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CONTENTS

The Impact of Tree and Shrub Vegetation on the Ecological Condition of the Urban Environment Maria Martynova, Ilyas Fazlutdinov, and Alina Musabirova	5
Biodiversity Conservation in the Mountain Forests of the Greater Caucasus Aydin Yakhyaev and Adilagha Malikov	16
Manifestation and Forecast of Global Climate Change in Azerbaijan Aruz Mikayilov and Fatima Huseynova	32
Ecological Aspects of Soil Pollution and Ornamental Planting Opheliya Gafarova, Ulviyya Karimova-Japharova, and Jala Jafarova	45
Evaluation of Correlation and Regression Relationships Between Soil Solution Electrical Conductivity and Major Ion Concentrations Amrakh Mamedov, Ulkar Gadiyeva and Turkan Aghazade	56
Sustainable Municipal Solid Waste Management in the City of Baku: Contemporary Challenges and Innovative Solutions Badriya Ahmadova and Govhar Aydemirova	64

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The Impact of Tree and Shrub Vegetation on the Ecological Condition of the Urban Environment

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Abstract

This article examines the role of woody vegetation in the development of an ecologically sustainable urban environment, using Baku (Azerbaijan) and Ufa (Russia) as case studies. The principal natural, climatic, and anthropogenic factors affecting the condition of urban green spaces are analyzed, including atmospheric air pollution, arid climate, high wind exposure, soil salinization and compaction, altered hydrological conditions, overheating of artificial surfaces, mechanical damage, and recreational pressure. The urban environment is considered as a multi-stress system, in which multiple adverse factors act simultaneously and interact synergistically, amplifying their overall impact on vegetation. The sanitary-hygienic, climate-regulating, soil-protective, noise-reducing, biological, and recreational functions of trees and shrubs are characterized. Particular attention is paid to the tolerance of different tree species to the specific environmental conditions of the Absheron Peninsula. Morphological and physiological responses of plants to water deficit, air pollution, soil salinity, heat stress, and restricted root-growing space are discussed. The study demonstrates that the ecological effectiveness of urban greening depends not only on the extent of green areas and the number of planted trees but also on appropriate species selection, soil quality, efficient irrigation management, proper silvicultural and horticultural practices, and regular monitoring of urban vegetation. The necessity of developing a multifunctional and species-diverse green infrastructure based on native species and promising introduced taxa adapted to arid climatic conditions and intensive anthropogenic pressure is substantiated. Recommendations are proposed for improving the urban greening system with the aim of increasing the longevity and resilience of urban plantings and enhancing the ecosystem services they provide.

Keywords: woody vegetation, urban greening, urban environment, ecological sustainability, green infrastructure, ecosystem services, anthropogenic pressure

1. Introduction

The current stage of social development is characterised by rapid urbanisation, the expansion of urban development and an increase in the anthropogenic pressure on the natural components of the environment. The development of transport infrastructure, industry, the energy sector and housing construction is accompanied by the transformation of natural landscapes, the sealing of soils with artificial surfaces, changes to the hydrological regime, air pollution and a reduction in the area of natural plant communities (Məmmədov & Xəlilov, 2005; Goryshina, 1991; Gill et al., 2007).

A city is a complex techno-natural system in which natural and man-made components are in constant interaction. Unlike natural ecosystems, which possess a marked capacity for self-regulation, the urban environment depends on a continuous supply of resources and targeted management interventions. Disruption of the natural cycle of matter, high-density development, the prevalence of asphalt and concrete surfaces, significant emissions of pollutants, and intensive land use create specific conditions for plant life (Goryshina, 1991; Kolesnikov, 1974; Kulagin, 1974; Mozolevskaya et al., 1984).

Trees and shrubs are one of the key natural components of the urban environment. They help to purify the air, trap dust particles, absorb some gaseous pollutants, regulate temperature and humidity, reduce wind speed, stabilise the soil, mitigate noise pollution and provide habitats for urban wildlife (Bukharina et al., 2007; Gill et al., 2007; Liang & Huang, 2023; Livesley et al., 2016; Roy et al., 2012). At the same time, green spaces fulfil architectural, planning, aesthetic and recreational functions, shaping the city's visual appearance and enhancing the comfort of the urban environment.

However, the trees themselves in the city are subjected to prolonged exposure to a range of adverse factors. Urban air may contain nitrogen and sulphur oxides, carbon monoxide, hydrocarbons, aerosol particles and heavy metal compounds. The soil is characterised by compaction, structural disruption, a lack of organic matter, poor aeration and localised salinisation. Artificial surfaces restrict the penetration of atmospheric precipitation to the roots, whilst the heating of tarmac, buildings and engineering structures raises the temperature of the air and soil (Qasimova & Hacıyev, 2008; Alekseev, 1989; Mozolevskaya et al., 1984; Nikolaev, 2003; Perel'man, 1975; Rozanov, 2004).

In addition to the factors listed above, there is mechanical damage to trunks and root systems, incorrect pruning, a limited number of planting sites, the impact of construction work, vibration from traffic, shading caused by buildings, and artificial lighting at night. The combined effect of these factors gives rise to a phenomenon which, in urban ecological research, is characterised as 'urban tree syndrome' or a state of chronic multi-stress (Alekseev, 1989; Mozolevskaya et al., 1984; Rozanov, 2004; Escobedo et al., 2011).

Issues relating to environmentally sound landscaping are of particular relevance. The natural and climatic conditions of the Absheron Peninsula (Republic of Azerbaijan) and the city of Baku are characterised by low levels of precipitation, prolonged dry spells, high summer temperatures, intense solar radiation and significant wind loads. Further factors include the salinity of certain soils, marine aerosols, high-density urban development, heavy road traffic and the local impact of numerous industrial sites (Məmmədov, 2010; Qasimova & Hacıyev, 2008; Məmmədov & Xəlilov, 2005; Məmmədov & Gülməmmədova, 2007; Baki Sheherinin Bash Planı, 2040).

The natural conditions of the city of Ufa (Republic of Bashkortostan, Russian Federation) are characterised by a temperate continental climate, with moderately harsh winters ((-14) – (-16) °C) and warm, humid summers (17–19 °C). The weather is characterised by high variability and unpredictability. At the same time, the city of Ufa is a major centre of industrial activity, making a significant contribution to the Russian economy, chiefly as a result of the high level of development of the petrochemical and chemical industries, as well as the engineering sector. Other issues include population size, the condition of road surfaces, a lack of public transport, and a lack of attention to environmental issues on the part of business owners (Kamynina, 2026; Khalikova & Isyanyulova, 2019).

Given the variety of conditions, the viability of green spaces is determined not only by the quality of the planting stock and the intensity of maintenance, but above all by the suitability of the plants' biological characteristics to the specific conditions of the site. The species used along major transport routes must be particularly resistant to gas, dust, salt and drought. Plants planted in parks and recreational areas should, in addition to being environmentally sustainable, be highly ornamental, have a well-developed canopy and be capable of creating a favourable microclimate. For coastal areas, such as Baku, resistance to wind and the effects of salt spray is particularly important (Məmmədov, 2010; Məmmədov & Gülməmmədova, 2007; Baki Sheherinin Bash Planı 2040).

Consequently, a modern urban greening system should be based not only on the decorative selection of plants, but also on ecological and functional principles. It involves taking into account natural and climatic conditions, the intensity of human impact, soil properties, moisture availability, the functional purpose of the area, and the resilience of each species to a combination of stress factors (Alekseev, 1989; Kulagin, 1974; Akbari et al., 2001). The relevance of this study stems from the need to carry out a comprehensive assessment of the ecological role of tree and shrub vegetation in an urban environment, to identify the factors limiting plant growth, and to develop scientifically sound recommendations for the creation of a sustainable urban green infrastructure.

2. Aims and objectives of the research

The aim of the study is to assess the impact of tree and shrub vegetation on the ecological condition of the urban environment, to analyse the conditions under which green spaces function, and to identify the main ways of improving their sustainability and ecological effectiveness.

To achieve this objective, the following tasks were set:

1. to characterise the urban environment as a specific ecological system;
2. to identify the main natural and human-induced factors affecting tree and shrub vegetation;
3. to examine the morphological and physiological responses of woody plants to complex urban stress;
4. to analyse the main ecological functions of green spaces;
5. to assess the resilience of individual tree species to drought, air pollution, salinisation and soil compaction;
6. to compare the condition of tree stands in the city's various functional zones;
7. to draw up practical recommendations for improving the greening scheme.

