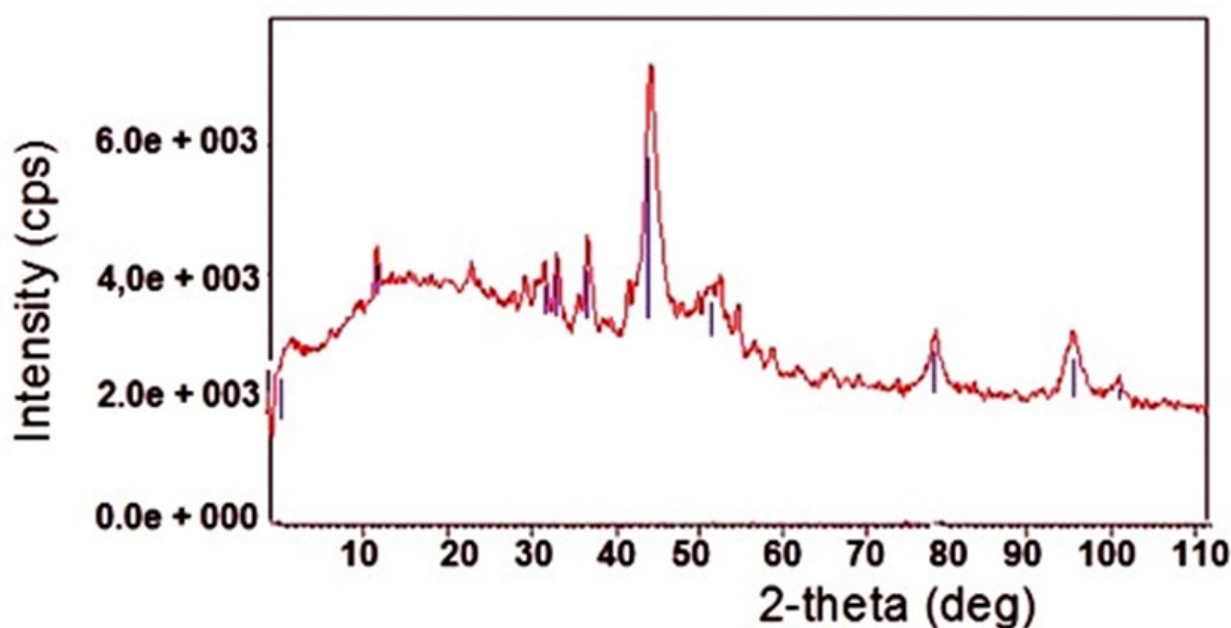


Figure 8. XRD diffractogram of Ag nanoparticles synthesized in the aqueous extract of *Melissa officinalis*

The diffraction (XRD) method was used to characterize the structural properties of the synthesized Ag nanoparticles. Information about the structure of the nanoparticles is obtained from the diffraction spectrum obtained from the penetration of X-rays into the nanomaterials by comparing the peaks obtained with standards (Mital et al., 2013; Mourdikoudis et al., 2018). Figure 8 shows the XRD diffractogram of Ag nanoparticles synthesized in the aqueous

extract of lemon balm. Several sharp intense peaks at 2 theta angles, confirming the crystallinity and formation of AgNPs. 37.9° (111), 45.1° (200), 78.8° (311), were observed. Some of these peaks indicate the presence of bioorganic compounds in the *M. officinalis* leaf extract (Anandalakshmi et al., 2016). Some are related to the reduced and remaining AgNO₃ in the extract ([Prakash et al., 2013).

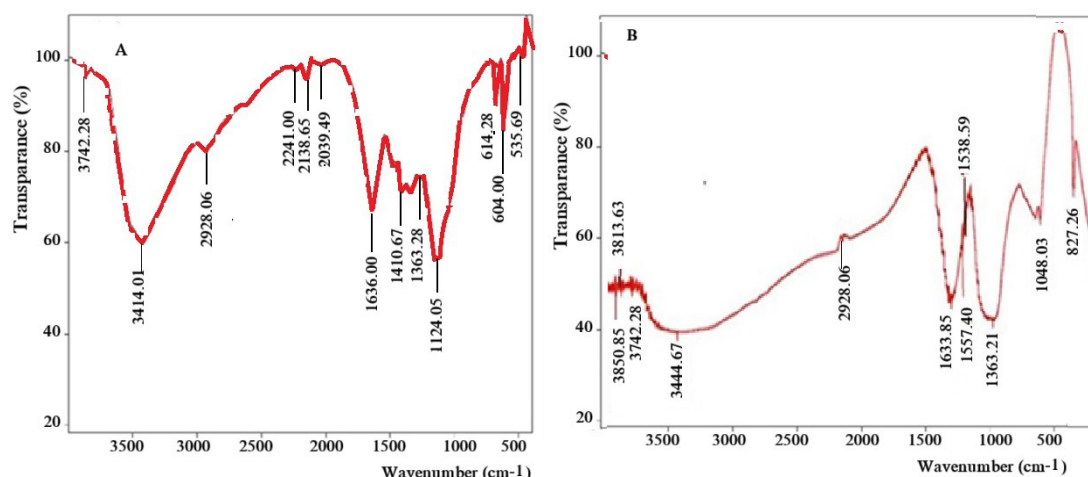


Figure 9. FTIR spectrum of the aqueous extract of *Melissa officinalis* leaves (A) and a solution of Ag nanoparticles synthesized in this extract

Fourier transform infrared (FTIR) spectroscopic analysis. One way to identify the biologically active molecules involved in the formation of silver nanoparticles in the green synthesis process is through FTIR analysis. This method allows us to determine which molecules act as reducing agents, which act as stabilizers, and which molecules are bound to the surface of the synthesized nanoparticles. Therefore, the FTIR spectra of the extract obtained from *M. officinalis* leaves and the crystallized samples of the solution from which Ag nanoparticles were synthesized were analyzed. In the FTIR spectrum of the extract obtained from *M. officinalis* leaves, peaks were observed at wavenumbers 3742.28 cm⁻¹, 3414.01 cm⁻¹, 2928.06 cm⁻¹, 2241.00 cm⁻¹, 2138.65 cm⁻¹, 2039.49 cm⁻¹, 1636.00 cm⁻¹, 1410.67 cm⁻¹, 1363.28 cm⁻¹, 1124.05 cm⁻¹, 614.28 cm⁻¹, 604.00 cm⁻¹, and 535.69 cm⁻¹ (Figure 9A). In the FTIR spectra of Ag nanoparticles synthesized in this extract, peaks were observed at wavenumbers 3850.85 cm⁻¹, 3813.63 cm⁻¹, 3742.28 cm⁻¹, 3444.67 cm⁻¹, 1633.85 cm⁻¹, 1557.40 cm⁻¹, 1538.59 cm⁻¹, 1360.21 cm⁻¹, 1048.03 cm⁻¹, and 827.26 cm⁻¹ (Figure 9B). Upon comparison of the FTIR spectra, it was evident that a shift occurred at the wavenumber 3414.01 cm⁻¹, corresponding to alcohols and phenols. The strong band at 3444.67 cm⁻¹ indicates O-H stretch H bonding (Vanaja et al., 2013). The wavenumber at 1636.00 cm⁻¹ also shifted to 1633.85 cm⁻¹, indicating the C=C group of aromatic compounds (Raghunandan et al., 2010). The peak at 1410.67 shifted to

1557.40, 1124.05 cm⁻¹ shifted to 1048.03 cm⁻¹, and 614.28 cm⁻¹ shifted to 827.26 cm⁻¹. The 1048.03 cm⁻¹ peak corresponds to the bending of alkanes, alcohols, carboxylic acids, and esters in the C-O plane. Finally, the peaks at 627.26 cm⁻¹ may represent the =CH group of aromatic bicyclic monoterpenes (Mamadaliyeva et al., 2017). Flavonoids in *M. officinalis* leaf extract act as strong reducing agents that reduce silver nitrate to form Ag nanoparticles. In addition, proteins can be attached to Ag nanoparticles through their free carboxylate group during the synthesis process and act as both surfactants to stabilize the nanoparticles (Ajitha et al., 2014). The OH and CO functional groups of *M. officinalis* extract play a dual role as reducing and stabilizing agents for Ag nanoparticles (Sre et al., 2015).

SEM Analysis of Ag Nanoparticles. SEM images and elemental analysis results of the sample prepared from a solution containing Ag nanoparticles are presented in Figures 10 and 11. In Figure 10, images from the same areas of the sample were scanned by changing the magnification factor in the microscope. When the sample was magnified 500,000 times, it was evident that the sizes of Ag nanoparticles varied. The distribution of nanoparticles according to their sizes was irregular, ranging from 9.52 nm to 60 nm. The shapes of nanoparticles were predominantly spherical. The varying sizes of nanoparticles can be attributed to the extract being rich in biologically active molecules. To control the size of nanoparticles, it is essential to regulate the

concentration of AgNO_3 salt, the amount of extract added, the temperature, and the pH of the solution. By adjusting these parameters appropriately within the reducing solution, it is possible to obtain Ag nanoparticles of any desired size. Elemental analysis of the solution in which Ag nanoparticles were synthesized was also conducted. In the elemental analysis performed

by SEM, the peak corresponding to the Ag element was more pronounced compared to other elements, indicating a higher concentration of Ag nanoparticles. Thus, it was confirmed that Ag nanoparticles synthesized within the aqueous extract of *M. officinalis* can be produced in a variety of sizes (Figure 11).

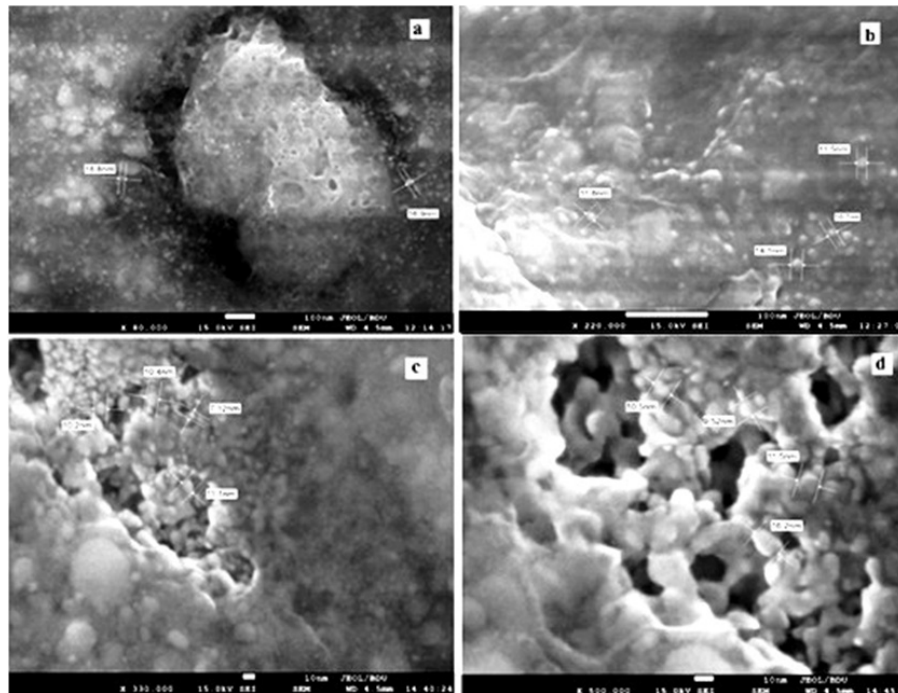


Figure 10. SEM image of Ag nanoparticles synthesized in an extract prepared from the leaves of *Melissa officinalis*.

