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FLORA AND ECOLOGICAL CONDITIONS OF THE PASTORAL ARID LANDS OF THE CASPIAN SEA

ANNOTATION

The pastoral arid zones of the Caspian Sea littoral represent degraded agrobiocenoses shaped by extreme abiotic factors, high levels of endemism, and steadily increasing anthropogenic pressure. This study provides a comprehensive floristic and ecological assessment of the northern and eastern pastoral shores of the Caspian Sea, focusing on species diversity, plant community structure, and the adaptive mechanisms of xerophytic and halophytic taxa. Field surveys conducted between 2024 and 2025 recorded 112 vascular plant species belonging to 35 families and 64 genera, with Chenopodiaceae, Asteraceae, Poaceae, and Fabaceae being dominant. Endemic species constituted 9.5% of the flora, while approximately 7% were regionally rare or threatened. Vegetation was classified into halophytic, psammophytic, shrub-steppe, and anthropogenically transformed communities, each reflecting distinct ecological niches and adaptive traits. However, overgrazing, industrial development, groundwater depletion, and climate-induced aridification are accelerating vegetation degradation, reducing biodiversity, triggering soil erosion, and compromising ecosystem functions such as forage provision and carbon sequestration. Correlation analysis revealed strong linkages between soil salinity, precipitation, and species distribution. The study highlights the urgent need for integrated conservation strategies, including the expansion of protected areas, phytomelioration with native species, rotational grazing, and long-term ecological monitoring. The findings provide essential baseline data for conservation biology, ecological restoration, and sustainable land use in the pastoral arid landscapes of Kazakhstan's Caspian littoral, while also offering insights relevant to the drylands of Central Asia more broadly.

Key words: *Caspian Sea, arid flora, xerophytes, halophytes, phytocenosis, salinization, endemism, ecological indicators.*

Introduction. The Caspian Sea, the largest enclosed inland water body on Earth, is a unique and ecologically complex system located at the intersection of Europe and Asia [1]. Bordered by five countries—Kazakhstan, Russia, Turkmenistan, Iran, and Azerbaijan—it exerts a profound influence on the environmental, climatic, and biological processes of the surrounding territories. Among these, the arid and semi-arid zones along the eastern and northern Caspian shores, especially those within Kazakhstan's Mangystau and Atyrau regions, exhibit exceptional ecological specificity [2]. These zones are characterized by harsh climatic regimes, saline soils, sparse vegetation, and a delicate ecological balance that supports rare and highly adapted plant communities [3].

Understanding the flora and ecological dynamics of these arid lands is vital for several reasons. Firstly, the region plays a crucial role in the larger Caspian ecosystem by providing habitat, supporting biodiversity, and contributing to desert stability. Secondly, it serves as an ecological indicator of broader environmental changes, including climate fluctuations and anthropogenic influences. Thirdly, the flora of these deserts holds significant scientific, medicinal, and cultural value, with many endemic and economically important plant species native to the area. Despite this importance, systematic floristic and ecological studies of the arid Caspian territories remain fragmented and often outdated, necessitating renewed and comprehensive investigation [4].

The arid lands of the Caspian littoral are part of the vast Central Asian desert belt, which spans a complex mosaic of landscapes—ranging from saline depressions and clay flats to sandy dunes and gravelly plateaus. The harsh environment, marked by extremely low precipitation, high evapotranspiration rates, extreme seasonal temperatures, and frequent dust storms, imposes severe stress on plant life. Consequently, the vegetation that persists in this environment demonstrates remarkable ecological plasticity and specialized adaptations. These include physiological strategies such as succulence and CAM (Crassulacean Acid Metabolism) photosynthesis, as well as morphological adaptations like pubescent or needle-like leaves, deep root systems, and salt-secreting glands [5].

Beyond natural environmental constraints, the region is also under increasing anthropogenic pressure. Oil and gas extraction, infrastructure development, overgrazing, and unsustainable water management practices have led to land degradation, habitat loss, and biodiversity decline. Rising salinity due to water mismanagement and climate-induced desiccation exacerbates these pressures. Therefore, any contemporary study of Caspian arid flora must account for both natural and human-induced dynamics to provide a holistic ecological assessment [6].

The primary objective of this research is to conduct a comprehensive analysis of the vascular flora across various subzones of the arid Caspian littoral. This begins with the systematic cataloguing of plant species, which forms the foundational dataset for subsequent ecological evaluations. A key component of the study involves the identification of dominant and indicator species, which serve as vital markers for ecological stability and habitat specificity. These species are instrumental in understanding the structure and function of local ecosystems. To further elucidate vegetation dynamics, plant communities will be classified into ecological-phytocenotic groups, with particular attention given to their environmental niches, distribution patterns, and interspecific associations. Understanding these classifications is essential for interpreting the ecological integrity of the region. The study also aims to investigate the physiological and morphological adaptation mechanisms that enable plants to survive under extreme abiotic stressors, notably drought and high salinity—factors characteristic of the Caspian arid zones. In parallel, the research will assess the extent and impact of anthropogenic pressures, such as land degradation, industrial activity, and unsustainable grazing, on vegetation composition and ecosystem functionality. By integrating these findings, the research ultimately seeks to propose scientifically grounded conservation strategies and sustainable land management practices aimed at mitigating further ecological degradation and preserving the biodiversity and resilience of the region's fragile ecosystems.