3. Materials and methods

The subject of the study was the trees and shrubs used in the city's landscaping scheme. The study examined green spaces serving various purposes: city parks, public gardens, boulevards, inner-neighbourhood areas, roadside plantings, areas along major transport routes, and green spaces located within industrial impact zones. The subject of the study was the patterns governing the influence of natural, climatic, and anthropogenic factors on the condition, resilience, development, and ecological functions of tree and shrub vegetation.

The methodological framework for this work was based on a systemic and comparative-analytical approach. The study drew on material from a dissertation, the results of route surveys, visual assessments of tree stands, an analysis of the literature, and a synthesis of data relating to dendrology, plant physiology, urban ecology and landscape architecture (Məmmədov & Xəlilov, 2005; Alekseev, 1989; Bukharina et al., 2007; Goryshina, 1991; Kolesnikov, 1974).

The surveys took into account: the species of the plants; their general health and condition; crown density and uniformity; the presence of dry and damaged branches; the condition of the foliage; signs of necrosis, chlorosis and premature leaf fall; mechanical damage to the trunk; the condition of the root zone; the degree of soil compaction and salinisation; the nature of the surrounding built-up area; and the intensity of traffic and recreational pressure.

The assessment of the trees' health was carried out taking into account generally accepted indicators of tree decline: a reduction in crown density, a decrease in annual growth, branch dieback, leaf damage, the formation of dead tops, and a general deterioration in ornamental appearance (Alekseev, 1989). When comparing tree species, their tolerance to gas, drought, and salinity, as well as their ability to thrive in compacted urban soil, were taken into account (Kulagin, 1974; Mozolevskaya et al., 1984; Rozanov, 2004; Akbari et al., 2001).

The data obtained were categorised according to the main groups of urban stress factors. For each group, the nature of the impact, the possible reactions of the plants and the consequences for their viability and ornamental value were determined.

4. Results and Discussion

The urban environment differs significantly from natural ecosystems in terms of its high spatial heterogeneity, intense human impact and the simultaneous influence of a multitude of adverse factors. In natural conditions, plants grow under a relatively stable combination of soil, climatic and biotic conditions, whereas in an urban environment most of these parameters have been altered by human economic activity (Goryshina, 1991; Kulagin, 1974).

The main components of the urban environment are air pollution, degraded soils, altered hydrological conditions and local climatic anomalies. The air is constantly exposed to emissions from motor vehicles, industrial plants, power stations and construction dust. The soil cover consists mainly of urbanised soils, characterised by high density, disturbed structure, low biological activity and limited water and air exchange.

A distinctive feature of the urban environment is the emergence of multi-stress exposure, in which the physiological condition of plants is determined not by individual factors, but by their combined effect. For example, soil compaction restricts root system development and reduces water absorption, high temperatures increase transpiration, and soiling of the leaf surface reduces the rate of gas exchange and photosynthesis. The combined effect of these factors leads to chronic physiological stress, reduced growth rates, premature leaf ageing, thinning of the crown and a shorter lifespan in woody plants (Table 1).

Table 1. Key factors in the urban environment and the nature of their impact on tree and shrub vegetation

Group of factors	Specific effects	Main plant responses	Possible consequences
Air pollution	NO _x , SO ₂ , CO, dust, aerosols, heavy metals	Leaf damage, impaired gas exchange, increased oxidative stress	Necrosis, chlorosis, reduced photosynthesis and growth
Soil conditions	Compaction, salinisation, alkaline reaction, organic matter deficiency	Lack of oxygen in the root zone, impaired water absorption	Root hypoxia, physiological drought, desiccation
Water regime	Insufficient rainfall, poor infiltration, uneven irrigation	Stomatal closure, reduced transpiration and photosynthesis	Wilting, reduction in leaf area, premature leaf fall
Temperature conditions	Heat from asphalt and buildings: the urban 'heat island'	Tissue overheating, increased evaporation, metabolic disturbance	Heat-related injuries, dehydration
Light factor	Shading caused by buildings, artificial night-time lighting	Changes in photoperiod and seasonal rhythms	Slowing growth, delayed preparation for dormancy
Noise and vibration	Transport, construction, industrial equipment	Additional mechanical and physiological strain	Weakening of plants following prolonged, combined exposure
Mechanical impact	Damage to trunks and roots, incorrect pruning, vandalism	Damage to conductive tissues, wound formation	Infection, rot, crown deformation
Biotic factors	Pests and plant pathogens	Damage to leaves, shoots, roots and wood	Accelerated decline and dieback of trees

A comprehensive assessment of the environmental characteristics of plants is required for each functional zone of the city (Kulagin, 1974; Mozolevskaya et al., 1984; Rozanov, 2004; Akbari et al., 2001).

Prolonged exposure to adverse conditions gives rise to a range of morphological, anatomical, and physiological changes. In the early stages, these mechanisms are adaptive in nature; however, if the stressors persist over a long period, the compensatory mechanisms gradually become exhausted. This is accompanied by a reduction in shoot growth, a decrease in leaf area, impaired root system development, and a decline in the plants' overall vitality.

One of the most informative indicators of the condition of tree stands is the structure of the crown. In healthy trees, it is characterised by an even distribution of skeletal branches, dense foliage and the absence of dry shoots. In urban environments, it is common to observe dry tips, crown asymmetry, a reduction in leaf size and a decrease in foliage density. Such changes are caused by disturbances in the water regime, atmospheric pollution, nutrient deficiencies, mechanical damage, and restricted root system development.

The condition of the root system is one of the key factors in the resilience of woody plants. Unlike natural ecosystems, where roots develop in loose, biologically active soil, in urban environments their growth is restricted by engineering structures, road surfaces, building foundations and underground utilities. Soil compaction impairs aeration, reduces water infiltration, and causes oxygen deprivation in the roots, thereby reducing the supply of moisture and mineral nutrients to the above-ground parts of the plant.

Even when there is sufficient moisture in the soil, plants may experience physiological drought. It most commonly develops when the soil solution becomes saline, as the increase in osmotic pressure restricts the flow of water into the root system. This factor is of particular significance for areas characterised by naturally mineralised soils, the influence of marine aerosols and the accumulation of salts when irrigation practices are disrupted.

The primary physiological response of plants to water stress is the closure of their stomata, which helps to reduce water loss. However, at the same time, the supply of carbon dioxide to the leaves is restricted, which leads to a reduction in the rate of photosynthesis and a decrease in the synthesis of organic compounds. Prolonged exposure to drought leads to a reduction in leaf area, increased leaf fall, thickening of the cuticle and increased development of a waxy coating, which helps to reduce transpiration and increase resistance to overheating.

An important component of the stress response is the accumulation of reactive oxygen species. When exposed to high temperatures, drought, atmospheric pollution and salinisation, their concentration increases significantly, causing damage to cell membranes, proteins and photosynthetic pigments. To prevent oxidative stress, plants activate an antioxidant system comprising enzymatic and non-enzymatic defence mechanisms (Nikolaev, 2003; Perel'man, 1975).

Air pollution remains one of the main factors contributing to the deterioration of urban green spaces. The main sources of pollution are road transport, industrial plants, energy facilities, construction sites, and the accumulation of waste. The long-standing operation of the oil and gas industry has placed an additional environmental burden on cities such as Baku and Ufa, affecting the condition of certain urban and suburban areas (Məmmədov, 2010; Qasımova & Hacıyev, 2008; Məmmədov & Xəlilov, 2005; Məmmədov & Gülməmmədova, 2007; Baki Sheherinin Bash Planı 2040; Khalikova, & Isyanyulova, 2019).

Motor vehicles contribute to comprehensive atmospheric pollution caused by nitrogen oxides, carbon monoxide, hydrocarbons, soot, and fine particulate matter. Other sources of heavy metals include wear and tear on tyres, braking systems, and road surfaces. Dust that settles on the leaves reduces the light reaching the photosynthetic tissues, lowers the rate of gas exchange, and impairs the physiological condition of the plants. At the same time, toxic elements accumulate in the soil, its acidity changes, and the soil microbiota is suppressed (Table 2) (Savo et al., 2025).