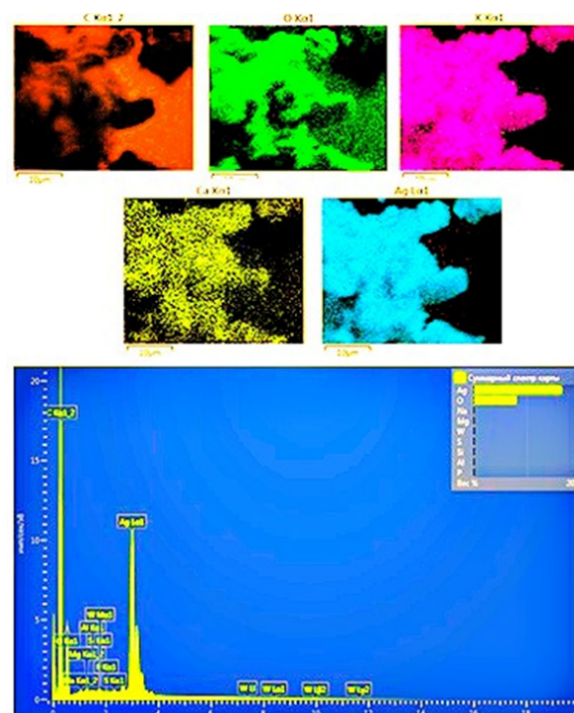


Figure 11. Mapping and histogram showing the results of elemental analysis in a solution containing Ag nanoparticles synthesized in an extract prepared from the leaves of *Melissa officinalis*.

DISCUSSION

The main goal of this research was to develop an optimal version of the technology for obtaining medicinal nanoparticles from extracts of medicinal plants using the green synthesis method. The synthesis of nanoparticles from extracts obtained from various organs of plants (root, stem, fruit, flower, leaf) is an alternative to the synthesis of nanoparticles by physical and chemical methods. This method is considered more promising due to its simplicity, ecological purity, and economic efficiency. Nanoparticles synthesized by this method demonstrate higher biocompatibility for living organisms, including the human body. The medicinal plant *Melissa officinalis*, widely used in folk medicine and containing a high amount of antioxidant polyphenols, especially flavonoids, was chosen as the object of research. The active phytochemicals in the extract of *M. officinalis* not only help convert silver salts into nanoparticles but also act as stabilizers, enveloping nanoparticles and adhering to their surface. As the Ag nanoparticles synthesized in Melissa extracts are likely to have medicinal properties, experiments in this area have become more relevant recently. The results of our experiments showed that the composition of Melissa extract is indeed dominated by flavonoids. UV-vis analysis of the extract proved that its absorption spectrum contains peaks at 283 nm and 321 nm, corresponding to the wavelength ranges of 240-280 nm and 300-400 nm, which are characteristic of flavonoids. Therefore, it can be said with high probability that flavonoids are the main agents involved in the reduction of Ag⁺ ions to neutral Ag⁰ atoms in silver salt. Comparative analysis of the FTIR spectra of *M. officinalis* extract and Ag nanoparticles synthesized in this extract showed that phenolic compounds containing hydroxyl and carboxyl groups play a key role in the synthesis and stabilization of silver nanoparticles. Thus, flavonoids present in *Melissa* extract can bind to the surface of Ag nanoparticles through interaction with OH and CO groups.

The main issue in the application of nanoparticles as drugs is their crystalline nature. Crystalline nanoparticles tend to be more mobile and eliminated by the organism. XRD analysis

was performed to determine the structure of Ag nanoparticles synthesized in the extract obtained from the leaves of the *M. officinalis* plant. Peaks corresponding to the crystal structure in the XRD spectrum confirmed the synthesis of Ag nanoparticles and their crystalline nature. In addition, the peak corresponding to the (111) plane in the XRD spectrum was more intense than the other planes, indicating its dominant orientation. XRD analysis also allows us to calculate the size of the formed nanoparticles. In our experiments, the average size of Ag nanoparticles synthesized with the *M. officinalis* extract was 14 nm. SEM analysis also confirmed the presence of nanoparticles of this size. When taking SEM images, it was observed that the smallest Ag nanoparticles fell in the range of 7.12 nm, and the largest ones fell in the range of 11-16 nm. Therefore, it can be concluded that Ag nanoparticles obtained by optimal synthesis in the aqueous extract obtained from the leaves of the medicinal plant *M. officinalis* can be used as drug carriers in the future.

4. CONCLUSION

The proposed green route for the synthesis of nanoparticles from plant extracts has already been proven to be an efficient and functional methodology. The preparation of nanoparticles by this method is simple, economical, and environmentally friendly. Silver nanoparticles can be synthesized by adding different amounts of plant extracts to the optimal $5 \cdot 10^{-3}$ M concentration solution of AgNO₃ salt and heating it to 70-80°C. The color change of the solution and the observation of different surface plasmon resonance bands around 300 - 450 nm in the UV-Vis spectra confirmed the formation of Ag nanoparticles. It was found that the size, shape, and amount of Ag nanoparticles depend on the dose of the extract and homogenate, the infusion time of the extract, and the stabilization time of the nanoparticles. Based on the results of FTIR analysis, it was confirmed that organic compounds such as metabolites and phenols in the composition of the *M. officinalis* plant help reduce the Ag⁺ ion to Ag⁰. The functional groups of the aqueous extract involved in the synthesis and stabilization of Ag nanoparticles were

also elucidated by FTIR analysis. The OH and CO functional groups of *M. officinalis* extract play a dual role as reducing and stabilizing agents of Ag nanoparticles. SEM images helped to determine the shapes, sizes, and morphology of the Ag nanoparticles. The sizes of the Ag nanoparticles obtained from the aqueous extract and homogenate vary between 10 and 80 nm and are mainly spherical in shape. XRD analysis showed that it is possible to synthesize Ag nanoparticles with a crystalline structure using *M. officinalis* extract.

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ARTICLE 9

Antioxidant Activity of the Aerial Parts of *Ajuga orientalis* L.Nargiz Mammadova^{1*} | ORCID: 009-0002-8587-7057Ilkin Nasirli² | ORCID: 0000-0002-1704-9009Nigar Namazova¹ | ORCID: 0009-0005-8048-8054¹ Department of Pharmacognosy, Azerbaijan Medical University, Baku, Azerbaijan² Department of Pharmaceutical Toxicology and Chemistry, Azerbaijan Medical University, Baku, Azerbaijan

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ABSTRACT

The antioxidant activity of 70% and 90% ethanolic extracts obtained from the aerial parts of *Ajuga orientalis* L. (*Lamiaceae*) was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay across six concentrations ranging from 5 to 100 µg/mL. Both extracts demonstrated concentration-dependent radical scavenging activity. The 90% ethanolic extract exhibited higher antioxidant activity ($IC_{50} = 122.09$ µg/mL, $R^2 = 0.827$) compared to the 70% ethanolic extract ($IC_{50} = 160.26$ µg/mL, $R^2 = 0.832$), indicating that higher ethanol concentration improves the extraction efficiency of moderately polar phenolic compounds. Gallic acid was used as a reference standard ($IC_{50} = 2.41$ µg/mL, $R^2 = 0.971$). The moderate R^2 values for the extracts reflect natural variability in crude extract composition and fall within the acceptable range reported for plant extract DPPH assays (Brand-Williams et al., 1995). The observed antioxidant activity is attributed to phenolic constituents — including rosmarinic acid, caffeic acid derivatives, and flavonoids — known to be present in *Ajuga* species. These findings support the traditional medicinal use of *A. orientalis* in Azerbaijan and justify further phytochemical characterisation and pharmacological validation.

Keywords: *Ajuga orientalis* L.; antioxidant activity; DPPH assay; phenolic compounds; free radical scavenging; IC_{50} ; ethanol extract; Azerbaijan

1. INTRODUCTION

Among the angiosperms of Azerbaijan, the family *Lamiaceae* ranks fourth in terms of species diversity, highlighting its considerable botanical and pharmacological significance (Karyagin et al., 1957). Within this family, particular attention has been drawn to representatives of the insufficiently studied cosmopolitan genus *Ajuga* L., which includes species with notable biological and medicinal potential. Among the species of this genus, Eastern bugleweed (*Ajuga orientalis* L.) is the most widespread and commonly utilized in Azerbaijan. The species is broadly distributed across the country, occurring from lowland areas to the subalpine zone. It grows on grassy slopes and meadows, as well as in forests, shrublands, agricultural fields, gardens, and vegetable plots. *A. orientalis* is a

perennial herbaceous plant, reaching 10–30 cm in height and characterized by dense coverage of long, soft trichomes (Karyagin et al., 1957).

The aerial parts of *A. orientalis* have long been employed in traditional medicine due to their anti-inflammatory, antibacterial, hypotensive, and other therapeutic properties (Namazova et al., 2025). This traditional use underscores the relevance of comprehensive phytochemical and pharmacological investigations of the species as a potential medicinal resource.

Phytochemical investigations of *A. orientalis* and related *Ajuga* species have revealed a rich and diverse chemical composition. The genus is characterized by the presence of phenolic acids (particularly rosmarinic acid and caffeic acid derivatives), flavonoids (luteolin, apigenin, and their glycosides), iridoid glycosides,

neo-clerodane diterpenoids, phytoecdysteroids, triterpenoids, and sterols (Oran et al., 2022; Küpeli Akkol et al., 2009; Harborne & Williams, 2000). Among these groups, phenolic compounds are regarded as the principal contributors to antioxidant activity. Quantitative studies have demonstrated a positive correlation between total phenolic content and antioxidant capacity in several *Ajuga* species, supporting the key role of polyphenols in radical scavenging mechanisms (Tepe et al., 2006; Wojdyło et al., 2007).

The antioxidant activity of *Ajuga* extracts is commonly assessed using in vitro methods such as DPPH, ABTS, FRAP, and CUPRAC assays. Among these, the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay remains one of the most widely applied methods due to its simplicity and reproducibility (Brand-Williams et al., 1995). This method is based on the reduction of the stable DPPH radical, resulting in a decrease in absorbance at 517 nm.

Extracts obtained from the aerial parts of *A. orientalis*, particularly using polar solvents such as methanol, ethanol, and aqueous fractions, have demonstrated moderate to strong DPPH radical scavenging activity. This activity is mainly attributed to hydroxyl-substituted phenolic compounds and flavonoids capable of stabilizing free radicals through resonance and electron delocalization (Tepe et al., 2006; Wojdyło et al., 2007).

According to several international studies, methanolic extracts of *A. orientalis* exhibit pronounced biological activity. These extracts have been shown to inhibit the proliferation of MCF-7 breast cancer cell lines, suggesting their potential as a promising source of anticancer agents (Oran et al., 2022). Moreover, they demonstrate significant antioxidant activity and antiproliferative effects against breast and colorectal cancer models.

Studies conducted in different regions have further confirmed that the antioxidant activity of *A. orientalis* is strongly associated with its phenolic composition. Additionally, the extracts exhibit metal-chelating properties, which reduce metal-catalyzed free radical formation and enhance overall antioxidant potential

(Brand-Williams et al., 1995; Wojdyło et al., 2007).

In traditional and experimental medicine, *A. orientalis* has been used for the treatment of fever, rheumatism, oral inflammation, gastrointestinal diseases, gout, and skin disorders, as well as for enhancing immune function and reducing oxidative stress (Namazova et al., 2025).

2. MATERIALS AND METHODS

The object of our study was the aerial part of *Ajuga orientalis* L. (Fig.1). The plant material was collected on April 28, 2025, at the initial flowering stage in the vicinity of the village of Altağac, Khizi district (40°51'29" N). The plant material was authenticated at the Department of Pharmacognosy, Azerbaijan Medical University. After collection, the material was air-dried at room temperature (25 ± 2°C) in a shaded, well-ventilated area for 10 days and subsequently ground into a coarse powder.