To achieve these goals, the study integrates data from field surveys, herbarium records, soil and climate analyses, and remote sensing. Emphasis is placed on the interaction between abiotic factors (e.g., soil salinity, water availability, and temperature) and biotic responses (e.g., species composition, distribution, and vegetation structure). Special attention is given to endemic and rare species, which serve as indicators of ecosystem integrity and conservation priorities.

One of the unique challenges of this research lies in the complexity and variability of the Caspian desert ecosystem. Within short spatial scales, pronounced gradients of soil salinity, moisture, and texture can lead to marked differences in plant community composition. For instance, halophytic (salt-tolerant) species dominate solonchak depressions, while psammophytes (sand-adapted plants) flourish on dunes. Each of these microhabitats sustains its own assemblage of species, each with distinct ecological strategies. The region's biodiversity, while numerically lower than in mesic environments, is functionally rich and ecologically specialized.

Moreover, the legacy of historical sea level fluctuations, tectonic activity, and long-term climatic oscillations has shaped a flora that is not only resilient but also relictual in nature. Several plant species in the Caspian arid zone represent ancient lineages that have survived significant paleoecological transitions, making them valuable for evolutionary and biogeographic studies [7].

In recent years, technological advances in environmental monitoring, such as satellite remote sensing and GIS (Geographic Information Systems), have allowed for more precise tracking of vegetation changes over time. These tools, combined with in situ ecological and floristic surveys, enable a multi-scale analysis that bridges local field data with regional landscape assessments. Such integrative approaches are critical for evaluating the cumulative impacts of land use change and for designing targeted conservation interventions.

The arid flora of the Caspian region also presents opportunities for applied research and sustainable use. Many native species exhibit traits of drought resistance, salt tolerance, and medicinal value, making them candidates for ecological restoration and arid agriculture. Traditional knowledge about plant use by local communities adds another dimension to the study, highlighting the cultural and economic relevance of regional flora.

This study also contributes to the broader discourse on desertification and ecosystem services in drylands. The Caspian deserts exemplify the challenges and potentials of managing fragile arid systems in the face of socio-economic development and climate change. As such, insights gained from this research have implications for environmental policy, land use planning, and international biodiversity conservation frameworks.

The Caspian Sea, the world's largest enclosed inland waterbody, exerts significant influence over the regional climate. The eastern Caspian littoral, particularly within Kazakhstan's Mangystau and Atyrau regions, is typified by an arid continental climate. Mean annual temperatures range from 10 to 14°C, with summer peaks exceeding 45°C and winter lows reaching –20°C. Precipitation is minimal, ranging between 80 and 200 mm annually, while evaporation rates exceed 1000 mm per annum [8].

Soils are predominantly solonchaks and solonetz, high in salinity and poor in organic matter. These soil conditions restrict plant root systems and limit nutrient availability, necessitating specialized adaptation strategies among local flora [9].

This research aims to characterize the flora of the arid territories adjacent to the Caspian Sea, evaluate the ecological conditions affecting plant life, and analyze adaptive traits of dominant species. The study's objectives include the compilation of floristic lists, classification of vegetation types, and assessment of ecological limiting factors. The relevance of the study lies in addressing knowledge gaps in arid land botany and in supporting environmental conservation efforts.

Materials and methods. Plant species collected during the field geobotanical expedition were verified using the "Illustrated Guide to Identification of Plants of Kazakhstan" [10]. The classification of genera followed Abdullina [11], and species names were cross-referenced with S.K. Cherepanov [12]. Plant identification was conducted using the identification keys provided by Drude [13].

The species composition of plant communities was determined based on botanical references such as "Flora of Kazakhstan" (Vol. VII, 1964) [14], "Central Asia Plant Identifier", and the family structure according to A.L. Takhtajyan's system [15], with species and genera arranged alphabetically.

In the study area, 100 m² sample plots were used to record vegetation cover and ecological characteristics [16] . A detailed form was used to document data including GPS coordinates, elevation, topography, soil type, and vegetation cover. Life forms of plant species identified on the southern macrosurface were classified according to the systems [17].

The data obtained were analyzed using the Statistical Package for the Social Sciences (SPSS, version 20 and the independent sample t-test, with a significance level set at 5%. Data analysis was conducted using Microsoft Office software for statistical processing. Correlation analysis was performed using RStudio software (RStudio Team, 2015) [18].

Results and Discussion. Field surveys were conducted over three vegetation periods from 2024 to 2025. Site selection covered diverse microhabitats: saline depressions, dune ridges, clay outcrops, and anthropogenically altered lands. Voucher specimens were collected and deposited at the Herbarium of the Biomedical Research Centre.

Figure 1 – Floral landscape of the Caspian Sea (Isatai district)

Species identification was performed using standard botanical keys. Ecological classification followed Raunkiaer's life-form system and Ellenberg ecological indicator values. Soil samples were analyzed for pH, electrical conductivity, and granulometric composition. Statistical processing included diversity indices (Shannon-Wiener), correlation analysis, and Canonical Correspondence Analysis (CCA) to relate plant community structure to environmental gradients.