Construction waste and de-icing agents have a significant impact, altering the chemical properties of the soil, increasing its density, and reducing the available volume of the root zone. As a result, root system development is impaired, and the plants' ability to adapt over the long term is reduced.

Table 2. The main sources of urban pollution and the potential damage to trees and shrubs

Source	Main pollutants	Area of impact	Possible consequences
Vehicles	NO _x , CO, hydrocarbons, soot, heavy metals, rubber dust	Leaves, bark, roadside soil	Necrosis, stomatal blockage, reduced photosynthesis
Oil and gas facilities	Hydrocarbons, sulphur compounds, petroleum products	Air, soil, root system	Toxic damage, reduced soil aeration
Construction work	Mineral dust, cement particles, building rubble	Leaves, soil, roots	Alkaline load, compression, mechanical damage
Waste	Filtrate, organic and inorganic contaminants	Soil and groundwater	Toxic effects, disruption of soil properties
Power plants	Nitrogen oxides, sulphur oxides, combustion particles	Atmospheric air and the phyllo mass	Oxidative stress, damage to pigments
Reagents and salt aerosols	Ions Na ⁺ и Cl ⁻	Soil, leaves, young shoots	Osmotic stress, burns, malnutrition

The climatic characteristics of arid regions significantly exacerbate the impact of human activities. The main limiting factors are low levels of precipitation, prolonged dry spells, high solar radiation, intense evaporation, and frequent strong winds (Məmmədov, 2010; Məmmədov & Gülməmmədova, 2007; Baki Sheherinin Bash Planı 2040). Plants' peak water requirements coincide with the period of lowest rainfall; consequently, the resilience of urban greenery is largely determined by the effectiveness of artificial irrigation.

Strong winds have mixed effects. On the one hand, they help to disperse pollutants; on the other, they increase moisture evaporation, cause mechanical damage to shoots and contribute to the transport of dust and salt aerosols. The most unfavourable combination is that of high temperatures, low humidity and strong winds, which leads to a sharp increase in transpiration and the development of chronic water stress.

Table 3. Extreme climatic factors and requirements for woody plants

limatic factor	Environmental impact	Required plant characteristics
Low levels of rainfall	Chronic soil moisture deficit	High drought tolerance, economical water use
High summer temperatures	Tissue overheating and increased perspiration	Heat tolerance, thick cuticle, robust foliage
Intense solar radiation	Photo-oxidative stress and sunburn	Light-loving, tolerant of direct sunlight
Strong winds	Wilting, crown deformation, broken branches	Wind resistance, strong wood, flexible shoots
Low humidity	Accelerated water loss through the leaves	The ability to regulate transpiration
Marine salt aerosol	Damage to leaves and young shoots	Salt tolerance
Abrupt local changes in the microclimate	Alternating exposure to overheating, shade and wind loads	High environmental adaptability

Therefore, the selection of plants for landscaping should be based on environmental conditions. Using a species solely on the basis of its ornamental qualities, without taking environmental requirements into account, increases the risk of widespread weakening and death of the plant population (Table 3).

A comparative analysis shows that the resilience of woody plants in an urban environment is determined by a combination of their morphophysiological characteristics and ecological plasticity. The species that demonstrate the greatest resilience are those capable of withstanding water shortages, atmospheric pollution, soil compaction and salinisation, as well as high temperatures.

In the context of the city of Baku (Republic of Azerbaijan), these types include Tree of heaven (*Ailanthus altissima*), Chinese scholar tree (*Styphnolobium japonicum*), Russian olive (*Elaeagnus angustifolia*), Honeylocust (*Gleditsia spp.*) Oriental plane (*Platanus orientalis*), and certain species of poplar (*Populus spp.*). These plants are characterised by a well-developed root system, high drought tolerance, and a relatively good ability to maintain physiological activity when exposed to adverse conditions over a prolonged period. Among the species with moderate hardiness that are suitable for

planting in parks and public gardens are the lime (*Tilia spp.*), the maple (*Acer spp.*) and the chestnut (*Aesculus spp.*).

Less resilient species include the small-leaved lime (*Tilia cordata*), the Norway maple (*Acer platanoides*), birch (*Betula spp.*) and most coniferous species, which are sensitive to a combination of atmospheric pollution, soil salinisation and water stress. However, resilience is not an absolute characteristic of a species. Even the most well-adapted plants can quickly lose their vitality if their root zone is restricted, they are not watered, they are planted incorrectly, or they are not cared for properly.

The city of Ufa (Republic of Bashkortostan, Russian Federation) ranks third amongst the 16 cities in Russia with a population of over one million. In terms of green space (30.9% of the city's area), Ufa is second only to Perm and Yekaterinburg. The area of green spaces in public areas in Ufa per capita is 25 m², which is 1.6 times higher than the standard for large cities (16 km²) (Kamynina, 2026).

The following key species predominate in Ufa's urban landscape: small-leaved lime (*Tilia cordata*), Bashkir pyramid poplar (*Populus nigra var. pyramidalis*), Norway spruce (*Picea abies*), field maple (*Acer campestre*), silver birch (*Betula pendula*), box elder (*Acer negundo*), Siberian larch (*Larix sibirica*), Scots pine (*Pinus sylvestris*), common rowan (*Sorbus aucuparia*), common lilac (*Syringa vulgaris*) and others.

Other species found in urban plantings include the common ash (*Fraxinus excelsior*), blue spruce (*Picea pungens*), Russian olive (*Elaeagnus angustifolia*) and common ninebark (*Physocarpus opulifolius*) (Kamynina, 2026).

The condition of tree stands varies significantly depending on the functional purpose of the urban area. The most favourable conditions are found in parks, public gardens and boulevards, where plants have a large volume of soil at their disposal, are less likely to suffer mechanical damage and receive regular care. Under these conditions, the trees have a higher foliage density, better growth and a longer lifespan.

In the courtyards within the estate, the environmental impact is of an intermediate nature. Although air pollution levels here are lower than along major transport routes, plant growth is restricted by shading, soil compaction, a lack of bare soil, root damage caused by repairs to utility networks, and human activity.

The most adverse conditions occur along motorways and in industrial areas. Constant exposure to vehicle emissions, dust, vibration, high temperatures, salinisation and soil compaction leads to a deterioration in the physiological condition of plants, a reduction in crown density and an increase in the proportion of weakened and dying trees. In industrial areas, this negative impact is exacerbated by the presence of petroleum products, sulphur compounds, heavy metals and other toxic substances, which alter the physical and chemical properties of the soil and disrupt the functioning of the root system.

The results of the surveys indicate a direct correlation between the level of human impact and the condition of the tree stands. In recreational areas, the proportion of healthy trees is significantly higher than in industrial areas, where the number of weakened and dying trees is on the rise. At the same time, foliage density declines, crown density decreases, and annual growth slows. These changes reflect not only the impact of atmospheric pollution, but also the long-term degradation of the soil environment.

When designing urban green spaces, the correct selection of tree species for different functional areas is of particular importance. Along major transport routes, preference should be given to species that are highly resistant to gas and dust, drought-tolerant, able to withstand soil salinity, and resistant to mechanical damage. The use of environmentally sensitive species in areas subject to high human impact significantly reduces the longevity of green spaces and increases the costs of maintaining them.

Tree cover performs a wide range of ecological functions that ensure the sustainability of the urban environment. One of the most important is the sanitary and hygienic function. Leaves, shoots and bark trap dust particles, adsorb gaseous pollutants and help to improve air quality. At the same time, plants absorb carbon dioxide, store carbon in their biomass and release oxygen, thereby maintaining the gas balance in the urban atmosphere.

Equally important is the climate-regulating function of green spaces. Woody plants lower the ambient temperature through shading and transpiration. The evaporation of water from leaves is accompanied by the absorption of thermal energy, which reduces the warming of the air and mitigates the urban ‘heat island’ effect.

Green spaces also have an impact on wind patterns and the water balance of the area. Protective strips reduce airflow velocity, limit the spread of dust and create a more favourable microclimate. The root system helps to improve soil structure, increase its water permeability and make more efficient use of rainfall and irrigation water, which is particularly important given the limited water resources on the Absheron Peninsula.