Two alcoholic extracts were prepared using 70% and 90% ethanol as extraction solvents. For each extraction, 100 g of powdered plant material was macerated with 1 L of the respective solvent for 72 hours at room temperature with occasional shaking. The extracts were filtered and concentrated under reduced pressure using a rotary evaporator at 40°C until dryness. The dried extracts were stored at 4°C in airtight containers until analysis.

DPPH (2,2-diphenyl-1-picrylhydrazyl) was purchased from Sigma-Aldrich (D9132-5G). Gallic acid was used as a reference antioxidant standard. Methanol of analytical grade was used throughout the study.

The DPPH assay is based on the method described by Blois et al. and was adapted for a 96-well microplate (Sterilin Ltd., UK). For each experimental session, a fresh 0.060 mg/mL DPPH solution was prepared 1–3 hours before the assay by dissolving 6.0 mg of DPPH (2,2-diphenyl-1-picrylhydrazyl) (Sigma Aldrich, D9132-5G, batch 0000187174) in 100 mL of methanol. The reagent was stored in the dark at room temperature. A positive control solution of gallic acid (Sigma Aldrich, batch SLBB4446) at 250 µg/mL was prepared by dissolving 25 mg of the compound in 100 mL of methanol. Using this

stock solution, six different concentrations ranging from 0.5 to 5.0 $\mu\text{g/mL}$ were prepared (0.5, 1.0, 1.25, 2.0, 2.5, 5.0 $\mu\text{g/mL}$)[10].



Figure 1. *Ajuga orientalis* L. in nature

The preparation of test samples varied depending on whether the compounds were individual substances or extracts. For individual compounds, a 300 $\mu\text{g/mL}$ stock solution was prepared by dissolving 15 mg of the compound in 50 mL of methanol. Subsequently, six sample concentrations ranging from 1 to 20 $\mu\text{g/mL}$ were prepared (1, 2.5, 5, 10, 15, 20 $\mu\text{g/mL}$). For plant extracts, a 1 mg/mL stock solution was first prepared by dissolving the extract in methanol, followed by the preparation of six concentrations ranging from 5 to 100 $\mu\text{g/mL}$ (5, 10, 20, 25, 50, 100 $\mu\text{g/mL}$)[11].

Prepared solutions were loaded into a 96-well microplate in a specific order and predefined layout for spectrophotometric analysis. In the eight-row plate, the first row served as the blank and contained 250 μL of methanol only. The second row served as the negative control, containing 50 μL methanol and 200 μL DPPH solution. In the subsequent rows, three rows contained 50 μL of the test sample at different concentrations plus 200 μL DPPH, and one row served as the sample blank, containing only 200 μL methanol. Samples were incubated with DPPH for 60 minutes. The microplate was

covered with a lid and analyzed using a spectrophotometer (Biotek Epoch, USA) at a wavelength of 517 nm.

To determine the antioxidant activity of compounds and extracts, a series of calculations were performed. First, the absorbance of each well was recorded. The percentage inhibition of each sample was calculated, and a dose-response curve was plotted to determine the IC₅₀ value. The IC₅₀ is a key parameter for comparing antioxidant activity and represents the concentration at which 50% of DPPH radicals are scavenged. For the negative control row, the percentage inhibition was calculated using the formula: $A_{\%} = 100 \times (A_0 - A_1) / A_0$, where A_0 – the absorbance of the control solution, A_1 – the absorbance of the blank well. The percentage of inhibition was calculated using the following formula: $((A_{\%} - (A_{bs.sample} - A_{bs.negative\ control})) / A_{\%}) \times 100$, где $A_{bs.sample}$ — is the absorbance of the sample measured at 517 nm, and $A_{bs.negative\ control}$ is the absorbance of the negative control measured at 517 nm.

The IC₅₀ value was determined from the inhibition versus concentration curve using a quadratic equation: $Y = aX^2 + bX + c$, with the condition $Y = 50$

In cases where a linear relationship between the parameters was not observed, appropriate mathematical equations were applied for data analysis: $\log(Y) = A \cdot \log(X) + B$ or $Y = A \cdot X + B$.

Dose-response curves were constructed and IC₅₀ values (concentration required to inhibit 50% of DPPH radicals) were calculated using linear regression analysis. The goodness of fit was expressed as the coefficient of determination (R^2).

3. RESULTS AND DISCUSSION

The antioxidant activity of the 70% and 90% ethanolic extracts of *Ajuga orientalis* L. was evaluated using the DPPH radical scavenging assay and compared with gallic acid as a reference standard. A linear regression model ($Y = AX + B$)

was applied for the determination of IC₅₀ values.

Gallic acid exhibited strong antioxidant activity with an IC₅₀ value of 2.41 µg/mL and a high correlation coefficient ($R^2 = 0.971$), confirming the reliability of the assay (Fig.2).

Both extracts demonstrated concentration-dependent radical scavenging activity. The calculated IC₅₀ values were:

- 90% ethanolic extract: 122,09 µg/mL ($R^2 = 0.827$)
- 70% ethanolic extract: 160,26 µg/mL ($R^2 = 0.832$)

The 90% ethanolic extract showed approximately 1.3-fold higher antioxidant activity compared to the 70% extract, as indicated by its lower IC₅₀ value (Fig.3,4).

Although the antioxidant activity of the extracts was significantly lower than that of gallic acid, the observed radical scavenging capacity confirms the presence of bioactive antioxidant constituents in the aerial parts of *Ajuga orientalis*. The enhanced activity of the 90% extract suggests that higher ethanol concentration improves the extraction efficiency of moderately polar phenolic compounds (Tab.1).

This difference suggests that higher ethanol concentration improves the extraction efficiency of phenolic and other antioxidant compounds from the aerial parts of *Ajuga orientalis*.

The observed antioxidant activity is likely attributable to phenolic constituents known to be present in species of the genus *Ajuga*. The enhanced activity of the 90% extract may be explained by improved solubility of moderately polar bioactive compounds in higher ethanol concentrations.

Overall, the results confirm that *Ajuga orientalis* possesses measurable antioxidant potential, supporting its traditional medicinal use and justifying further phytochemical characterization.

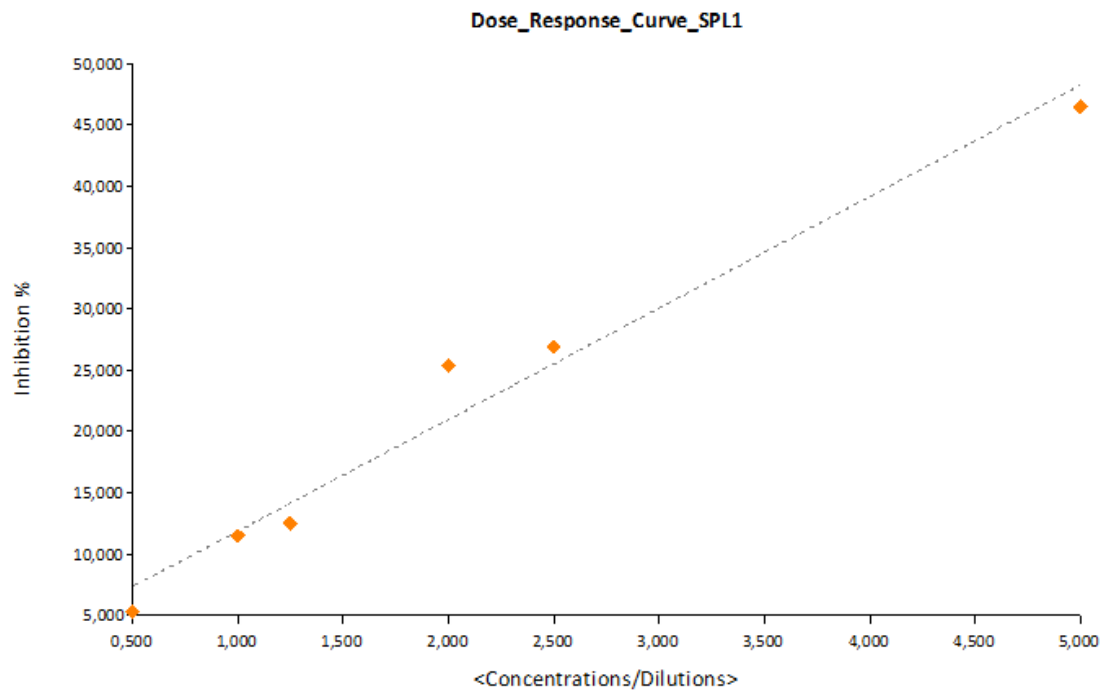


Figure 2. Graphical representation of the DPPH assay results of Gallic acid

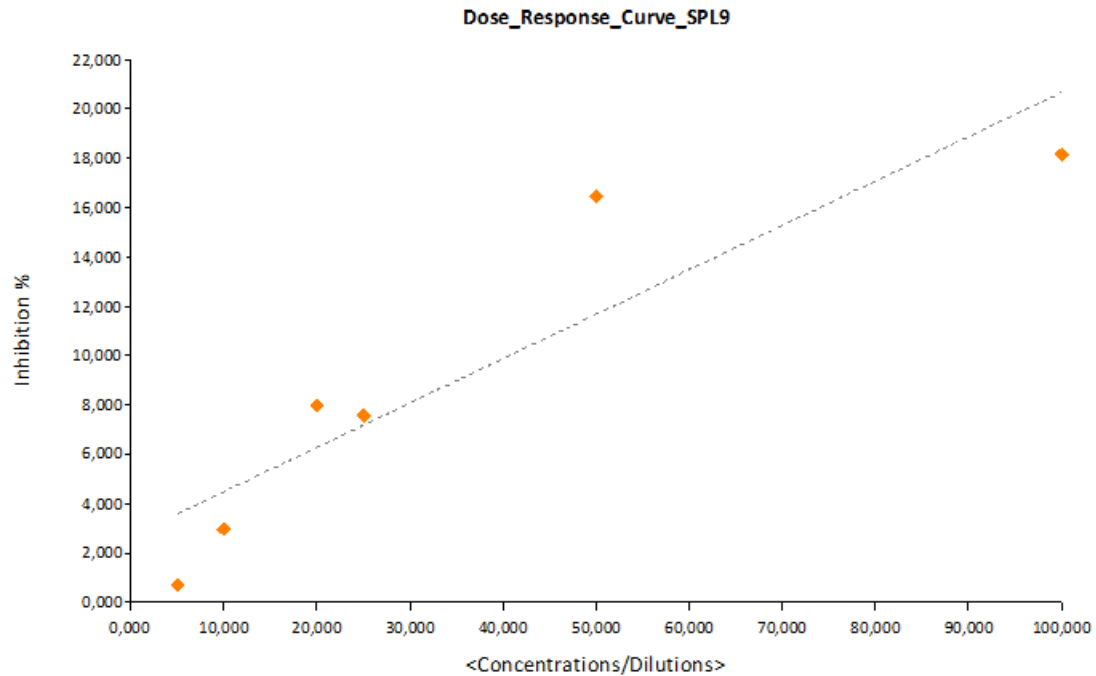


Figure 3. Graphical representation of the DPPH assay results of 90% alcohol extract of *Ajuga orientalis*