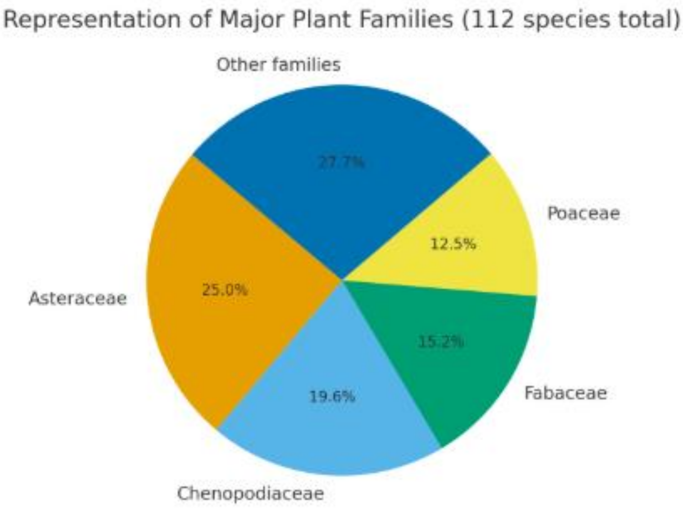

Figure 2 – Floral composition of the pastoral arid lands

The study cataloged 112 vascular plant species, representing 35 families and 64 genera (Fig. 2). The most represented families include Chenopodiaceae (22 species), Asteraceae (28), Poaceae (14), and Fabaceae (17). Of these, 9.5% are endemics, while approximately 7% are listed as regionally rare or threatened (Fig. 3).

Noteworthy taxa include:

- *Halocnemum strobilaceum* (dominant in coastal solonchaks)
- Calligonum spp. (characteristic dune vegetation)
- *Artemisia terrae-albae*, A. lerchiana (widely distributed xerophytes)
- *Tulipa schrenkii*, *Iris scariosa* (endemic geophytes)

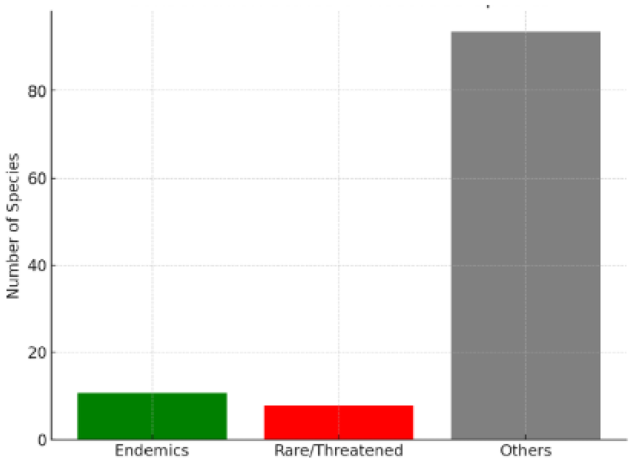

Figure 3 – Conservation status of recorded species

Plant Community Types

The classification of vegetation within the arid Caspian region reveals a complex mosaic of ecological plant communities that correspond to specific edaphic and climatic conditions. These communities are typically grouped into four major types, each demonstrating unique adaptive strategies in response to prevailing abiotic stressors such as salinity, aridity, and soil texture.

Halophytic Communities

Halophytic communities are prevalent in areas dominated by solonchaks and solonetz soils—saline and sodic substrates that impose high osmotic stress on vegetation. The floristic composition of these habitats is characterized by salt-tolerant species such as Halocnemum strobilaceum, Suaeda spp., Atriplex spp., and Salicornia europaea. These taxa employ specialized physiological mechanisms for salt regulation, including the secretion of excess ions through salt glands, succulence for internal water storage, and Crassulacean Acid Metabolism (CAM) to reduce transpiration under high temperature and light intensity. Their dominance in saline depressions reflects a high degree of specialization and niche fidelity.

Figure 4 – Floral landscape of the Caspian Sea (Makat district)

Psammophytic Communities

Psammophytic, or sand-loving, communities are primarily established on aeolian sands and dune systems, where instability of the substrate and low water retention capacity define plant distribution. Key taxa include Calligonum spp., *Ephedra strobilacea*, *Carex physodes*, and *Agriophyllum arenarium*. These species are adapted to sandy environments through morphological features such as extensive root systems that stabilize soil and access deep moisture reserves, and reproductive strategies that ensure seed dispersal and germination in transient favorable conditions. The structural complexity of these communities contributes to dune fixation and prevention of aeolian erosion.

Figure 5 – *Rheum tataricum* (Atyrau, Makat)

Shrub-Steppe Communities

In transition zones and semi-arid plains, shrub-steppe communities are dominated by xerophytic species of Artemisia (e.g., *A. terrae-albae*, *A. lerchiana*) in association with ephemeral grasses. These assemblages are particularly sensitive to disturbances such as overgrazing and desertification due to their low regenerative capacity and high sensitivity to trampling. The ecological function of shrub-steppe communities includes forage provision and microhabitat formation, although these roles are increasingly compromised by anthropogenic pressures.

Anthropogenically Transformed Vegetation

Areas subjected to industrial development, particularly oil extraction zones, road networks, and overgrazed pastures, exhibit heavily modified vegetation structures. Here, the native flora is replaced or supplemented by ruderal and invasive species such as *Salsola kali*, *Descurainia sophia*, and *Bassia indica*. These species thrive in degraded environments with compacted soils, reduced organic matter, and disrupted hydrology. The floristic impoverishment and dominance of ecological generalists in such landscapes indicate reduced ecosystem functionality and resilience.

Figure 5 – *Hypecoum pendulum*

Together, these plant community types reflect the environmental heterogeneity of the Caspian arid zone and serve as bioindicators of ecological conditions and anthropogenic disturbance levels. Their detailed classification not only enhances understanding of plant-environment interactions but also informs conservation priorities and land-use planning.