The environmental sustainability of urban green infrastructure increases when mixed and multi-layered plantings are established. The use of tree and shrub species with varying root depths, crown shapes and growth rates enables more efficient use of soil and climatic resources, reduces the likelihood of widespread pest and disease outbreaks, and enhances the overall resilience of plantations to adverse factors.

As well as their environmental functions, green spaces play an important role in recreation. Parks, squares, boulevards and green public spaces create a pleasant visual environment, provide opportunities for the public to relax and help to reduce psychological and emotional stress. Tree and shrub vegetation is therefore a vital component of urban green infrastructure, ensuring the environmental sustainability and comfort of the urban environment.

Table 4. The ecological condition of woodlands in various functional zones of Baku

Type of area	Average quality of life score	The proportion of healthy Category I trees, %	The proportion of dying trees in categories IV–VI, %	Crown density, score	Soil pH	Salt content (%)	Lead (Pb) content in soil
Parks, boulevards, public gardens	1,9–2,3	45–55	3–5	4,0–4,5	7,5–8,0	0,15–0,25	Does not exceed TLV
Courtyards within the estate	2,7–3,1	15–20	15–20	2,8–3,2	7,8–8,3	0,30–0,50	1,5–2 TLV
Main roads	3,4–3,8	8–12	25–30	2,1–2,4	8,2–8,7	0,60–0,90	3,7–5,6 TLV
Industrial estates	3,6–4,0	5–7	40–45	1,8–2,2	8,5–9,0	1,0–1,2	9–15 TLV

The data in Table 4 demonstrate a consistent relationship between the intensity of anthropogenic pressure and the deterioration in plant health. In parks and public gardens, the proportion of healthy trees is as high as 45–55%, whereas in industrial areas it falls to 5–7%. At the same time, the proportion of plants dying back increases from 3–5% to 40–45%. Soil parameters are also changing significantly. In major transport corridors and industrial areas, the concentration of lead in the soil exceeds the maximum permissible level by several times. These findings confirm that the deterioration in the condition of the tree canopy is linked not only to air pollution, but also to long-term degradation of the root environment.

The reduction in crown density from 4.0–4.5 points in recreational areas to 1.8–2.2 points in industrial areas indicates a marked impairment of growth and foliage. A thinned-out canopy reduces trees’ ability to trap dust, provide shade and dampen noise.

Major roads are characterised by high concentrations of nitrogen and sulphur oxides, high levels of particulate matter, heavy metal pollution, soil compaction and a limited number of parking spaces. The main selection criteria are therefore resistance to gas and dust, drought tolerance, tolerance to salinity and the strength of the timber (Table 5).

For such areas, sycamore, sophora, gleditsia, poplar, loch and tamarisk are recommended. The use of birch, spruce, lime and sycamore maple along the busiest main roads is considered less suitable due to their sensitivity to a combination of pollution, salinity and lack of moisture.

Table 5. Recommended selection of plants for various functional areas

Functional area	Key stress factors	Recommended breeds	Breeds that are less recommended	The main principle of selection
Main lines	NO _x , SO ₂ , dust, salts, seal	Sycamore, sophora, gleditsia, poplar, oleaster, tamarisk	Spruce, lime, sycamore maple	Resistance to gas, dust and salt
Local roads and courtyards	Shading, lack of moisture, trampling	Globosum maple, hornbeam, lime, ailanthus, cotoneaster	Chestnut, magnolia, forsythia	Shade tolerance and drought tolerance
Parks and boulevards	Wind, sea spray, recreational activity	Chestnut, rowan, lilac, spirea, magnolia	Determined by the site conditions	Aesthetic appeal and microclimatic function
Industrial estates	HF, NH ₃ , heavy metals, petroleum products	Ailanthus, white poplar, oleaster, black locust	Mesophytes and sensitive conifers	Tolerance to toxicants

Improving the effectiveness of greening requires a shift from a predominantly decorative approach to a scientifically based system for managing green infrastructure. When selecting a range of plants, it is essential to take into account the climatic characteristics of the site to be landscaped, the functional purpose of the area, the level of human impact, the ecological characteristics of the species, and projected climate change. The primary objective of urban greening should be not only to increase the area of green spaces, but also to ensure their longevity, sustainability and ability to fulfil public health, climate-regulating and recreational functions.

An integral part of effective management is the regular monitoring of the condition of trees. Regular inspections enable the timely detection of signs of weakness, damage, disease, reduced stability and the risk of trees falling, which is particularly important along major transport routes, in areas frequented by large numbers of people and in areas subject to high wind loads.

Thus, the sustainability of green spaces in an urban environment is determined by the complex interplay of climatic, soil and human factors. The selection of tree species based on scientific evidence, the preservation of favourable soil conditions, the rational organisation of irrigation and the systematic monitoring of the condition of the plantations are of paramount importance. Implementing these measures will enhance the environmental performance of urban green infrastructure, increase the longevity of trees and shrubs, and improve the quality of the urban environment in the face of increasing human impact and climate change.

5. Conclusion

The study confirmed that tree and shrub vegetation is one of the most important components of the city's ecological infrastructure. Green spaces have a multifaceted impact on the quality of the urban environment, helping to purify the air, regulate temperature and humidity, reduce wind and noise pollution, stabilise the soil, preserve biodiversity and create recreational spaces.

It has been established that the urban environment constitutes a multi-stress system. Woody plants are simultaneously exposed to air pollution, water stress, high temperatures, strong winds, soil compaction and salinisation, mechanical damage, shading and light pollution. The combined effect of these factors leads to a reduction in photosynthetic activity, disruption of water balance, deterioration of the root system and a gradual thinning of the crown.

Particularly challenging conditions for plant growth arise along busy transport routes and in industrial areas. Here, air pollution is compounded by soil degradation, restricted root space and high thermal stress. As a result, the proportion of weakened and dying trees is increasing, and the ecological functions they perform are gradually diminishing.

A comparison of functional areas revealed that the best condition of the plantings is found in parks, public gardens and boulevards, where the plants have a greater volume of soil and receive more regular

care. In courtyards within residential blocks, significant factors include shading, trampling and damage to the root zone. Air pollution, salinisation, soil compaction and water scarcity are the predominant issues along major roads and in industrial areas.

It has been found that plant resilience is determined not by a single characteristic, but by a combination of tolerance to gas, dust, salt, heat, wind and drought. The species most promising for areas subject to high human impact are those capable of remaining viable whilst exposed to multiple stressors simultaneously. However, even hardy species require proper planting, sufficient soil, sensible watering and professional care.

The environmental effectiveness of green infrastructure depends not only on the number of trees, but also on their age, health, crown size, spatial structure and species diversity. Healthy, multi-species and multi-layered plantings are significantly more effective at trapping dust, providing shade, regulating the microclimate and supporting urban biodiversity.

Based on the research carried out, it is recommended that a differentiated approach be adopted to the greening of various functional zones in large cities. For main roads and industrial areas, species that are resistant to pollution and salinity should be selected; for parks and boulevards, plants that combine environmental resilience with high ornamental value; and for inner-neighbourhood spaces, species capable of tolerating shade, limited soil volume, and recreational use.

The key areas for improving the urban greening system are increasing species diversity, improving soil conditions, introducing water-saving irrigation technologies, protecting root zones, professional pruning, and regular monitoring of tree health. The creation of a digital register of green spaces and the development of a unified green framework for the city are promising initiatives.

Consequently, the sustainable use of woody and shrubby vegetation should be regarded as a key priority of environmental policy. Preserving existing mature trees, creating sustainable mixed plantings and applying scientifically sound management techniques will help to enhance the environmental sustainability of the urban environment and improve the quality of life for the population.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Biodiversity Conservation in the Mountain Forests of the Greater Caucasus

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Abstract

In this article, the theoretical foundations and significance of biodiversity and the natural-geographical features of the Greater Caucasus are examined, including the features of mountain forest ecosystems. At the same time, particular attention was paid to the current state of biodiversity; a spatial analysis of the biodiversity of the Greater Caucasus was conducted. In addition to this, the study also analyzed the main threats to biodiversity and ways to conserve it. The issues of international experience in biodiversity conservation and state policy and environmental legislation in this area are discussed. At the end of the article, the main directions for biodiversity conservation and practical recommendations for the conservation of the Greater Caucasus's biodiversity are outlined.

Keywords: biodiversity, flora, fauna, mountain forest ecosystems, biodiversity conservation, spatial analysis.