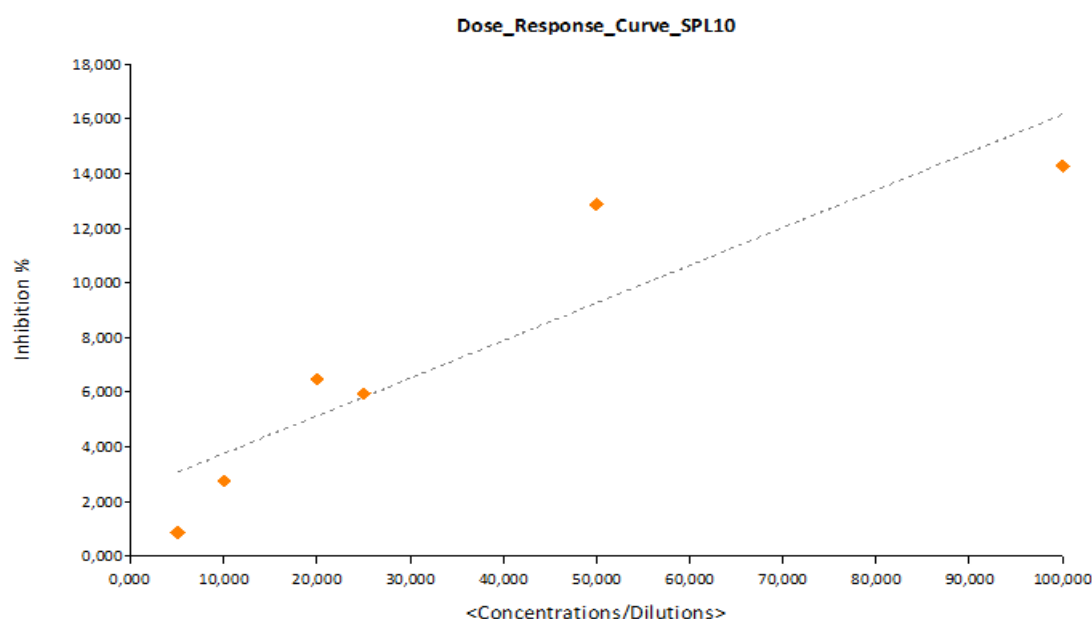


Figure 4. Graphical representation of the DPPH assay results of 70% alcohol extract of *Ajuga orientalis*

TABLE 1. IC_{50} values representing the antioxidant activity of *Ajuga orientalis*

Curve name	Name	Curve formula	A	B	R2	Results
Gallic acid	SPL1	$Y=A*X+B$	9,09	2,78	0,971	2,41
90% alcohol extract of <i>Ajuga orientalis</i>	SPL9	$Y=A*X+B$	0,18	2,67	0,827	122,09
70% alcohol extract of <i>Ajuga orientalis</i>	SPL10	$Y=A*X+B$	0,138	2,37	0,832	160,26

4. CONCLUSION

This study demonstrates that the aerial parts of *Ajuga orientalis* L. possess measurable antioxidant activity, as confirmed by the DPPH radical scavenging assay. The 90% ethanolic extract exhibited stronger antioxidant potential ($IC_{50} = 122.09 \mu\text{g/mL}$) compared to the 70% extract ($IC_{50} = 160.26 \mu\text{g/mL}$), indicating that higher ethanol concentration enhances the extraction

efficiency of bioactive antioxidant constituents. These findings support the traditional medicinal use of *A. orientalis* in Azerbaijan and highlight its potential as a natural source of antioxidant agents. Further studies focusing on phytochemical profiling, isolation of active constituents, and evaluation using complementary antioxidant assays (ABTS, FRAP, CUPRAC) are warranted.

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ARTICLE 10

Some Ecological Factors Controlling the Distribution of Forested Areas in the Zangilan and Gubadli Regions

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ABSTRACT

Forest ecosystems in the Zangilan and Gubadli regions of Azerbaijan have formed under the complex interaction of geological structure, relief, climate, hydrography, and soil cover. This study examines the influence of these ecological factors on the formation and spatial distribution of forest communities in the south-eastern part of the Lesser Caucasus, characterised by elevations ranging from 300–350 m to 2,000–2,300 m a.s.l. The relief is divided into three main geomorphological zones: a denudation middle-mountain zone, a foothill zone, and a deluvial foothill gentle plain zone. Elevation analysis identified the 401–800 m zone as dominant (approximately 40,000–42,000 ha per district), corresponding to the most extensive forest coverage. Climate data from 1971–1985 and 2020–2024 indicate temperature increases of 1–2°C over recent decades, with current mean annual temperatures of 13–15°C. Note: an intermediate data gap exists for 1986–2019 due to meteorological station record availability; the two-period comparison captures long-term baseline and recent conditions. The hydrographic network — primarily the Hakari, Bargushad, and Okhchuchay rivers — creates specific microclimatic conditions favouring unique forest communities, including *Platanus orientalis* stands in the Basitchay valley. Among 30 identified soil types, carbonate mountain brown soils (25,613 ha), steppe mountain brown soils (24,183 ha), and leached mountain brown soils (15,491 ha) are dominant. The extensive area of steppe mountain brown soils reflects significant historical forest degradation. Conservation and restoration strategies should prioritise degraded zones and match species selection to topographic and edaphic conditions.

Keywords: *ecological factors; forest distribution; Lesser Caucasus; GIS analysis; soil types; climate change; forest restoration; Azerbaijan*

1. INTRODUCTION

Forest ecosystems represent one of nature's most complex and multifunctional components, whose formation and development result from the interaction of numerous ecological factors. Forest trees exhibit different growth characteristics under different environmental conditions (Doğru & Güngöroğlu, 2021). The literature contains numerous studies examining the impact of ecological factors such as climate, topography (Candel-Pérez et al., 2012), bedrock (Hahm et al., 2014), and tree distribution patterns in forested areas (Acharya et al., 2011) on forest

productivity. Environmental conditions can affect the functioning of trees and their communities, while tree communities and environmental conditions influence the structural characteristics of the forest (Pretzsch et al., 2015). In a mountainous basin, strong spatial and temporal variations can occur in the organisation of ecosystem productivity, structure, and photosynthetic activity due to slope topography and location within the topoclimatic continuum (Hoylman et al., 2018). Furthermore, topography is related to various mechanistic factors affecting vegetation processes, such as near-surface microclimate and

soil formation (Chytrý et al., 2022).

The Zangilan and Gubadli regions of Azerbaijan harbour unique forest communities that have evolved under specific environmental conditions. These forests play crucial roles in biodiversity conservation, soil protection, and water regulation in the region (Grossheim, 1948; Prilipko, 1954). The study area is located in the southeastern part of the Lesser Caucasus mountain system, characterised by complex orographic structure and diverse environmental conditions. Understanding the factors influencing forest ecosystem formation is particularly important given recent climate changes and anthropogenic pressures affecting the region (Alizade et al., 2015).

Previous research has examined various aspects of forest vegetation in the Caucasus region (Gulisashvili, 1964; Solovyova, 1951), but comprehensive analysis of the interrelationships between natural factors and forest

ecosystem formation in Zangilan and Gubadli regions remains limited. This study aims to fill this gap by examining how geological structure, relief, climate, hydrography, and soil characteristics collectively influence forest ecosystem development and spatial distribution. Identifying the complex natural factors influencing forest growth in this region is critical for the sustainable management of these forests.

2. MATERIALS AND METHODS

Study Area

The research was conducted in Zangilan and Gubadli administrative regions of Azerbaijan, located in the southeastern slopes of the Small-Caucasus. The study area extends from 38°54' to 39°42' N latitude and 46°03' to 47°08' E longitude, covering approximately 1,400 km². Elevations range from 300-350 m to 2000-2300 m above sea level.

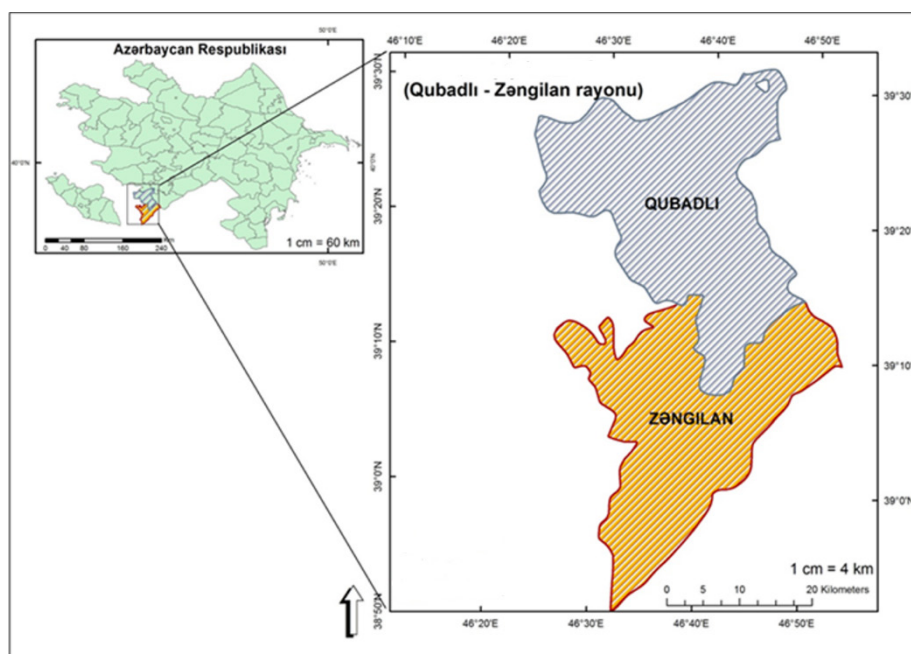


Figure 1. Geographical locations of the study sites

Data Collection

Climate data were obtained from meteorological stations for two periods: 1971-1985 (historical period) and 2020-2024 (modern period). Parameters included temperature, precipitation, relative humidity, and solar radiation. Long-term average data were used for comparative analysis.

Topographic analysis was conducted using digital elevation models (DEM) with 30-meter resolution. Relief parameters including elevation, slope, aspect, and Topographic Wetness Index (TWI) were calculated using GIS software (ArcGIS 10.8).

Soil data were compiled from existing soil surveys and field observations. Soil samples

were collected from representative forest sites at different elevations to determine mechanical composition, humus content, and physicochemical properties.

Geospatial Analysis

All spatial data were processed in ArcGIS 10.8 environment. The following analyses were performed:

- Elevation classification: Five elevation zones were identified (251-400 m, 401-800 m, 801-1200 m, 1201-1600 m, 1600-2300 m)
- Slope analysis: Five slope classes (0-10°, 10-20°, 20-30°, 30-40°, >40°)
- Aspect classification: Eight cardinal directions plus flat areas
- TWI calculation using the formula: $TWI = \ln(A_s / \tan \beta)$, where A_s is the specific catchment area and β is the slope angle

Statistical Analysis

Descriptive statistics were calculated for all relief parameters. Area calculations were performed for each elevation zone, slope class, and aspect category. Correlation analysis was

conducted to examine relationships between topographic parameters and forest distribution.

3. RESULTS AND DISCUSSION

3.1 Relief Characteristics and Forest Distribution

The study area exhibits complex orographic structure divided into three main geomorphological zones. The denudation middle mountain zone encompasses the southeastern slopes of the Bargushad Mountains and southwestern slopes of the Karabakh Range. The foothill zone represents a transition area with moderately dissected terrain. The deluvial foothill gentle plain zone occupies the lowest elevations with wave-like topography.

Elevation analysis reveals that the largest area in Zangilan region (40,904.98 ha) is located at 401-800 m elevation (Table 1). In Gubadli region, the maximum area (42,417.71 ha) also occurs within this elevation range. These middle elevation zones support the most extensive forest coverage, primarily consisting of oak-hornbeam and mixed deciduous forests.