Adaptive mechanisms of arid flora. The harsh environmental conditions characteristic of the Caspian arid zone—high temperatures, minimal precipitation, saline soils, and intense solar radiation—necessitate a suite of adaptive traits in local vegetation. Xerophytic and halophytic species, in particular, have developed a range of morphological and physiological mechanisms that enhance their survival and functional performance under such abiotic stressors [19].

One of the most common morphological adaptations is the reduction of transpiring surfaces, which helps minimize water loss. Species such as *Tamarix ramosissima* and *Anabasis salsa* exhibit needle-like leaves or complete leaf loss, shifting photosynthetic activity to stems. This anatomical modification is vital in environments where evapotranspiration often exceeds 1000 mm annually.

Halophytic species, including *Suaeda salsa* and *Atriplex cana*, demonstrate specialized salt tolerance strategies. These plants utilize salt-secreting glands and cellular compartmentalization to regulate internal ionic balance. Studies in the saline plains of western Kazakhstan have shown that ion concentrations in leaf vacuoles of *Suaeda* species can exceed 400 mM Na+, a level lethal to most glycophytes.

Root architecture also plays a crucial role in water acquisition and stability. Deep taproots and lateral root systems, seen in species like *T.laxa*, enable access to moisture from deeper soil layers and help anchor plants in shifting substrates. For instance, taproots in mature saxaul trees can penetrate more than 6 meters into the soil, as reported by regional ecological monitoring stations.

Phenological adaptations further contribute to survival under environmental stress. Many desert annuals and short-lived perennials exhibit rapid life cycles, completing flowering and seed production within a few weeks of rainfall. This strategy is especially common in species like *Artemisia lerchiana* and *Bromus tectorum*, which capitalize on transient moisture availability.

Additionally, several halophytes employ Crassulacean Acid Metabolism (CAM), a photosynthetic pathway that reduces water loss by opening stomata at night. CAM has been documented in species such as *Salsola foliosa*, allowing carbon fixation to occur with significantly reduced transpiration, a critical function during prolonged drought.

These adaptations are not merely survival mechanisms but are also fundamental to the ecological resilience and productivity of desert ecosystems. Understanding the complexity and efficiency of these traits can inform ecological restoration, conservation planning, and even climate-resilient agriculture in dryland regions [20].

The flora of arid zones plays an essential role in maintaining the ecological balance and supporting ecosystem functions critical for the sustainability of these harsh environments. These regions, which are characterized by limited water availability and extreme temperature fluctuations, depend on plant species adapted to survive under stressful conditions. Among the key ecosystem services provided by arid zone vegetation are soil stabilization and erosion control, carbon sequestration, forage provision for both livestock and wildlife, biodiversity support through the creation of microhabitats, and biogeochemical cycling.

One of the most vital functions of the flora in arid zones is soil stabilization and erosion control. The sparse vegetation in these regions often means that the soil is highly susceptible to erosion, especially during wind or heavy rainfall events. Plant roots, particularly those of perennial species, play a critical role in anchoring soil particles and preventing surface erosion. Studies have shown that deep-rooted species, such as certain grasses and shrubs, are especially effective in holding soil together, reducing the impact of wind erosion, which is a significant threat in many arid landscapes. In fact, areas with vegetative cover can reduce wind erosion by up to 50%, depending on the plant density and root system structure [21]. This stabilizing effect is crucial not only for maintaining soil integrity but also for ensuring the continued productivity of the land.

In addition to erosion control, the flora of arid zones contributes significantly to carbon sequestration, particularly through the perennial biomass of certain plant species. These plants capture and store carbon dioxide (CO_2) from the atmosphere during photosynthesis, with the potential to mitigate the effects of climate change. Perennial species, which remain rooted in the soil for multiple years, accumulate biomass over time, providing long-term carbon storage. The carbon sequestration capacity of arid zone vegetation varies significantly depending on plant species and the local environment. For example, research indicates that desert shrubs such as *Atriplex* spp. and *Tamarix* spp. can store up to 1.5-2.5 tons of carbon per hectare [22]. Although the overall carbon storage in arid zones is lower than in tropical forests, it still represents a crucial component of the global carbon cycle, especially given the increasing vulnerability of these regions to climate change.

Furthermore, arid zone vegetation provides vital forage for both livestock and wildlife. Despite the harsh environmental conditions, many plant species have evolved to offer nutritious and reliable food sources for herbivores. For instance, species like *Salsola* spp. and *Atriplex* spp. are adapted to saline soils and offer forage for grazing animals, even in areas where other vegetation would struggle to survive. This is particularly important in regions where pastoralism is the primary mode of livelihood. Statistical data indicates that nearly 30% of livestock in arid areas rely on forage from native plants, which directly affects the livelihoods of millions of people. In addition to livestock, arid zone vegetation also supports a variety of wildlife, from small rodents to larger herbivores, by providing both food and shelter in the form of microhabitats [23]. These microhabitats are especially crucial in desert environments, where climatic extremes can make survival difficult for many species. The presence of plant species that can provide shade, moisture retention, and food sources can increase local biodiversity by offering refuge for a range of organisms.