1. Introduction

The mountain forests of the Greater Caucasus constitute an important part of Azerbaijan's natural ecosystems and play a significant role in maintaining the ecological balance of the region. They perform water protection, soil protection, and climate-regulating functions, and also serve as a habitat for a large number of plant and animal species. Due to the peculiarities of the geographical location of Azerbaijan, the country's territory, situated at the junction of several biogeographic zones, is characterized by a high level of biodiversity.

The forests of the Greater Caucasus account for a significant share of the country's forest resources. They are considered one of the main centers for the conservation of flora and fauna. Both widespread and rare species are found here, including endemic and disappearing species, many of which are listed in the Red Book. The richness of species composition makes these ecosystems particularly important from a nature conservation perspective.

In recent decades, an intensification of anthropogenic activity has been observed to impact the region's natural ecosystems. Among the main factors are deforestation, expansion of agricultural land, construction of infrastructure, population growth, as well as the impact of climate change. These factors lead to a reduction in the numbers of many plant and animal species and the disruption of the natural equilibrium.

The decline in biodiversity in the mountain forests of the Greater Caucasus is a serious environmental problem as it disrupts the stability of ecosystems and reduces their capacity for self-recovery. This results in long-term changes in forest structure. Despite the existence of scientific research, the problem of

conserving biodiversity in the mountain forests of the Greater Caucasus remains relevant. A more detailed assessment of the state of individual ecosystems is required, as well as the identification of factors influencing their degradation, and the development of effective measures for the conservation of natural diversity. Thus, the study of the biodiversity of the mountain forests of the Greater Caucasus is an important area of environmental research aimed at preserving natural heritage and ensuring the sustainable development of the region.

2. The Concept of Biodiversity and Its Types

Biodiversity is the totality of all forms of life on Earth, including species diversity, genetic diversity within species, as well as the diversity of ecosystems and ecological processes that ensure the stability of the biosphere. The term "biodiversity" was introduced into scientific circulation at the end of the 20th century, but the very idea of the diversity of living beings has deep roots in ecology and biogeography. Three main levels of biodiversity are distinguished: genetic, species-level, and ecosystem-level. These levels are closely interconnected and support the functioning of natural systems.

Genetic diversity reflects the variation of hereditary traits within populations and between populations of the same species. It serves as the foundation of adaptive processes that ensure the resistance of organisms to environmental changes of the environment and the influence of anthropogenic factors. The higher the genetic variability, the higher the ability of a species to adapt to new conditions and survive environmental stresses.

Species diversity is the totality of all types of living organisms in a specific ecosystem or biosphere. This level of biodiversity is the most obvious, and usually it is used as a primary indicator of the richness of the natural world. The Greater Caucasus is characterized by an extremely high level of diversity, including many endemic and relict species. The region is part of one of the world's centers of biodiversity - the Caucasus bioregion. Over 6,000 species of vascular plants are found here, of which about 25% are endemic. Species diversity also plays a critical role in ecosystem resilience. Each type performs a specific functional role, and the loss of even a single component can lead to a disruption of the ecological balance.

Ecosystem diversity reflects the differences between natural systems. This level includes diversity of biogeocenoses, their structural and functional features, as well as the interrelationships between organisms and abiotic factors. Biodiversity in Azerbaijan is a combination of all living organisms, ecosystems, and genetic resources that are formed in various natural areas of the country. The territory of Azerbaijan, located at the junction of Europe and Asia, is characterized by high natural landscape diversity, which has given rise to a wealth of flora and fauna.

There are three main levels of biodiversity in the country: genetic, species, and ecosystem. Genetic diversity manifests itself in the presence of a multitude of endemic and relict species (for example, different forms of oak and beech in forests of Azerbaijan). Species diversity is particularly rich in mountainous regions. Greater Caucasus is where rare species of plants and animals are found. Ecosystem diversity encompasses forest, mountain, subalpine, and alpine ecosystems. Azerbaijan has more than:

- 4,500 species of higher plants
- hundreds of animal species
- a significant number of endemics of the Caucasus region.

Thus, biodiversity constitutes a multi-level phenomenon based on the interaction of genetic, species, and ecosystem components. Conservation of all three levels of diversity is particularly relevant for the Caucasus as it is a region with unique natural history and a high level of endemism, where the violation of one level inevitably affects others.

3. The Importance of Biodiversity

The ecological significance of biodiversity lies primarily in ensuring the sustainable functioning of ecosystems and maintaining their self-regulation. Diversity of species forms complex food chains and networks that ensure the circulation of substances and the flow of energy in nature. The higher the level of biodiversity, the more resilient the ecosystem's response to external impacts, such as climatic fluctuations, natural disasters, and anthropogenic interference.

In the mountain forests of the Greater Caucasus, this aspect takes on a special significance, since these ecosystems are highly sensitive to changes in natural conditions. Forest communities perform important ecological functions, including the regulation of the water regime, the prevention of soil erosion, the maintenance of microclimate and the preservation of the genetic pool of rare species. Loss of individual species can lead to a disruption of the ecological balance and a decline in the resilience of the entire ecosystem.

In addition, biodiversity plays a key role in the natural process of self-healing. Different types perform specific functions in the ecosystem, and their disappearance leads to functional gaps that are difficult to compensate for. Thus, biodiversity conservation is a necessary condition for maintaining the environmental stability of the region.

The economic importance of biodiversity is reflected in its role as a source of natural resources and the basis for various types of economic activity. Biological resources are used in forestry, agriculture, pharmaceutical and food industry. For example, forest ecosystems provide wood, medicinal plants, mushrooms, and other natural products of economic value. In mountainous regions such as the Greater Caucasus, development of ecotourism is also gaining momentum. Unique landscapes and rich flora and fauna create conditions for sustainable tourist development that, if properly organized, could become an alternative to resource-intensive economic activity. However, the excessive exploitation of natural resources without regard for the principles of sustainable development leads to ecosystem degradation and long-term economic losses. For example, cutting down forests may be temporarily profitable, but subsequently leads to soil erosion, reduced land productivity, and deterioration of water resources. Therefore, the economic value of biodiversity should be considered from the perspective of long-term sustainability.

The social significance of biodiversity is expressed in its impact on an individual's quality of life, public health, and the cultural development of society. Natural ecosystems provide recreational services and contribute to psychological well-being. For the populations of mountain regions, biodiversity is also of cultural and traditional significance. Many species of plants and animals are used in folk medicine, economic activities, and cultural practices. Thus, biodiversity is part of the intangible cultural heritage of local communities. Furthermore, the preservation of biodiversity is directly linked to ensuring food and environmental security of the population. Sustainable ecosystems help maintain clean water, air, and soil, which have a positive effect on human health. In turn, degradation of the natural environment can lead to an increase in diseases and a decline in quality of life. Thus, biodiversity possesses not only a natural but also a profound socio-economic significance, making its preservation a priority task of modern environmental policy.

4. Theoretical Approaches to the Study of Biodiversity

The study of biodiversity in modern science is based on several theoretical approaches that allow us to examine the structure, functioning, and dynamics of natural ecosystems. Among the most significant are the ecosystem approach, the landscape approach, and the population approach. These approaches complement each other and provide a comprehensive analysis of natural systems, including the mountain forests of the Greater Caucasus.

The ecosystem approach examines the interaction of living organisms with the environment within natural complexes of the Greater Caucasus. It views biodiversity as an integral part of the functioning of an ecosystem where all living organisms interact with each other, with themselves and with the environment. The main focus is not only on the species composition, but also on the functional connections between ecosystem components, including energy flows, the cycle of matter, and trophic chains.

According to this approach, the sustainability of ecosystems directly depends on the level of biodiversity: the higher the diversity of species and functional groups, the more stable the system is against external impacts. In the context of mountain forests, an ecosystem approach to the Greater Caucasus makes it possible to assess the role of individual species in maintaining the ecological balance, as well as to identify the consequences of their loss for the entire system.

The landscape approach allows us to analyze the spatial distribution of natural resource complexes, including forests, mountain meadows, and subalpine zones. The landscape approach considers biodiversity in a spatial aspect, analyzing the structure and dynamics of natural complexes at the landscape level. In contrast to the ecosystem approach, here special attention is paid to the spatial mosaic nature of the natural environment, the interaction of various ecosystems, and the influence of relief, climate, and soils on species distribution.