Elevation map - placeholder for Figure 2

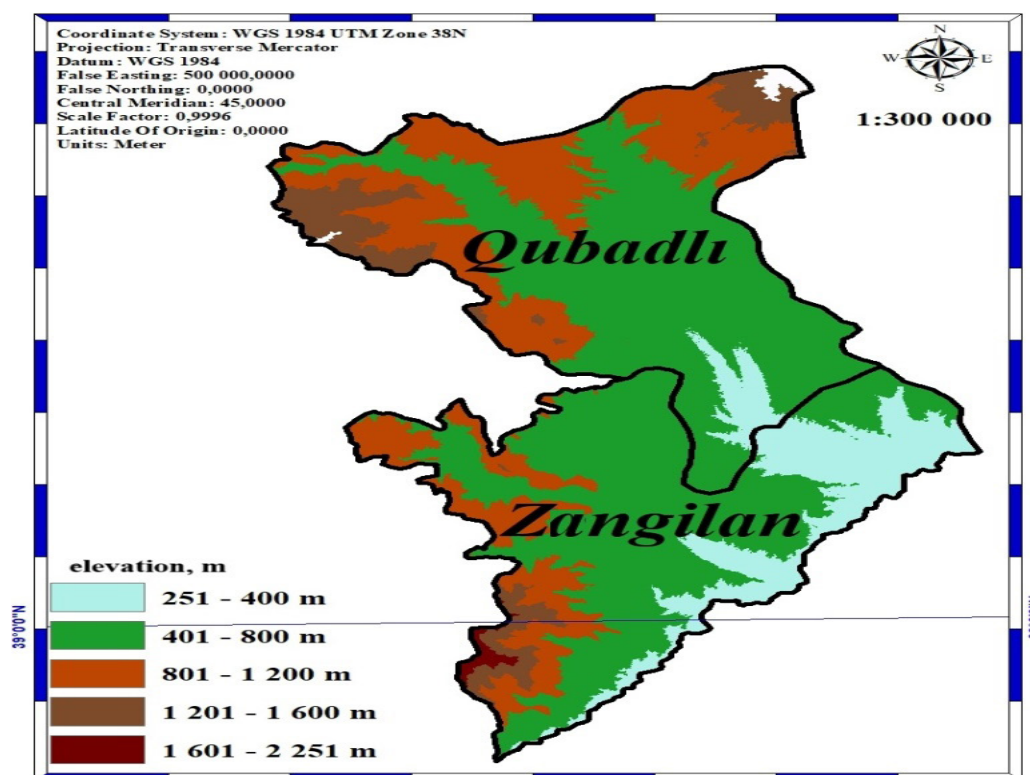


Figure 2. Elevation map of the study area showing the distribution of altitudinal zones and their correspondence with forest vegetation types.

Table 1. Elevation distribution in study area

Elevation range (m)	Zangilan area (ha)	Gubadli area (ha)
251-400	14,555.04	2,793.01
401-800	40,904.98	42,417.71
801-1200	11,921.86	24,453.45
1201-1600	2,726.96	7,407.45
1600-2300	844.15	815.62

Slope analysis indicates that gentle slopes ($0-10^\circ$) dominate both regions, covering 34,946.57 ha in Zangilan and 35,889.17 ha in Gubadli (Table 2). Moderate slopes ($10-20^\circ$) occupy 21,293.75 ha and 2,765.19 ha respectively. Steep slopes ($>30^\circ$) represent relatively small areas but support specialized forest communities adapted to difficult terrain conditions.

Slope map - placeholder for Figure 2

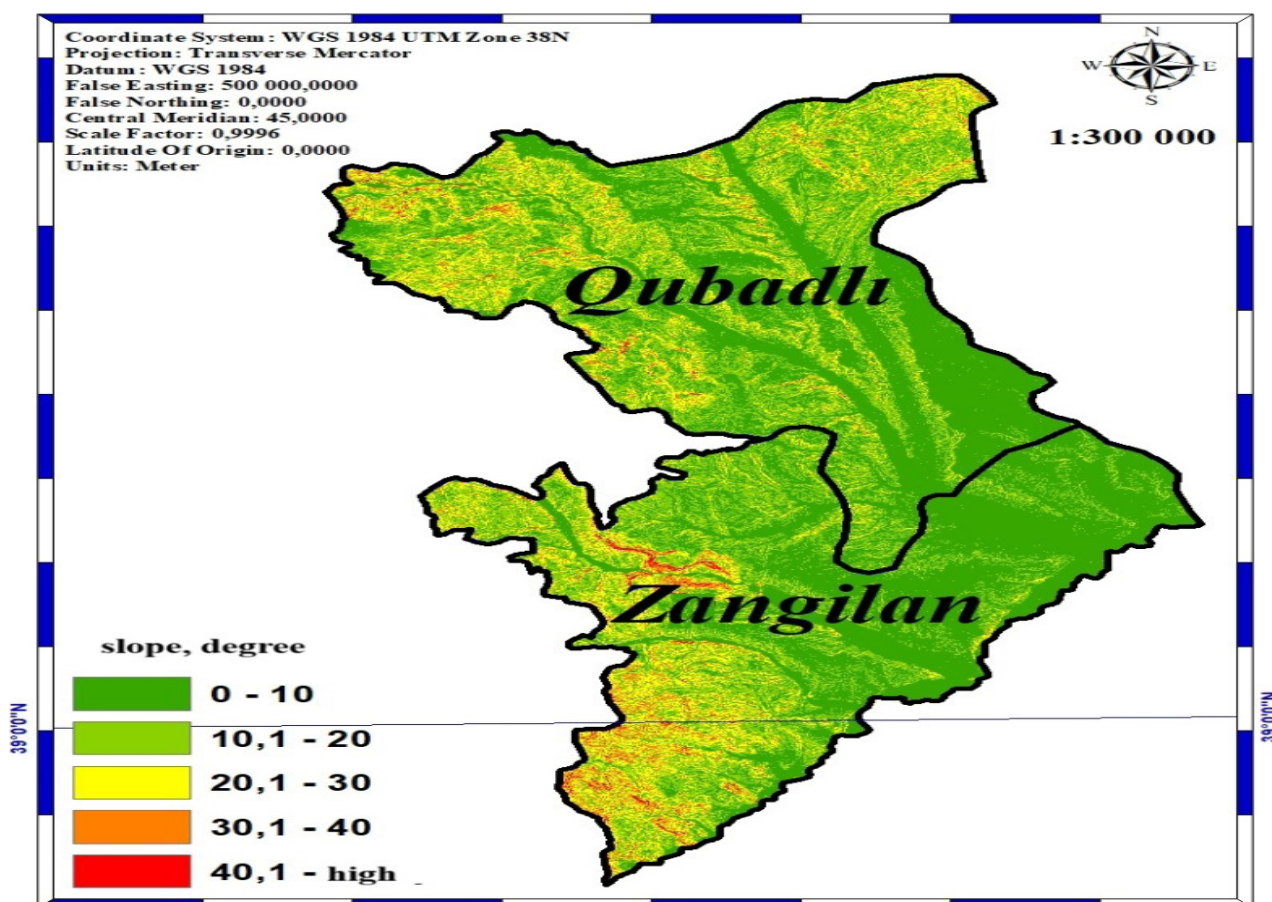


Figure 3. Slope gradient distribution map demonstrating the relationship between terrain steepness and forest community types.

Table 2. Slope distribution in study area

Slope class	Zangilan area (ha)	Gubadli area (ha)
0-10°	34,946.57	35,889.17
10-20°	21,293.75	2,765.19
20-30°	1,008.49	11,361.37
30-40°	3,509.01	2,338.63
>40°	625.05	229.60

Aspect analysis demonstrates relatively uniform distribution across cardinal directions, with flat areas covering 11,731.13 ha in Zangilan and 13,842.29 ha in Gubadli. Northern aspects (8,399.27 ha in Zangilan) support more mesophytic forest communities, while southern aspects favor xerophytic species composition.

Climatic Conditions

Long-term climate analysis (1971-1985) reveals significant temporal variations affecting forest ecosystems. Mean annual temperature ranges from 10-13°C depending on elevation. The warmest month is July (25-27°C mean), while January is coldest (1.0-1.4°C mean at middle elevations).

Temperature analysis for successive five-year periods shows warming trends. At foothill elevations (400-500 m), mean annual temperature increased from 13.3°C (long-term average) to 13.8°C (1971-75), 14.5°C (1976-80), and 14.4°C (1981-85). This 1-2°C increase affects vegetation patterns and potentially shifts forest zone boundaries.

Annual precipitation varies with elevation from 460-470 mm at 400-500 m to 600-650 mm at 800-1200 m. Precipitation distribution shows two maxima: spring (April-May) and autumn (October-November). Summer months experience minimum precipitation, with July-August totaling only 63 mm on long-term average.

Modern climate data (2020-2024) confirm continued warming trends. Average daytime temperature reaches 15.72°C annually, with July maximum of 27.13°C. Annual precipitation averages 304.8 mm, with maximum in May (53.2 mm) and minimum in August (8.75 mm). Solar radiation hours range from 8-10 hours daily in winter to 14+ hours in summer.

Hydrographic Network

The Hakari River, one of Azerbaijan's most water-abundant rivers, originates at 948 m elevation from confluence of Shalva and Hojas

ivers. Its catchment area covers 2,558 km² with mean annual discharge of 9.16 m³/s and annual runoff volume of 300 million m³. The river is fed primarily by groundwater (49%), snowmelt (30%), and rainfall (13%).

The Bargushad River originates at 845 m elevation with catchment area of 2,020 km². Its length is 179 km with mean annual discharge of 20.3 m³/s and annual runoff volume of 750 million m³. The river carries substantial sediment load, transporting approximately 137,000 tons annually.

River valleys create specific microhabitat conditions favorable for unique forest communities. In the Basitchay valley, oriental plane (*Platanus orientalis*) forests develop under elevated humidity conditions. These riparian forests demonstrate the critical importance of hydrographic network in forest ecosystem formation.

Soil Cover

Soil cover analysis identifies 30 soil types and subtypes distributed according to elevation and parent material. The dominant types include carbonate mountain brown soils (25,613.3 ha), steppe mountain brown soils (24,183.4 ha), and leached mountain brown soils (15,491.1 ha).

Mountain forest soils occur primarily at 800-1300 m elevation on north-facing slopes under oak-hornbeam forests. These soils contain 3-5% humus with well-developed profile structure. Carbonate accumulations appear at 40-60 cm depth in carbonate variants.

Steppe mountain brown soils develop at 500-800 m elevation under xerophytic vegetation. These soils result from forest degradation

due to human activity and climate change. Humus content ranges from 1.5-2.0% with granular to blocky structure.

Mountain gray-brown soils occupy foothill zones (300-600 m) covering 21,287.5 ha in Gubadli region. These soils support sparse juniper forests and xerophytic shrub communities. The soil profile shows brown-gray coloration in

upper horizons becoming lighter with depth.

Alluvial-meadow soils develop along river valleys covering 8,346.1 ha of stratified weakly developed type and 8,429.2 ha of irrigated variant. Despite limited extent, these fertile soils historically supported diverse agricultural use and riparian forest vegetation.