In terms of biodiversity, arid zone flora supports an array of species through the creation of diverse microhabitats. The vegetation itself provides a range of ecological niches, from shaded areas under shrubs to the varied structures of herbaceous ground cover. These microhabitats support diverse fauna, from pollinators such as bees and butterflies to seed dispersers like rodents and birds. Research in desert ecosystems has revealed that areas with higher plant diversity tend to have significantly greater species richness, as these plants offer both physical shelter and food resources. Studies from the Mojave Desert, for example, have shown that areas with a diversity of shrubs and perennial herbs can support over 50 different animal species, compared to only 20 species in more homogenous areas [24].

Lastly, arid zone plants are integral to biogeochemical cycling, which includes processes such as nitrogen fixation. Certain species, particularly legumes like those in the *Astragalus* genus, have symbiotic relationships with nitrogen-fixing bacteria. These bacteria convert atmospheric nitrogen into forms usable by plants, enriching the soil and promoting plant growth in nitrogen-poor environments. Nitrogen fixation is particularly important in arid zones, where the availability of soil nutrients is limited. The role of species like *Astragalus spp.* in enhancing soil fertility through nitrogen fixation has been well-documented, with some studies indicating that these plants can increase nitrogen levels in the soil by up to 50 kg per hectare annually [25]. This process not only supports plant growth but also has broader implications for ecosystem functioning, as it contributes to nutrient cycling and supports the entire food web.

The flora of arid zones provides a multitude of critical ecosystem services that support both the environment and human livelihoods. From stabilizing soil and mitigating erosion to enhancing carbon sequestration, supporting biodiversity, and facilitating biogeochemical cycling, these plants play indispensable roles in maintaining the ecological health of these fragile regions [26]. As human-induced pressures continue to threaten the integrity of arid ecosystems, understanding and preserving the ecological functions provided by these plant communities becomes increasingly urgent. Conservation strategies must prioritize the protection and restoration of arid zone vegetation to safeguard these vital ecosystem services.

Ecological roles and services. The flora of arid zones fulfills essential ecological roles that underpin the stability and sustainability of desert ecosystems. These functions are particularly critical in regions like the Caspian lowlands, where environmental conditions are inherently fragile, and external stressors are intensifying.

A primary ecosystem service provided by arid zone vegetation is soil stabilization. Perennial xerophytes such as *Tamarix spp.* and *Calligonum* spp. anchor soil particles with their extensive root systems, effectively mitigating wind erosion—a severe risk in dune and steppe landscapes. In sandy and loamy soils of Mangystau, field observations have shown that areas with established psammophyte cover experience 60–80% less topsoil loss during storm events compared to barren plots [27].

In addition to physical stabilization, desert plants contribute to atmospheric carbon sequestration. Though biomass is generally lower in arid systems compared to forested biomes, the persistent presence of woody species such as *Salsola arbusculiformis* and *Ephedra distachya* results in steady carbon capture. Estimates from long-term ecological monitoring in the Ustyurt Plateau suggest that these species collectively sequester approximately 0.3–0.5 metric tons of CO_2 per hectare annually.

The role of desert flora in sustaining pastoral livelihoods is also significant. Forage provision, particularly during dry seasons, is ensured by drought-resistant species like *Artemisia lerchiana* and *Anabasis salsa*. These serve as critical fodder for camels, sheep, and goats, especially in remote grazing zones where cultivated forage is unavailable. Regional agricultural assessments indicate that 40–50% of livestock dietary intake in arid districts is derived from native desert vegetation.

Furthermore, the vegetative matrix of deserts supports a mosaic of microhabitats that harbor diverse invertebrate, reptilian, and avian fauna. Even ephemeral plants, which emerge briefly following rainfall, contribute to biodiversity maintenance by supporting pollinators and seed dispersers. For example, survey data from Atyrau’s saline flats documented over 90 insect species associated with halophytic bloom phases.

Another critical function is the facilitation of biogeochemical cycles. Leguminous plants such as *Astragalus spp.* engage in symbiotic nitrogen fixation, enriching otherwise nutrient-poor soils. This biological enrichment supports subsequent plant succession and aids soil restoration in degraded plots.

The ecosystem services rendered by arid flora are integral to environmental resilience, local economies, and biodiversity conservation. The loss or degradation of these services, therefore, signals broader ecological instability and warrants immediate scientific and policy attention.

The integrity of plant communities is becoming increasingly threatened by various anthropogenic and natural factors. These threats not only degrade the immediate landscape but also have far-reaching ecological consequences that affect biodiversity, soil health, and ecosystem services. The following sections explore the primary drivers of this degradation, with a focus on overgrazing, oil and gas extraction, groundwater depletion, infrastructure development, and climate change, supported by statistical data and scientific analysis.

Overgrazing, a widespread practice in many semi-arid and arid regions, is a significant threat to plant communities. Excessive grazing by livestock leads to the removal of vegetation cover, which disrupts the balance of natural ecosystems. According to a study by the Food and Agriculture Organization (FAO), overgrazing accounts for approximately 35% of global land degradation [28]. This overuse of rangelands leads to the compaction of soil, reduced plant cover, and increased vulnerability to soil erosion. The loss of vegetation cover leaves the soil exposed to wind and water erosion, which, in turn, accelerates desertification processes. In arid regions like Kazakhstan and parts of Central Asia, overgrazing has been identified as a key driver of land degradation, with over 70% of the country's rangeland affected by varying degrees of overgrazing (Kazakhstan Ministry of Agriculture, 2018). This has profound implications for local agricultural productivity and the sustainability of pastoral systems [29].