For mountainous regions such as the Greater Caucasus, this approach has particular importance, since vertical zonation and complex relief create diverse natural zones within a relatively small area. This contributes to a high concentration of species and endemism. The landscape approach also makes it possible to identify zones of heightened vulnerability, which is important for conservation planning. The population approach focuses on studying the population dynamics of individual species, especially rare and endangered ones.

The concept of sustainable development considers biodiversity in the context of a balance between economic development, social stability, and preservation of the natural environment. According to this concept, the satisfaction of the needs of the present generation must not jeopardize the ability of future generations to meet their own needs. Theoretical foundations of the biodiversity of the Greater Caucasus are based on the principle of vertical zonation. The main idea is that natural conditions and biodiversity change significantly depending on altitude above sea level. The lower sections of the mountain profile comprise foothill and low-mountain zones, characterized by a warmer climate and relatively high levels of human development. Agricultural areas, shrub vegetation, and isolated forest patches are found here. As elevation increases, broad-leaved forests – comprising species such as oak and beech – develop; these forests are characterized by high levels of species diversity and ecological resilience. Beyond lie subalpine and alpine meadows, where woody vegetation gradually disappears due to falling temperatures and changing climatic conditions. These territories are characterized by distinctive herbaceous communities and animal species adapted to harsh conditions. The highest elevation is occupied by the nival zone. Here, the biodiversity is limited due to perpetual snow and glaciers. Key natural factors influencing biodiversity and determining the spatial distribution of ecosystems:

- climatic conditions,
- geological structure,
- hydrological networks.

Thus, the image illustrates the complex structure of the mountain ecosystems of the Greater Caucasus and highlights that biodiversity in this region depends directly on altitudinal zonation and the interaction of natural factors.

5. Factors Affecting Biodiversity

Thus, the concept of sustainable development integrates environmental, economic, and social aspects, ensuring the long-term preservation of biodiversity and the stability of natural systems. Biodiversity is a dynamic system, the level and structure of which are shaped by a complex of interrelated factors. In scientific literature, it is customary to distinguish two main groups of factors determining the state and stability of biological systems: natural (abiotic and biotic) and anthropogenic.

Natural factors include climatic conditions, topography, geological structure, soil characteristics, the hydrological regime, and biotic interactions between species. Climate is one of the key determining factors, as temperature, precipitation, humidity, and seasonality directly influence the formation of species ranges and the structure of ecosystems. In mountainous regions, including the Greater Caucasus, vertical climatic zonation creates distinct vegetation belts and a highly mosaic pattern of biodiversity.

Azerbaijan's biodiversity is influenced by natural and anthropogenic factors. Among natural factors, the climate, relief, and vertical zonation of the Greater Caucasus play a key role. Anthropogenic factors include deforestation, livestock grazing, urbanization, and land-use change. In recent years, the impact of climate change has also intensified, leading to shifts in the ranges of many species.

Topography also has a significant impact on biota, creating a diversity of ecological niches. Changes in elevation, slope aspect, the degree of terrain dissection, and geomorphological features determine microclimatic conditions, the water regime, and soil formation. As a result, communities differing sharply in species composition can form even within relatively small areas.

The soil cover is a crucial factor determining ecosystem productivity and species richness. Differences in soil composition, acidity, and humus and mineral content influence the distribution of plant communities, which, in turn, affects the animal world. Hydrological conditions also play a significant role in shaping ecosystem structure, including the presence of rivers and groundwater, as well as moisture levels.

Biotic factors include competition, predation, symbiosis, parasitism, and other forms of interspecific interactions. These processes regulate population sizes, determine community structure, and contribute to maintaining ecological balance. For example, the presence of keystone species can have a disproportionately large impact on the stability of the entire ecosystem. In the modern era, anthropogenic factors are assuming a dominant role in changes to biodiversity. These include:

- climate change,
- deforestation,
- extensive agricultural development,
- urbanization, industrial pollution,
- the expansion of infrastructure, and
- the overexploitation of natural resources.

The outcomes include habitat fragmentation, a decline in population numbers, and a loss of genetic diversity. Of these, climate change poses a particular threat to biodiversity. Rising average annual temperatures, changes in precipitation patterns, and extreme weather events lead to shifts in the ranges of species and disruption of established ecosystems. This is especially important in mountain ecosystems, since many species there are usually adapted to a narrower range of environmental conditions and possess limited ability to migrate.

6. Natural and Geographical Features of the Greater Caucasus

The Greater Caucasus is a mountain system characterized by a complex tectonic structure, significant elevation gradients, and a pronounced mosaic of climates and landscapes. These factors collectively give

rise to the region's high biodiversity. The Greater Caucasus stretches between the Black and Caspian Seas, forming a massive barrier that separates the air masses of the temperate and the subtropical zones. The topography is characterized by significant complexity and contrast, featuring high mountain ranges, intermontane basins, deep river valleys, and glacial landforms. This terrain creates the vertical zonation of landscapes, which is a key factor in the formation of biodiversity. The climate in this region is characterized by significant variability, which is determined by both its geographic position and complex topography. On the northern slopes, a temperate continental climate prevails, whereas the southern slopes tend towards a subtropical climate, usually characterized by higher humidity and milder winter conditions.

Vertical zonation plays a crucial role in the Greater Caucasus. As elevation increases, temperatures drop and precipitation patterns change. At higher elevations, snow cover deepens. A transition is observed here from a subtropical climate in the lower, more southern regions to colder conditions in the high-mountain areas. This leads to the formation of distinct climatic zones, ranging from steppe and forest-steppe areas at the foothills to alpine and nival landscapes in the high mountains. The distribution of precipitation is extremely uneven. Western regions receive significantly more moisture than eastern ones, a pattern driven by the influence of westerly air mass transport and the local relief. This leads to the dominance of xerophytic and drought-tolerant species in the Eastern regions.

The soil cover of the Greater Caucasus is characterized by high patchiness, resulting from the diversity of climatic conditions, topography, and vegetation. Chernozems and chestnut soils, which are highly fertile, are widespread in the foothill regions. Thus, the natural and geographical characteristics of the Greater Caucasus are shaped by the complex interaction of relief, climate, and soil cover. These components create unique conditions for the development of diverse ecosystems.

7. Characteristics of Mountain Forest Ecosystems

Mountain forest ecosystems perform important functions such as:

- water regime regulation,
- soil protection,
- climate regulation.

Mountain forest ecosystems are characterized by a high proportion of endemic and relict species in their flora and fauna. Many plant and animal species have limited distribution ranges and are closely associated with specific altitudes. This makes them particularly vulnerable to climate change. Recent research shows that even a small increase in average annual temperature causes forest zones to shift upslope and disrupt existing ecosystem relationships.

In Azerbaijan and in the Greater Caucasus region, the mountain forest ecosystems are characterized by high bioproductivity and species-level biodiversity. About 49% of the country's forests are located in the Greater Caucasus. Broad-leaved forests predominate here.

The forests of the Greater Caucasus are composed primarily of oak, beech, hornbeam, and other broad-leaved species. These species make up the bulk of the forest cover (over 80%). Vertical zonation influences forest ecosystem types:

- low mountains are characterized by oak forests;
- mid-Mountain Zone is composed of hornbeam, oak, and maple;
- highland communities are made of beech, mountain oak, and in some parts birch.

At the upper limit of the forest belt, open woodlands and subalpine shrub communities develop, transitioning into alpine meadows. One of the most important features of the mountain forest ecosystems of the Greater Caucasus is their high degree of fragmentation. This fragmentation is caused by both natural factors (complex topography, cut slopes, differences in size and heterogeneity of microclimate) and the

long-term impact of human activity. Fragmentation of forest areas limits the migration of species and reduces genetic exchange between populations, which in turn strengthens isolation processes and increases the risk of local extinction of individual species.

Analysis of data from 2000 to 2018 indicates slow changes in forest cover. Even though a slight increase in overall forest cover is observed, processes of both regeneration and degradation occur simultaneously. Land use changes lead to the expansion of agriculture, the growth of residential areas, and changes in land structure contributing to this complex dynamic.