Hydrographic map - placeholder for Figure 5

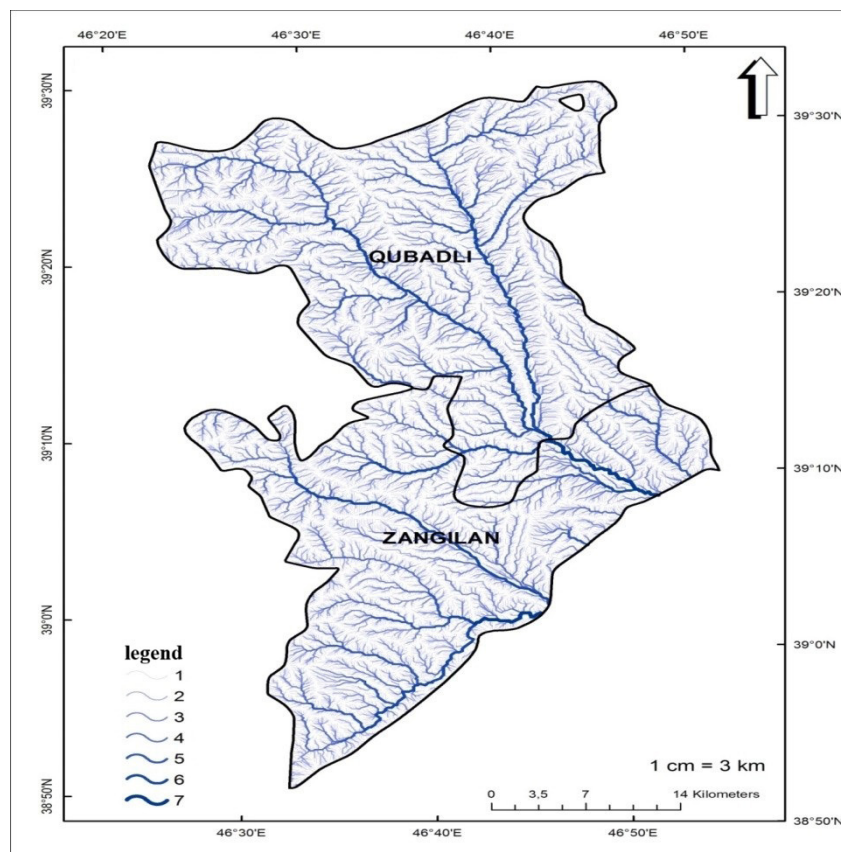


Figure 4. Hydrographic network map depicting major rivers (Hakari, Bargushad, Okhchuchay) and their influence on forest distribution patterns.

Integrated Effects of Ecological Factors

Our results demonstrate that forest ecosystem formation results from complex interactions among multiple natural factors. Relief characteristics fundamentally control spatial distribution of climate, hydrology, and soil patterns, which in turn determine forest community composition and structure.

Elevation emerges as the primary factor structuring forest zones. The dominance of 401-800 m elevation zone (40-42 thousand ha) coincides with optimal conditions for oak-dominated forests in the region. This elevation range experiences moderate temperatures (13-15°C

annually) and receives sufficient precipitation (480-500 mm) to support closed-canopy forests while avoiding excessive moisture that characterizes higher elevations.

The observed temperature increase of 1-2°C during 1971-1985 parallels global warming trends documented across the Caucasus region (Kerimov, 2004). This warming may explain upward shift of forest boundaries noted in field observations. Similar temperature-driven vegetation changes have been reported for other Caucasus mountain regions (Nakhutsrishvili et al., 2011).

Slope and aspect effects manifest primarily

through moisture availability. Steep south-facing slopes experience high evapotranspiration rates leading to dominance of drought-resistant species including *Quercus araxina* and *Juniperus* species. North-facing slopes retain moisture more effectively, supporting mesophytic communities with *Carpinus caucasica* and *Fagus orientalis*.

Hydrological Controls

The hydrographic network exerts localized but significant influence on forest distribution. River valleys provide moisture corridors extending drought-tolerant vegetation into otherwise xeric zones. The unique *Platanus orientalis* forests of Basitchay valley exemplify this effect, where elevated humidity and alluvial soils support relict forest communities.

Groundwater contributions (49% of river flow) suggest substantial subsurface moisture availability. This may explain persistence of mesophytic forest islands in apparently xeric environments where local groundwater emergence creates favorable microhabitats. Groundwater depth, regime, and water stress have a significant impact on the limited distribution and structure of some vegetation types in the landscape (Glanville et al. 2023).

Soil-Vegetation Relationships

Strong correspondence between soil types and forest communities confirms soil as proximate control on vegetation in the study areas. Mountain brown forest soils with 3-5% humus support productive oak-hornbeam forests, while gray-brown soils with <2% humus support only sparse juniper woodlands.

Soil degradation through steppification represents major concern. The extensive area of steppe mountain brown soils (24,183 ha) indicates widespread forest loss and soil deterioration. This process appears driven by both historical deforestation and recent climate warming, which favors grassland over forest vegetation. It has been determined that the amount of nutrients in the brown mountain steppe soils in the southeastern parts of the Small- Caucasus decreases significantly as the degree of erosion increases (Aliyev, 2017).

Climate Change Implications

Continued warming documented in modern

climate data (2020-2024) portends further changes in forest distribution. Temperature increases of 1-2°C can shift vegetation zones upward by 150-300 m elevation in mountain regions (Körner, 2003). This implies potential loss of high-elevation forest communities while lower elevation forests may face increased drought stress.

Changes in precipitation seasonality, with summer drying intensification, may prove particularly detrimental. Summer drought already limits forest productivity at lower elevations. Further precipitation reduction during growing season could cause forest dieback and conversion to woodland or shrubland.

Comparison with Regional Patterns

Our findings align with broader patterns of Caucasus forest ecology. The elevation range (800-1800 m) of optimal forest development matches that reported for eastern Caucasus regions (Grossheim, 1948). Similarly, the dominance of *Quercus* species on southern aspects and *Carpinus-Fagus* on northern aspects follows the established regional pattern (Gulisashvili, 1964). However, the extensive forest degradation and soil steppification appear more severe than in other Caucasus regions. This likely reflects the combination of continental climate, human pressure, and recent disturbance history in the study area. This highlights the fact that the dynamics of forest development in the study area are much more sensitive to external factors. Considering the consequences of climate change alongside these factors, the need for more careful afforestation and forestry activities in the study area becomes apparent.

Management Implications

Understanding natural controls on forest distribution provides foundation for restoration planning. Priority areas for restoration include:

1. Steppe mountain brown soil zones (24,183 ha) where forest recovery potential exists
2. Degraded foothill forests on mountain gray-brown soils (21,288 ha)
3. Riparian corridors where hydrological conditions favor rapid forest establishment

Species selection for restoration should

match topographic positions and soil types. Drought-resistant species (*Q. araxina*, *Juniperus* spp.) suit southern aspects and lower elevations, while mesophytic species (*Carpinus*, *Fagus*) should target northern aspects and higher elevations.

Climate change adaptation requires emphasis on drought-resistant species and maintenance of genetic diversity within populations. Preserving relict forests in hydrologically-favorable sites provides critical refugia for mesophytic species under warming scenarios.

4. CONCLUSION

Forest ecosystems in Zangilan and Gubadli regions develop under the integrated influence of geological structure, relief, climate, hydrography, and soil. Relief characteristics, particularly elevation (optimal zone 401-800 m), exert primary control on forest distribution by mediating climate and soil patterns.

Climate warming of 1-2°C documented over

recent decades affects forest boundaries and potentially accelerates degradation processes. The hydrographic network creates moisture corridors supporting relict forest communities in otherwise xeric environments. Soil types closely correspond to forest communities, with mountain brown forest soils supporting productive forests while degraded gray-brown soils support sparse woodlands.

Forest degradation and soil steppification over extensive areas (24,183 ha) represent major conservation challenges. Restoration efforts should prioritize degraded zones while matching species selection to topographic and edaphic conditions. Climate change adaptation requires emphasis on drought-resistant species and preservation of mesophytic refugia.

Understanding ecological factors controlling forest distribution provides essential foundation for sustainable forest management, conservation planning, and restoration strategies in this ecologically important region of the Caucasus.

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ARTICLE 11

Effect of Medium Hormonal Composition on In Vitro Micropropagation and Rooting of *Paulownia tomentosa*

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ABSTRACT

Paulownia tomentosa (Thunb.) Steud. is a fast-growing, multifunctional tree species of high economic and ecological value; however, large-scale propagation remains limited by variability in conventional vegetative methods. This study developed and optimised an in vitro micropropagation protocol for *P. tomentosa* through systematic evaluation of initiation, shoot proliferation, rooting, and acclimatisation stages. Nodal explants were successfully established using a 10% NaOCl sterilisation protocol with an 80% survival rate on ½ MS medium supplemented with 1.0 mg/L BAP. During the proliferation stage, three concentrations of 6-benzylaminopurine (BAP; 0.2, 0.5, and 1.0 mg/L) were evaluated on MS medium. The highest multiplication coefficient (3.0, with 3–4 shoots per explant and very low callus formation) was achieved on MS medium with 0.5 mg/L BAP. At 0.2 mg/L BAP, shoot development was weak; at 1.0 mg/L BAP, excessive callus formation suppressed morphogenesis. Rooting experiments demonstrated that ½ MS medium containing 1.0 mg/L indole-3-butyric acid (IBA) and 0.1 mg/L naphthaleneacetic acid (NAA) was optimal, yielding 100% rooting frequency with a mean of 5–6 roots per microshoot (length: 4–5 cm). Rooted plantlets were successfully acclimatised in cocopeat substrate and transferred to greenhouse conditions with high survival rates. The developed protocol provides a reliable and reproducible basis for mass production of genetically uniform *P. tomentosa* planting material suited to Azerbaijani environmental conditions.

Keywords: *Paulownia tomentosa*; in vitro micropropagation; plant tissue culture; cytokinin; auxin; BAP; IBA; rooting; MS medium; Azerbaijan

1. INTRODUCTION

At present, environmental protection issues are highly relevant for many countries. Intensive development, industrial activities, and the high density of transport systems lead to the accumulation of various pollutants in the biosphere and the atmosphere. Soil is one of the most important components of the ecosystem that accumulates chemical contaminants. Among numerous pollutants, heavy metals occupy a special place, as they form complexes with mineral and organic compounds, thereby

increasing the overall level of soil toxicity. In addition, the release of large quantities of harmful compounds, including carbon dioxide, into the atmosphere represents a global problem, as it contributes to climate change.

The expansion of green areas, particularly fast-growing plant species that are resistant to high levels of anthropogenic pressure, is considered one of the effective approaches to solving the problem of air and soil pollution in urban environments. One such plant is paulownia (*Paulownia*). *Paulownia* is a fast-growing and

completely waste-free tree, as all of its organs (trunk, roots, leaves, seeds, flowers, and bark) can be utilized for various purposes [Azzarello et al., 2012; Zhu et al., 1986]. Therefore, this tree is highly valued both economically and environmentally [Bahri, 2013; Barton et al., 2007; Carpenter, 1997; Owfi Reza, 2017].

Today, paulownia trees are cultivated for commercial, medicinal, and ornamental purposes in Asia, Europe, North America, and Australia. This plant species, distinguished by its rapid growth and high adaptability, is capable of adjusting to a wide range of environmental conditions and is characterized by a high growth rate and exceptional regenerative capacity. In fact, paulownia is considered one of the fastest-growing tree species in the world, producing several times more biomass annually than many other tree species. This characteristic has, in turn, increased interest in the establishment of paulownia plantations for biomass production [Bahri, 2013; Garagurbanly & Suleymanova, 2024; Owfi Reza, 2017; Yadav et al., 2013].

The lifespan of the paulownia root system reaches nearly 100 years. During this period, the tree can undergo 8–9 growth cycles, each lasting approximately 8 years, which enables repeated regeneration of the plantation without additional planting costs [Garagurbanly & Suleymanova, 2024; Yadav et al., 2013]. Paulownia is also notable for its large leaves, which can reach a diameter of 45–75 cm. The species contributes to the purification of polluted air by absorbing harmful gases and particulate matter. Compared with other tree species, paulownia is capable of absorbing up to 10 times more CO₂. Its leaves grow rapidly and exhibit a high capacity for CO₂ assimilation. On average, the canopy of a single tree absorbs approximately 22 kg of carbon dioxide per year and releases about 6 kg of oxygen. Consequently, a 10-ha plantation can absorb up to 300 tons of CO₂ and prevent the dispersion of approximately 1,000 tons of dust over a 12-month period [Barton et al., 2007].

In addition, pellets produced from paulownia wood are economically more efficient and provide higher heat output during combustion. Compared with pellets derived from other tree species, they are significantly more

environmentally friendly. During pellet combustion, CO₂ emissions are 10–50 times lower, ash formation is reduced by 15–20 times, and sulfur content in the residues is almost negligible [Zhu et al., 1986].