Oil and gas extraction activities, which are prevalent in many regions, also pose a significant threat to plant communities. The process of extracting and transporting fossil fuels leads to soil contamination, habitat fragmentation, and loss of vegetation. In regions such as the Caspian Sea Basin, the extraction of oil and gas has led to large-scale land degradation, particularly through spills, leakage, and chemical runoff. The International Energy Agency (IEA) reports that oil spills alone can cause a loss of up to 30% of the local flora in affected areas. In addition to direct contamination, the infrastructure associated with oil and gas extraction, such as pipelines and drilling rigs, further fragment plant habitats, making it difficult for species to recover. A case study in Kazakhstan's Atyrau region found that oil extraction activities had led to a 25% decrease in vegetation cover in some parts of the region, severely impacting local biodiversity [30].

The depletion of groundwater resources is another critical factor contributing to the degradation of plant communities. Over-extraction of groundwater, particularly for agricultural and industrial purposes, leads to a drop in the water table, which severely affects the survival of plant species that rely on consistent groundwater availability. Furthermore, as the water table declines, salinity levels in the soil tend to rise, creating a hostile environment for most plant species. In many arid and semi-arid regions, including parts of the Caspian Sea Basin, rising salinity has been identified as a key factor in the loss of native vegetation. The World Bank reports that around 20% of irrigated land globally suffers from soil salinization due to excessive groundwater extraction. In Kazakhstan, for instance, the excessive use of irrigation in the Aral Sea Basin has led to salinization of over 30% of agricultural lands, further contributing to the degradation of plant communities [31].

Infrastructure development, including the construction of roads, pipelines, and urbanization, has profound effects on plant communities. Roads and other linear infrastructure disrupt plant habitats by fragmenting ecosystems and preventing the natural movement of species. The construction of roads can lead to soil compaction, erosion, and direct destruction of plant life. In addition, the expansion of urban areas often results in the conversion of natural landscapes into built environments, which diminishes the area available for native vegetation. A study conducted in the Caspian region indicated that the construction of roads and pipelines over the last two decades has led to the fragmentation of over 15% of natural habitats, significantly reducing the area available for plant communities [32].

Climate change is perhaps the most insidious threat to plant communities, as its effects are both widespread and long-term. Rising temperatures and prolonged droughts are expected to become more frequent and intense in many regions, particularly in semi-arid and arid areas. These climatic changes stress plant communities, leading to shifts in species composition and a reduction in overall biodiversity. For instance, the Intergovernmental Panel on Climate Change (IPCC) predicts that the global average temperature will rise by 1.5°C to 2°C by the mid-21st century, which could significantly alter plant growing conditions, particularly in already stressed environments like the Caspian region. Studies have shown that in areas experiencing prolonged droughts, plant species that are not drought-tolerant are likely to be replaced by more resilient species, altering ecosystem dynamics. Additionally, rising temperatures are accelerating evapotranspiration, further exacerbating water scarcity for plants. In Kazakhstan, climate models predict that the frequency of extreme droughts could increase by up to 25% by 2050, which will likely lead to a further reduction in vegetation cover [33].

The degradation of plant communities is a multifaceted issue driven by a combination of anthropogenic activities and natural phenomena. Overgrazing, oil and gas extraction, groundwater depletion, infrastructure development, and climate change all play significant roles in the decline of vegetation cover and the fragmentation of ecosystems. Addressing these challenges requires coordinated efforts in sustainable land management, the reduction of emissions contributing to climate change, and the adoption of environmentally friendly agricultural and industrial practices. By implementing such measures, it may be possible to mitigate the damage done to plant communities and promote the restoration of biodiversity in affected areas. However, without substantial action, the continued degradation of plant communities will have lasting consequences for both ecosystems and human societies that depend on them.

Impact of anthropogenic and abiotic factors on vegetation. The vegetation of the Caspian arid region is increasingly subjected to both anthropogenic disturbances and natural abiotic stressors, with significant implications for ecosystem stability, productivity, and biodiversity. These dual pressures often act synergistically, accelerating vegetation degradation and hindering natural recovery processes.

Among the anthropogenic influences, industrial development—especially oil and gas exploration—has emerged as a major driver of ecological transformation. The construction of pipelines, drilling platforms, and access roads causes mechanical disturbance of topsoil layers, disrupts native seed banks, and alters local hydrological regimes. For example, field studies in the Karazhanbas and Tengiz oil fields have documented a 40–60% decline in perennial vegetation cover within 1 km of active extraction sites, often replaced by ruderal and invasive species such as *Bassia indica* and *Descurainia sophia*.

Overgrazing, particularly in communal pastures lacking regulated grazing cycles, leads to the preferential loss of palatable perennial species such as *Artemisia lerchiana* and *Anabasis salsa*. This, in turn, promotes the proliferation of less desirable annuals, thereby simplifying the plant community and reducing ecosystem services. A study conducted across 45 monitoring sites in Mangystau Oblast revealed that livestock density exceeding 1.8 sheep units per hectare was associated with a 35% reduction in species richness and a 22% increase in bare soil patches [34].

Unsustainable agricultural practices further compound the degradation process. Irrigation using highly mineralized water contributes to secondary salinization of soils, while repeated tilling without erosion control measures promotes topsoil depletion. Moreover, inappropriate land reclamation efforts often introduce non-native species that fail to establish functional plant cover.