The preservation of mountain forest ecosystems is a priority area of Azerbaijan's environmental policy. Thus, the mountain forest ecosystems of the Greater Caucasus constitute a dynamic natural system subject to the influence of a complex array of natural and anthropogenic factors. Their structure and functioning are determined by altitudinal zonation, climatic heterogeneity, and the region's geographical location. These factors collectively account for their high ecological significance and the need for their preservation in the face of intensifying anthropogenic impact.

8. Current State of Biodiversity in the Greater Caucasus

Floral diversity. The Greater Caucasus has exceptional floral diversity and high levels of endemism. Azerbaijan alone is home to more than 4,700 plant species. This is understood to be the result of natural-historical isolation and the high diversity of environmental conditions. Common tree species in the Greater Caucasus include oak, beech, hornbeam, maple, linden, and various coniferous species. The Oriental beech (*Fagus orientalis*) is widely distributed in the forests of the Greater Caucasus. Its primary growing areas are Zaqatala, Qakh, and Shaki. Beech forests help retain soil moisture, prevent erosion, and create a favorable microclimate.

Another one of the principal tree species in the region is oak. The chestnut-leaved oak (*Quercus castaneifolia*) is the most widespread variety. Oak forests play a role in soil conservation and serve as a habitat for a wide range of animals.

Hornbeam (*Carpinus betulus*) is found in mixed forests of the Greater Caucasus. It is characterized by durable wood and resistance to various climatic conditions. Hornbeam forests play an important role in maintaining biodiversity.

The Eldar pine (*Pinus eldarica*) is an example of a rare endemic species in Azerbaijan. Its primary distribution areas are in the Eldarian steppe, where it can be found in protected nature reserves. This species is highly drought-resistant and is used in reforestation.

The ironwood tree (*Parrotia persica*) is a relict species. It is mostly found in the Talysh forests, with many other relict species. Its wood is characterized by high density



Figure 1. Ironwood tree.

Figure 1 shows the ironwood tree, which is listed in the Red Book of Azerbaijan as a rare relict species. It is found only in the eastern part of the Greater Caucasus region, while its main populations are concentrated in the Hyrcanian forests of south-east Azerbaijan.

In Eastern parts of the South Caucasus, the Oriental plane (*Platanus orientalis*) forests have been preserved along the banks of the Basitchay River. Azerbaijan is particularly rich in giant plane trees. One of the world's largest plane trees grows near the settlement of Qirmizi Bazar (Khojavend district of Azerbaijan). It is approximately 1,500 years old, 50 m tall, and has a trunk circumference of 28 m; the area of its hollow is 50 m², and the area of its crown projection is 1,400 m².

The walnut (*Juglans regia*), like the Oriental plane tree, belongs to the wild flora of the Caucasus, a fact that is evidenced by its widespread distribution in characteristic relict refugia (Colchis, Talysh, Dagestan), as well as the regions situated between the Greater and Lesser Caucasus. The walnut tree often grows alongside broad-leaved species such as beech and oak. Its total distribution in Azerbaijan covers an area of 25,000 hectares. According to forest inventory data, the share of the Persian walnut in the composition of the plantings ranges from 10% to 70%. Several other rare and endangered species of plants are listed in the Red Book of Azerbaijan. These include:

- Colchic boxwood (*Buxus colchica*)
- European yew (*Taxus baccata*)
- Many rare orchid species (Orchidaceae)

The presence of endemic and relict plant species in isolated mountain ecosystems is of particular importance to regional and global biodiversity. These species help maintain the stability of natural-territorial complexes.

Faunal diversity. The fauna of the Greater Caucasus is also characterized by a rich diversity of mammals, birds, amphibians, and reptiles, as well as many relict and endemic species. The mammals of the Greater Caucasus could be divided into typical forest, mountain, and steppe species. The most characteristic among them are the Caucasian red deer (*Cervus elaphus maral*), the brown bear (*Ursus arctos*), the chamois (*Rupicapra rupicapra caucasica*), West Caucasian tur (*Capra caucasica*), lynx (*Lynx lynx*), and wolf (*Canis lupus*). Mountain ecosystems serve as important refugia for large mammals, many of which are under threat due to population declines and habitat fragmentation. A significant number of rare and endangered mammal species are listed in national and regional Red Books: Among mammals, these include:

- the West Caucasian tur (*Capra caucasica*),

- the Persian leopard (*Panthera pardus tulliana*),
- the Caucasian chamois (*Rupicapra rupicapra caucasica*), and
- the Caucasian brown bear.

These species are under strict protection and require continuous monitoring of their population numbers. The preservation of ungulate populations is of particular importance. In recent years, a partial recovery in the numbers of certain species has been observed thanks to the establishment of nature reserves, national parks and special protected areas.

The region's bird fauna includes eagles, vultures, falcons, and other birds of prey. High-altitude mountain areas serve as important nesting and migration sites for many regional and transregional bird species. Habitat loss, pressure from human activity, and climate change are negatively affecting the populations of certain predatory and rare bird species, necessitating enhanced monitoring and conservation measures. Caucasian bird species included in the Red Book are:

- the golden eagle (*Aquila chrysaetos*),
- bearded vulture (*Gypaetus barbatus*),
- Caucasian black grouse (*Lyrurus mlokosiewiczi*),
- and griffon vulture (*Gyps fulvus*).

Their populations are declining primarily due to the destruction of nesting sites and the disruption of migration routes. Diversity of natural conditions facilitates the high levels of resilience of the Caucasian fauna, yet it still faces severe pressure from anthropogenic factors.

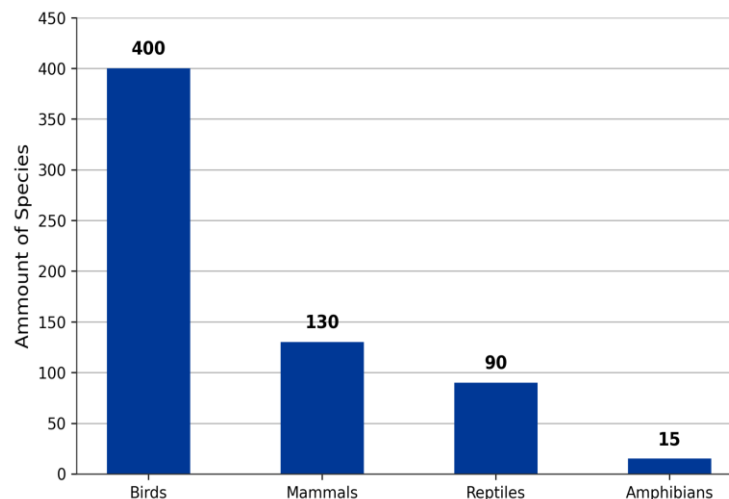


Figure 2. Number of animal species in the Greater Caucasus.

Figure 2 shows a chart illustrating the number of animal species in the territory of Azerbaijan from 2025 to 2026. The chart shows that birds account for the largest number (over 400 species), while amphibians account for the smallest number (about 15 species).

9. The Conservation of Rare and Endemic Species

The main factors leading to the reduction in the populations of many species in the Greater Caucasus are anthropogenic impact and changes in natural conditions. Key causes include deforestation and expansion of agricultural areas, infrastructure construction, and poaching. These factors lead to the

destruction of natural habitats and the disruption of ecological balance. An additional negative factor is climate change, which causes a shift in altitudinal vegetation zones and a contraction of the ranges of cold-loving species. High mountain ecosystems are particularly vulnerable, where even minor climate change leads to significant environmental consequences. To preserve them, nature reserves and national parks are being established in Azerbaijan. Parks such as Shahdag National Park play a key role in conserving the biodiversity of the Greater Caucasus. Modern research shows that without strengthening security measures, there is a risk associated with expanding the network of specially protected natural areas, further decline in the numbers of rare species, and loss of the region's biodiversity.

10. Spatial Analysis of Biodiversity

The biodiversity of the Greater Caucasus is characterized by a high degree of patchiness, which is due to complex terrain, significant elevation changes, variations in climatic conditions, and heterogeneity of the landscape structure. These factors shape a clearly defined vertical and horizontal differentiation of ecosystems, which determines the uneven distribution of flora and fauna across the region's territory.

Several natural-biogeographic zones are distinguished within the Greater Caucasus, each characterized by a specific level of biodiversity. The western part of the region is characterized by a more humid climate and the presence of Colchian forests, which are distinguished by dense vegetation cover and a significant number of relict species. The eastern part, by contrast, is characterized by more continental conditions and a predominance of drought-resistant vegetation, which is reflected in the species composition.