Furthermore, the ability of paulownia trees to tolerate high concentrations of heavy metals (such as Mn, Pb, or Zn) makes them suitable for the rehabilitation of contaminated soils and for forest restoration programs [Azzarello et al., 2012]. Paulownia wood is widely used in construction, as well as in the production of paper, furniture, and musical instruments, while the nectar of its flowers is an invaluable resource for the production of high-quality honey. The leaves contain a high protein content (approximately 20%) and can be used for the production of high-quality, low-cost animal feed [Yadav et al., 2013].

Trees of the genus *Paulownia* contain phenolic acids, phenolic glycosides, lignans, xanthones, and phytosterols. These compounds exhibit a broad spectrum of biological activities, including antioxidant, anti-inflammatory, antibacterial, antiviral, and anticancer effects. In China, paulownia has traditionally been used as a herbal remedy for the treatment of inflammatory bronchitis, tonsillitis, asthma, and other respiratory diseases [Barton et al., 2007; Bergmann & Moon, 1997].

Paulownia propagation is performed using three principal methods: generative (seed) propagation, vegetative propagation by cuttings, and microclonal propagation. Currently, numerous studies are being conducted to develop and refine in vitro propagation technologies for *Paulownia* species [Bahri, 2013; Bergmann & Moon, 1997; Chunchukov & Yancheva, 2015; Ipekci & Gozukirmizi, 2003; Ipekci & Gozukirmizi, 2004; Mohanty et al., 2008; Radojevic, 1979; Venkateswarlu et al., 2001].

Thus, studies conducted by Bahri demonstrated that *Paulownia tomentosa* possesses a high regeneration capacity under in vitro conditions and that optimization of the sterilization stage plays a decisive role in obtaining healthy explants [Bahri, 2013]. The author also determined that the BAP–NAA combination stimulates the multiplication process and significantly

increases proliferation rates.

Investigations by Bergmann and Moon on adventitious shoot formation in *Paulownia* species showed that cytokinins, particularly BAP, have a predominant effect on the proliferation coefficient, while their combination with kinetin results in morphologically healthier shoot formation. These studies revealed a direct relationship between hormone concentration and regeneration capacity, indicating that high cytokinin levels may enhance callus formation and thereby inhibit the regeneration process [Bergmann & Moon, 1997].

Chunchukov and Yancheva, through a comparative assessment of the micropropagation potential of various *Paulownia* species and hybrids, emphasized that the physiological state of the explant, the season of its collection, and the proper selection of the nutrient medium (MS and DKW) significantly influence proliferation parameters [Chunchukov & Yancheva, 2015].

Venkateswarlu et al. demonstrated the successful induction of multiple shoots from axillary bud explants of *P. fortunei* and confirmed the high efficiency of IBA during the rooting stage [Venkateswarlu et al., 2001]

Studies by Ipekci and Gozukirmizi on the somatic embryogenesis process in *Paulownia elongata* described the mechanisms of both direct and indirect embryogenic callus formation and identified 2,4-D and kinetin as the main regulatory factors in the induction of embryogenic tissues. The authors also demonstrated that the resulting somatic embryos can be encapsulated and used for the production of synthetic seeds, which is considered an important biotechnological approach for mass vegetative propagation and long-term conservation of *Paulownia* species [Ipekci & Gozukirmizi, 2003; Ipekci & Gozukirmizi, 2004].

The first description of somatic embryogenesis in *Paulownia tomentosa* was provided by Radojevic, who demonstrated at an early stage the possibility of plant regeneration from callus cultures [Radojevic, 1979].

Overall, the available literature indicates that *Paulownia* species possess a high in vitro regeneration potential, that optimization of hormone composition and nutrient media directly

affects proliferation efficiency, and that somatic embryogenesis represents a promising technology for genetically stable mass propagation.

Considering the high ecological and economic importance of *Paulownia*, its rapid adaptation to diverse environmental conditions, its efficient biomass regeneration capacity, as well as the relevance of expanding green areas in Azerbaijan, the Scientific Research Institute of Fruit- and Tea Growing of the Ministry of Agriculture has initiated comprehensive studies on this plant under local conditions [Garagurbanli & Suleymanova, 2024]. These studies include phenological observations, development of cultivation technologies, assessment of its growth potential on saline and oil-contaminated soils, investigation of propagation methods, and other related research activities.

The aim of the present study was to develop an optimal biotechnological protocol for the microclonal propagation of *Paulownia tomentosa* using shoot explants under the conditions of Azerbaijan. This approach is intended to provide a scientific basis for large-scale production of high-quality planting material adapted to local environmental conditions.

2. MATERIALS AND METHODS

Paulownia tomentosa was used as the research object. The study was carried out in the Plant Micropropagation Laboratory of the Scientific Research Institute of Fruit- and Tea Growing of the Ministry of Agriculture of Azerbaijan.

Selection of the optimal nutrient medium composition for explant establishment, micropropagation, and rooting was one of the main objectives of the study. For this purpose, the Murashige and Skoog (MS) medium was modified and several variants were tested. The efficiency of micropropagation was evaluated based on the following parameters: explant viability and regeneration rate (ratio of viable and regenerated explants to the total number of explants), multiplication coefficient (ratio of newly formed microshoots to the initial number of shoots), number of rooted microplants, and root formation characteristics.

In vitro culture conditions were maintained under constant illumination (2.5–3.0 thousand

lux), a temperature of +21 to +25°C, and a 16/8 h light/dark photoperiod. Subculturing (transfer to the next passage) was performed every 20–21 days.

Laboratory Experimental Procedure

Initiation Stage

At the initial stage, explants were sterilized. Explants collected from *Paulownia tomentosa* plants were washed under running tap water for 15 minutes and then rinsed with autoclaved sterile water. Surface sterilization was carried out using 10% NaOCl for 10 minutes, followed by three rinses in sterile distilled water for 5, 10, and 15 minutes, respectively.

The sterilized explants were cultured on half-strength Murashige and Skoog ($\frac{1}{2}$ MS) medium [Murashige & Skoog, 1962] supplemented with 1.0 mg/L BAP, 30 g/L sucrose, 0.2 mL/L Tween 80, and 7 g/L agar. The pH of the culture medium was adjusted to 5.8 prior to autoclaving.

Micropropagation Stage

Sterile explants were transferred to MS media containing vitamins and different concentrations of BAP: 0.2 mg/L (MS1), 0.5 mg/L (MS2), and 1.0 mg/L (MS3). The sucrose concentration was 30 g/L, agar was added at 7 g/L, and the pH was adjusted to 5.8.

Rooting and acclimatization stage

For the rooting stage, microplants containing two or more nodes were selected. The plants were transferred to modified Murashige and Skoog (MS) nutrient media. During the rooting phase, the effects of nutrient media with different compositions and culture conditions on the development of microshoots were investigated according to the variants listed below:

Variant I (control). $\frac{1}{2}$ Murashige and Skoog (MS) medium supplemented with 0.1 mg/L BAP and 0.5 mg/L IBA;

Variant II. $\frac{1}{2}$ Murashige and Skoog (MS) medium supplemented with 0.1 mg/L BAP, 0.5

mg/L IBA, and 0.1 mg/L NAA;

Variant III. $\frac{1}{2}$ Murashige and Skoog (MS) medium supplemented with 1.0 mg/L IBA and 0.1 mg/L NAA;

Variant IV. $\frac{1}{2}$ Murashige and Skoog (MS) medium supplemented with 1.0 mg/L IBA and 0.2 mg/L NAA.

3. RESULTS AND DISCUSSION

The sterilization protocol applied at the initiation stage resulted in an 80% success rate, indicating that the selected sterilization scheme was sufficiently suitable for *P. tomentosa* explants and caused minimal tissue damage. Following sterilization, all viable explants began to develop on $\frac{1}{2}$ MS medium supplemented with 1 mg/L BAP. This confirms the important role of the cytokinin BAP in stimulating initial meristematic activity and facilitating the in vitro adaptation of explants.

The results obtained during the micropropagation stage (Table 1) demonstrated that different BAP concentrations had significantly different effects on the proliferation capacity of the explants. The highest multiplication rate was recorded on the MS2 medium (0.5 mg/L BAP), where the multiplication coefficient reached 3. This result indicates that a moderate BAP concentration is optimal for *P. tomentosa* microplants, as it stimulates meristematic activity and increases both the number of newly formed shoots and their morphological quality. It should be noted that although no exogenous auxin was added at this stage, endogenous auxin present in the tissues actively functioned and, together with cytokinin, served as a key regulator of meristem activity. The moderate BAP concentration created an optimal balance with endogenous auxin, ensuring coordinated regulation of both cell division and differentiation.

Table 1. Effect of different BAP concentrations on micropropagation of *P. tomentosa*

Variant	BAP concentration (mg/L)	Mean shoot number per explant (no.)	Multiplication rate (%)	Callus formation level
MS1	0.2 mg/L	1–2	1.2	Low
MS2	0.5 mg/L	3–4	3.0	Very low
MS3	1.0 mg/L	0–1	0.5	Very high

On the MS1 medium (0.2 mg/L BAP), explants formed only one or two weakly developed shoots (Table 1). The low cytokinin level was insufficient to induce the stimulus required for active meristematic division. Under these conditions, the effect of endogenous auxin became relatively dominant, leading to enhanced apical dominance and suppression of lateral shoot formation. As a result, the hormonal balance shifted in favor of auxin rather than cytokinin, and proliferation remained at a low level.

In contrast, on the MS3 medium (1.0 mg/L BAP), the high cytokinin concentration led to the formation of an expanded callus mass rather than active shoot formation (Table 1). Excessive cytokinin disrupted the hormonal balance with endogenous auxin, weakened differentiation signals, and redirected cellular development

toward callus formation. This represents a typical manifestation of hormonal imbalance, resulting in reduced regeneration capacity and impaired morphogenesis.

The obtained results overall indicate that the MS2 variant, characterized by a moderate cytokinin level, is the optimal proliferation medium for the microclonal propagation of *Paulownia tomentosa* (Figure 1). Cytokinin deficiency in the MS1 medium resulted in weak shoot formation, whereas excessive cytokinin levels in the MS3 medium disrupted differentiation and enhanced callus formation. These findings confirm that cytokinin balance in the culture medium is a critical factor for in vitro regeneration and demonstrate that a BAP concentration of approximately 0.5 mg/L is optimal for *P. tomentosa*.