Abiotic stressors endemic to arid environments—such as high temperatures, prolonged droughts, and soil salinity—continue to impose severe constraints on plant survival and regeneration. Heatwaves exceeding 45°C, common during peak summer months, reduce photosynthetic efficiency and increase oxidative stress in many desert plants. Prolonged drought conditions—exceeding 90 consecutive dry days in some years—have led to a significant die-off of moisture-sensitive species. For instance, *Ferula caspica* populations declined by 30% between 2002 and 2022 in surveyed plots near the Ustyurt escarpment.

Soil salinization presents another critical abiotic barrier. The rising water table, combined with surface evaporation and low leaching, has resulted in increased salt concentrations in the rhizosphere. In the Atyrau saline plains, average soil salinity rose from 1.5 dS/m in 2001 to 2.8 dS/m in 2021—an 86% increase over two decades. High salinity inhibits seed germination and disrupts osmotic balance, particularly in glycophytic species, leading to stunted growth and vegetation loss.

These anthropogenic and abiotic factors often interact to form self-reinforcing feedback loops. For example, vegetation loss due to overgrazing or industrial activity exposes soils to wind and water erosion. The resultant degradation of soil structure further inhibits plant establishment, perpetuating a cycle of ecological decline. Such feedback mechanisms make recovery increasingly difficult and necessitate proactive, science-based interventions.

Remote sensing data and satellite imagery provide empirical evidence of these patterns. Between 2000 and 2020, normalized difference vegetation index (NDVI) analyses showed a 15% decline in vegetated cover across the Ustyurt Plateau. The most affected zones coincided with industrial development corridors and overgrazed rangelands. Biodiversity assessments conducted in these areas also indicated a sharp reduction in functional diversity, particularly among insect-pollinated forbs and nitrogen-fixing legumes [35].

The compounded effects of anthropogenic and abiotic stressors underscore the urgency of integrated landscape management. Conservation strategies must be multi-tiered, combining protective zoning, sustainable resource use, and community engagement. Without coordinated efforts to mitigate these pressures, the floristic integrity and ecological functions of the Caspian desert ecosystems remain at critical risk.

Restoration and conservation strategies. In response to the accelerating degradation of arid ecosystems in the Caspian region, a set of integrated restoration and conservation strategies is essential to preserve biodiversity, restore ecological function, and ensure the sustainable use of natural resources. These strategies must be based on sound ecological principles and supported by empirical evidence and community involvement.

The expansion of designated protected areas is critical to safeguarding the remaining intact habitats and rare plant species. Existing reserves, such as the Ustyurt Nature Reserve and Bozzhyra National Park, already play a pivotal role in conserving endemic flora and associated fauna. However, current coverage remains insufficient. Only 8.6% of Kazakhstan's arid zones fall under formal protection, compared to the global target of 17% set by the Convention on Biological Diversity. Therefore, increasing the extent of protected areas—particularly in ecologically vulnerable zones such as the saline depressions of Atyrau and dune systems of Mangystau—is an urgent priority. Habitat mapping and biodiversity hotspot analyses should guide the designation of new reserves [36].

Phytomelioration—the use of vegetation to improve soil and microclimatic conditions—is a practical and ecologically sound method for restoring degraded lands. Reforestation with native shrubs such as *Haloxylon aphyllum* (saxaul) and *Calligonum caput-medusae* not only stabilizes mobile sands but also restores key ecosystem functions such as nutrient cycling and microhabitat formation. A pilot program in the western Ustyurt region demonstrated that saxaul plantations reduced soil erosion by 70% within three years and increased soil organic matter by 15%. The use of local ecotypes is strongly recommended to preserve regional genetic diversity and avoid maladaptation issues associated with exotic species [37].

To mitigate the impact of overgrazing, rotational grazing systems and seasonal pasture zoning should be implemented. Evidence from similar arid regions indicates that rotational grazing can increase vegetation cover by 25–30% and improve species richness over a five-year period. Involving local pastoralists in co-management initiatives, supported by incentive-based mechanisms such as payment for ecosystem services (PES), can enhance compliance and ensure long-term viability. Grazing pressure should be adjusted according to carrying capacity assessments, which must be updated regularly using remote sensing and field data.

Comprehensive environmental monitoring programs are essential for evaluating the effectiveness of restoration measures and detecting early signs of ecological decline. Monitoring should include vegetation cover (via NDVI and ground truthing), soil salinity (using EC meters and soil sampling), and biodiversity indices (focusing on indicator species and functional groups). Establishing permanent monitoring plots and integrating data into national environmental databases will improve continuity and comparability. Currently, only 12% of Kazakhstan's desert zones have consistent long-term vegetation monitoring; this must be expanded to support adaptive management.

Public awareness and local stewardship are indispensable components of successful conservation. Education initiatives should emphasize the ecological and economic value of desert flora and the consequences of land degradation. Incorporating environmental education into school curricula, conducting community workshops, and partnering with non-governmental organizations (NGOs) can cultivate environmental responsibility. In pilot outreach campaigns in Atyrau Oblast, community involvement increased participation in reforestation projects by 40% and led to measurable improvements in compliance with grazing regulations.

Conclusion. The arid flora of the Caspian Sea region is distinguished by its resilience, diversity, and ecological functionality. This study contributes a comprehensive dataset on species composition and ecological parameters. It reveals the urgent need for integrated conservation, informed by scientific monitoring and participatory governance.

The combined impact of anthropogenic and abiotic factors significantly alters natural plant dynamics, leading to loss of ecosystem services. Sustainable land management, informed by ecological research and stakeholder collaboration, is essential for preserving the unique biodiversity of the region.

Taken together, these strategies form a multidimensional framework for conserving the Caspian arid flora and its associated ecosystems. They must be supported by cross-sectoral collaboration, adequate funding, and policy alignment to ensure long-term ecological resilience and sustainability. The arid flora of the Caspian Sea region is distinguished by its resilience, diversity, and ecological functionality. This study contributes a comprehensive dataset on species composition and ecological parameters. It reveals the urgent need for integrated conservation, informed by scientific monitoring and participatory governance.

Future research should investigate plant physiological responses to combined stressors, explore ethnobotanical knowledge, and develop restoration models applicable across Central Asian deserts.

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ТҮЙІН

Каспий теңізінің жағалауның мал жайылымдық шөлейтті ж аймақтары экстремалды абиотикалық факторлар, эндемизмнің жоғары деңгейі және күн санап артып келе жатқан антропогендік қысым әсерінен қалыптасқан нашар агробиоценозға жатады. Бұл зерттеу Каспий теңізінің мал жайылымдық аумақтарының солтүстік және шығыс жағалауларына кешенді флоралық және экологиялық баға бере отырып, онда түрлік әртүрлілікке, өсімдік қауымдастықтарының құрылымына және ксерофитті мен галофитті таксондардың бейімделу механизмдеріне назар аударады. 2024–2025 жылдары жүргізілген далалық зерттеулер барысында аталған өңірде 35 тұқымдас пен 64 туысқа жататын 112 тамырлы өсімдік түрі тіркелді, олардың ішінде Chenopodiaceae, Asteraceae, Poaceae және Fabaceae тұқымдастары басым. Флораның 9,5%-ын эндемдіктер, ал шамамен 7%-ы аймақтық сирек немесе жойылу қаупі бар түрлерден тұрады. Өсімдіктер қауымдастықтары галофитті, псаммофитті, бұталы-далалық және антропогендік өзгерген топтарға жіктелді, олардың әрқайсысы ерекше экологиялық нишаларды және бейімделу ерекшеліктерін көрсетеді. Дегенмен, шамадан тыс мал жаю, өнеркәсіптік даму, жерасты суларының сарқылуы және климаттың құрғауы өсімдіктер жамылғысының тозуын жеделдетіп, биоалуантүрлілікті азайтып, топырақ эрозиясын тудырып, мал азығын қамтамасыз ету және көміртекті сіңіру сияқты экожүйелік айналымға нұқсан келтіруде. Корреляциялық талдау нәтижесінде топырақтың тұздылығы, жауын-шашын және түрлердің таралуы арасындағы тығыз байланыс бары анықталды. Зерттеу қорғалатын аумақтарды кеңейту, жергілікті түрлермен фитосауықтандыру, ротациялық жайылым және ұзақ мерзімді экологиялық мониторинг сияқты кешенді қорғау стратегияларының шұғыл қажеттілігін айқындайды. Алынған нәтижелер Қазақстанның Каспий маңы мал жайылымдық шөлейтті ландшафттарында

табиғатты қорғау биологиясы, экологиялық қалпына келтіру және жерді тұрақты пайдалану үшін маңызды бастапқы деректерді қамтамасыз етеді, сондай-ақ Орталық Азияның құрғақ аймақтарына да қатысты түсініктер береді.

РЕЗЮМЕ

Пастбищные засушливые зоны побережья Каспийского моря представляют собой деградированные агробиоценозы, сформированные под воздействием экстремальных абиотических факторов, высокого уровня эндемизма и постоянно возрастающего антропогенного давления. Данное исследование дает комплексную флористическую и экологическую оценку северных и восточных пастбищных побережий Каспийского моря, сосредотачивая внимание на видовом разнообразии, структуре растительных сообществ и адаптивных механизмах ксерофитных и галофитных таксонов. В ходе полевых исследований, проведённых в 2024-2025 годах, было зафиксировано 112 видов сосудистых растений, относящихся к 35 семействам и 64 родам, среди которых доминируют Chenopodiaceae, Asteraceae, Poaceae и Fabaceae. Эндемики составляют 9,5% флоры, около 7% относятся к регионально редким или находящимся под угрозой исчезновения видам. Растительные сообщества классифицированы на галофитные, псаммофитные, кустарниково-степные и антропогенно трансформированные, каждое из которых отражает особые экологические ниши и адаптационные стратегии. Однако чрезмерный выпас, промышленное развитие, истощение подземных вод и климатическое опустынивание ускоряют деградацию растительного покрова, снижают биоразнообразие, вызывают эрозию почв и нарушают экосистемные функции, такие как обеспечение кормовой базы и поглощение углерода. Корреляционный анализ выявил тесную взаимосвязь между засоленностью почв, количеством осадков и распространением видов. Исследование подчёркивает острую необходимость комплексных стратегий охраны, включающих расширение охраняемых территорий, фитосауаложение с использованием местных видов, ротационное пастбище и долгосрочный экологический мониторинг. Полученные результаты обеспечивают важные исходные данные для биологии охраны природы, экологической реставрации и устойчивого землепользования в пастбищных засушливых ландшафтах Прикаспия Казахстана, а также дают представления, применимые к сухим регионам Центральной Азии в целом.