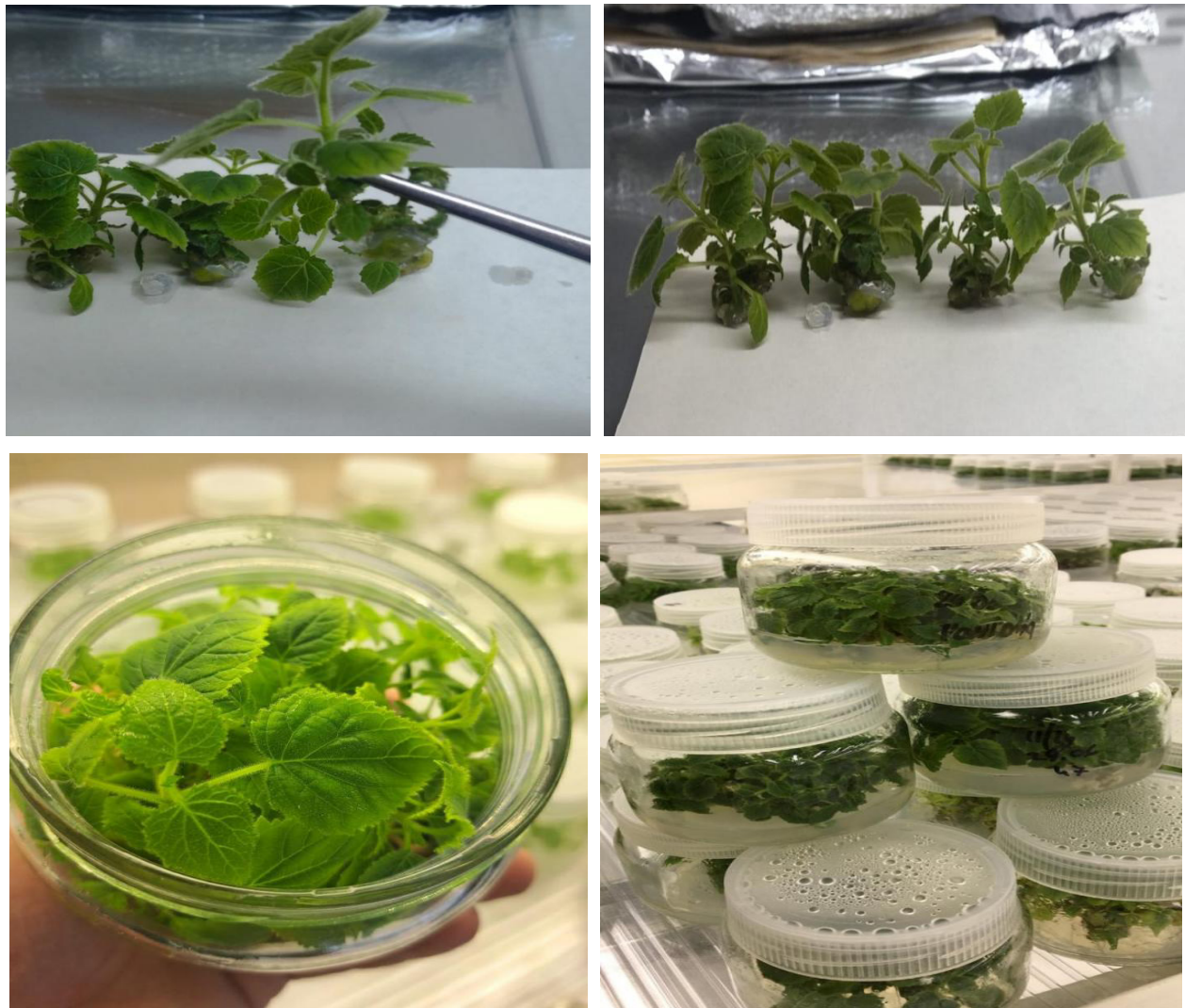


Figure 1. Development of *Paulownia tomentosa* microplants on MS2 culture medium during the micropropagation stage

The harmonic balance established between endogenous auxin present in the culture medium and the optimal BAP concentration (0.5 mg/L in the MS2 medium) ensures coordinated regulation of cytokinin-activated signaling pathways at the gene level together with the basal regulatory effect of auxin [Hill & Schaller, 2013; Suleymanova, 2024]. This hormonal interaction promotes synchronized cell division, shoot induction, and differentiation, thereby eliminating the limitations observed under cytokinin-deficient conditions (MS1) and excessive cytokinin

levels (MS3). Consequently, the optimal BAP concentration of 0.5 mg/L for *P. tomentosa* micropropagation is attributed not only to the direct positive effect of cytokinin but also to the establishment of a proper hormonal and genetic balance with endogenous auxin [Hill & Schaller, 2013; Zhenhua et al., 2020]. This balance is a key determinant for the successful completion of the in vitro regeneration process.

At the subsequent rooting stage, the parameters recorded for the development of *Paulownia tomentosa* are presented in Table 2.

Table 2. Effect of different hormone combinations on rooting of *P. tomentosa* microshoots

Variants	Plant medium composition	Rooting percentage (%)	Mean number of roots (no.)	Mean root length (cm)
I (Control)	0.1 mg/L BAP + 0.5 mg/L IBA	45%	2–3	1.5–2.0
II	0.1 mg/L BAP + 0.5 mg/L IBA + 0.1 mg/L NAA	65%	3–4	2.5–3.0
III	1.0 mg/L IBA + 0.1 mg/L NAA	100%	5–6	4.0–5.0
IV	1.0 mg/L IBA + 0.2 mg/L NAA	80%	4–5	3.0–3.5

As shown in Table 2, Variant I (0.1 mg/L BAP + 0.5 mg/L IBA — control) resulted in a rooting percentage of 45%, with an average of 2–3 roots formed per microshoot. The presence of BAP shifted the cytokinin–auxin balance away from the optimal level required for rooting and failed to sufficiently stimulate root induction in meristematic tissues. Consequently, both root number and root length were the lowest among all tested variants. This variant was therefore characterized by weak morphological development of the root system.

It should be noted that elevated cytokinin levels (BAP) during the rooting stage may negatively affect adventitious root formation. Although cytokinins stimulate cell division, they disrupt the auxin-dominant hormonal background by stabilizing AUX/IAA repressor proteins, which in turn suppress the activity of auxin-responsive genes belonging to the ARF, LBD, and WOX families [Wang et al., 2024; Zhenhua et al., 2020]. This inhibition impedes the formation of root primordia and their subsequent elongation, explaining the weak rooting observed in the control treatment.

In *Paulownia* species, sensitivity to cytokinins

is particularly high; thus, even 0.1 mg/L BAP can significantly reduce the effectiveness of auxin signaling. The absence of an auxin-dominant hormonal background limits the establishment of auxin gradients and the proper functioning of polar auxin transport, both of which are essential for root induction. While BAP-induced cytokinin signaling may enhance cell division, it simultaneously suppresses the cellular differentiation processes critical for rhizogenesis. As a result, variant I is characterized by poor root system development, indicating that this hormonal composition is far from optimal for rooting of *P. tomentosa* explants.

In variant II (0.1 mg/L BAP + 0.5 mg/L IBA + 0.1 mg/L NAA), the addition of 0.1 mg/L NAA to the MS medium, together with other hormones, had a partially positive effect on the rooting process, increasing the rooting percentage to 65%. The mean number of roots reached 3–4 per micro shoot, with an average length of 2.5–3.0 cm. In this treatment, partial improvement of the auxin balance stimulated root differentiation. This effect can be attributed to the low concentration of NAA, which influences auxin transport and contributes to the establishment of

intracellular auxin gradients. Auxin is the primary initiator of root formation and requires directional transport mediated by PIN transporters; low NAA concentrations support this transport and promote root differentiation. However, the presence of BAP prevented the complete elimination of cytokinin influence, and the auxin signaling pathway was therefore not fully activated. Elevated cytokinin levels affect the stabilization of AUX/IAA repressor proteins and restrict the activity of ARF transcription factors, which partially suppresses the formation of adventitious root primordia [Ma et al., 2024]. As a result, Variant II was characterized by moderate rooting performance. Nevertheless, the additional auxin supported polar auxin transport, facilitating lateral root formation and cell elongation. The partial hormonal harmony observed in this variant allowed stable root system development; however, achieving maximum rooting efficiency requires the cytokinin level to be minimized.

In variant III (1.0 mg/L IBA + 0.1 mg/L NAA — optimal), *Paulownia* micro plants exhibited the best overall performance across all evaluated parameters. The rooting percentage reached 100%, the mean number of roots was 5–6 per micro shoot, and root length ranged from 4 to 5 cm. These superior results can be explained by the auxin-dominant hormonal environment combined with a minimal cytokinin background. IBA effectively stimulated root induction, while NAA supported auxin distribution, activation of lateral root primordia, and root elongation. The 1.0/0.1 ratio of these two auxins provided an optimal auxin peak for *Paulownia*, maximizing both root number and root morphological quality.

From a hormonal perspective, this medium, in which cytokinin was completely minimized, maximally activated the ARF/Aux–IAA signaling pathway and the gene networks regulating root morphogenesis, thereby enabling effective differentiation of meristematic tissues toward root formation [Jan et al., 2024]. This combination optimally supports polar auxin transport, the establishment of intracellular auxin gradients, and root differentiation. Therefore, in *Paulownia*, complete elimination of cytokinin

during rooting corresponds to the species' auxin-demanding rhizogenesis strategy. Consequently, the 100% rooting frequency, average of 5–6 roots, and root length of 4–5 cm obtained in variant III can be interpreted as the result of harmonized auxin–cytokinin interactions at the cellular level, together with coordinated genetic signaling.

In variant IV (1.0 mg/L IBA + 0.2 mg/L NAA), the rooting percentage of micro plants reached 80%, with a mean root number of 4–5 per explant. The increased NAA concentration partially disrupted the auxin balance, leading to excessive auxin accumulation during the differentiation process. Under these conditions, ARF activity became unstable; although the root meristem was successfully initiated, the subsequent elongation phase was suppressed. As a result, roots were shorter and morphologically weaker, indicating that higher auxin concentrations do not necessarily result in improved rooting, and that hormonal balance plays a decisive role. Excessive NAA also increased the risk of callus formation, weakened the structural integrity of the meristematic zone at the root tip, and inhibited root elongation. High auxin levels did not prevent root primordium formation but interfered with cell elongation and differentiation processes. This effect may be associated with oxidative stress, hormonal toxicity, and reduced cell wall synthesis, ultimately leading to decreased root length and morphological quality. Although this variant was relatively effective, the elevated NAA level compromised stable root system development.

Overall, these results demonstrate that hormonal balance—specifically an auxin-dominant environment with minimal cytokinin and an optimal auxin concentration—plays a central role in the rooting of *P. tomentosa* microshoots. The ideal auxin/cytokinin ratio maximally activates root primordium formation, cell division, and differentiation, resulting in the development of healthy, elongated roots.

Thus, optimal rooting of *P. tomentosa* microshoots was recorded on MS medium supplemented with 1.0 mg/L IBA and 0.1 mg/L NAA (variant III), achieving a rooting frequency of 100%. The resulting root system development

was maximal for the studied plants and is expected to ensure high adaptation efficiency of plant regenerants to non-sterile conditions and to substrates that differ markedly from culture media in both physical and chemical properties.

After four weeks, the rooted plantlets were transferred to a cocopeat substrate. Cocopeat-filled paper pots containing the plants were placed in plastic transparent containers arranged in 60-cell trays and transferred to climate-controlled chambers. Fluorescent lamps were used as the light source (photoperiod 16/8 h, 3100–3500 lux), and the temperature was maintained at +23...+25°C. Acclimatization of the plants to ambient conditions was carried out gradually: during the first week, container lids were opened twice daily for 5 minutes; during the second week, twice daily for 15 minutes; and from the third week onward, twice daily for 30 minutes to provide ventilation. During the subsequent two weeks, plants were grown with the container lids fully open, after which they were transferred to the greenhouse [Suleymanova, 2022].

4. CONCLUSION

The conducted research allowed the determination of optimal conditions and culture media compositions for main stages of micropropagation of *Paulownia tomentosa*. At the initiation stage, the sterilization protocol achieved an effectiveness of 80%, indicating high efficiency of the selected sterilization scheme. During the micropropagation stage, the highest multiplication coefficient (3.0) was obtained on MS2 medium, whereas high BAP concentration in MS3 stimulated callus formation, and weak shoot development was observed on MS1 medium. At the rooting stage, several media were evaluated, and ½ MS medium supplemented with 1.0 mg/L IBA and 0.1 mg/L NAA was identified as optimal, resulting in 100% rooting and the formation of a strong, healthy root system. Overall, the obtained results confirm that a scientifically and practically efficient protocol for the micropropagation of *P. tomentosa* has been successfully developed. This method provides a reliable basis for the large-scale production of high-quality, genetically uniform, and healthy planting material in the future.

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