The northern part of the Greater Caucasus is characterized by harsher climate and lower biodiversity, whereas the southern parts of the Greater Caucasus have more favorable conditions for the development of forest and meadow ecosystems. High-mountain areas are characterized by a high degree of endemism and are therefore important for preserving the region's biodiversity.

Modern remote sensing methods play an important role in the study and analysis of the biodiversity of the Greater Caucasus. The use of satellite data and spatial modeling makes it possible to identify patterns of species distribution, assess the state of ecosystems, and predict changes driven by anthropogenic and climatic factors.

Geographic Information Systems (GIS) enable the creation of biodiversity maps that display areas of high species concentration, ecological corridors, and territories with heightened vulnerability. Such maps are an important tool for nature conservation planning and developing strategies for the region's sustainable development. Thus, Azerbaijan is a crucial part of the Caucasus biogeographic region where the spatial structure of biodiversity is formed under the influence of natural factors and human activity, which makes its territory particularly significant for research and conservation efforts.

11. Threats to Biodiversity and Ways to Conserve It

The modern biodiversity of the Greater Caucasus is experiencing a complex impact of anthropogenic and natural-climatic factors that lead to a decline in species numbers, ecosystem degradation, and the disruption of ecological regional equilibrium. The scientific literature of recent years has emphasized that the greatest dangers are deforestation, climate change, and intensive anthropogenic activities that act in concert, as well as synergistically, amplifying the negative consequences. These processes lead to the fragmentation of natural ecosystems and a reduction of habitats of many species.

Forest ecosystems play a key role in maintaining the stability of natural complexes by serving as a habitat for many endemic and relict species. However, economic activities related to timber harvesting and the expansion of agricultural areas, land, and infrastructure construction lead to the fragmentation of forest arrays and loss of biotopes. According to research in recent years, the reduction of forest areas directly contributes to the decline of populations of rare flora and fauna species.

Table 1. Key threats to the biodiversity of the Greater Caucasus and their characteristics.

Threats	Brief description	Key consequences
Deforestation	Intensive logging, expansion of agricultural land and infrastructure	Forest fragmentation, habitat loss, decline in species numbers
Climate change	Rising temperatures, changes in precipitation patterns, and an increase in the frequency of extreme events.	Shifting of natural zones, disruption of phenological cycles, disappearance of mountain species.
Anthropogenic activity	Urbanization, industry, mining, recreational pressure	Environmental pollution, soil degradation, ecosystem destruction

Climate change also acts as a critical factor transforming natural ecosystems of the Greater Caucasus. An increase in average annual temperatures, changes in precipitation patterns and the increased frequency of extreme weather events lead to the shifting of natural zones and the disruption of the phenological cycles of plants and animals. Scientific papers note that climate change is particularly dangerous for high-mountain ecosystems, where many species possess a narrow ecological amplitude and limited migration capacity.

Anthropogenic activities such as urbanization, industrial development, mining operations, and increasing recreational pressure lead to the degradation of the natural environment. Increased tourism contributes to soil erosion and the destruction of vegetation cover. Industrial pollution degrades the quality of soil and water resources.

As shown in Table 1, the biodiversity of the Greater Caucasus is affected by a complex of interrelated factors, among which three main groups of threats stand out: deforestation, climate change, and human activity. These factors act synergistically, amplifying the negative impact on the region's ecosystems. Thus, the primary threats to the biodiversity of the Greater Caucasus are multifaceted in nature and require a systemic approach to their study and mitigation. This highlights the need to integrate nature conservation measures, sustainable natural resource use, and climate adaptation to preserve the region's unique ecosystems.

12. Consequences of Biodiversity Degradation

The loss of species is a result of declines in population numbers, habitat destruction, climate change, and anthropogenic pressure. The decline in the population of certain species disrupts trophic networks and energy flow within ecosystems. If this leads to the dominance of certain species over others, it may cause a decrease in the overall stability of natural-territorial complexes. As a result, ecosystems become more vulnerable to external impacts such as droughts, fires, and climatic fluctuations. Even a slight reduction in key species can trigger cascading changes in the ecosystem's structure.

Furthermore, the degradation of biodiversity leads to a decline in the quality of ecosystem services, including water-regulating, soil-protecting, and climate-regulating functions. The decline in forest cover, especially in the mountainous regions of Azerbaijan, further increases soil erosion, landslides, and flood activity. The deterioration of ecosystems also has a negative impact on the quality of life and health of the local population.

Table 2. Consequences of biodiversity degradation in the Greater Caucasus.

Consequences	Content	Environmental effects	Examples of manifestation
Loss of species	Decline in population numbers and the extinction of individual species	Disruption of ecosystem stability, loss of genetic diversity	Disappearance of endemic and rare flora and fauna species of the Caucasus
Disruption of ecosystem connections	Disruption of food chains and trophic interactions	Destabilization of ecosystems, reduction of their resilience to external factors	Changes in the structure of forests and mountain ecosystems
Decline in ecosystem services	Degradation of natural ecosystem functions	Reduction in water regulation, soil protection, and climate regulation	Increased soil erosion, disruption of the water regime

As shown in Table 2, the degradation of biodiversity in the Greater Caucasus region leads to several consequences, notably the loss of species, the disruption of ecosystem linkages, and a decline in ecosystem services. Thus, an analysis of the table shows that the degradation of biodiversity has a complex negative impact on the ecosystems of the Greater Caucasus, reducing their resilience and functional significance.

13. International Biodiversity Conservation

Biodiversity conservation is a major priority in global environmental policy today. To that end, countries have created a mix of legal, financial, and organizational tools to preserve ecosystems. Worldwide, conservation usually relies on setting up protected natural areas, international treaties, and sustainable natural resources management. The 1992 Convention on Biological Diversity (CBD) and work under the auspices of UNEP laid the foundation for these initiatives. CBD encourages nations to design their own environmental strategies, focusing on sustainable resource use.

The adoption of the path of sustainable development as the global approach to conservation means that many countries, particularly in the developing world, are trying to balance nature protection with economic growth. UNESCO biosphere reserves, World Heritage sites, and other types of protected areas help to preserve ecosystems and give endangered species a chance for recovery.

Transboundary cooperation is essential. Initiatives like the Pan-European Biological and Landscape Diversity Strategy and WWF projects help neighboring states share scientific data and facilitate joint conservation programs.

Economic mechanisms also play a big part. Carbon markets, compensation systems, environmental taxation, and fines encourage businesses and governments to act more responsibly and reduce their impact on the biosphere. A multi-level strategy for environmental conservation requires integrating legal, scientific, and economic methods. Adapting these strategies to the Greater Caucasus will help protect the region's unique ecosystems in the long run.

Table 3. International biodiversity conservation.

Area	Contents	Key instruments	Impact
International conventions	Global agreements on biodiversity conservation	Convention on Biological Diversity (CBD, 1992)	Formulation of national nature conservation strategies
Specially protected areas	Conservation of unique ecosystems and species	UNESCO biosphere reserves, World Heritage sites	Population stabilization, ecosystem restoration
Regional cooperation	Coordination of nature conservation policy among countries	WWF programs, Pan-European Strategy	Strengthening of transboundary nature conservation
Economic mechanisms	Financial incentives for nature conservation	Environmental payments, carbon markets	Reduction of human-induced pressure

As shown in Table 3, international biodiversity conservation is based on a combination of legal, organizational, economic, and scientific coordination mechanisms aimed at preserving natural ecosystems and ensuring the sustainable use of natural resources.

Thus, an analysis of the table demonstrates that international experience in biodiversity conservation is characterized by a comprehensive and multi-level approach, integrating legal norms, protected areas, international cooperation, and economic instruments, which makes it an effective model for adaptation in various regions of the world.

14. State Policy and Environmental Legislation

State policy and environmental legislation form the framework for biodiversity conservation, combining legal, managerial, and economic tools to prevent ecosystem degradation. In Azerbaijan, this framework is based on the Law "On Environmental Protection", the Law "On Specially Protected Natural Areas", and other legal documents. Especially important is the expansion of special protected natural areas. Reserves and national parks, such as Shahdag National Park in the Greater Caucasus, lower anthropogenic pressure and preserve biodiversity; alongside land protection, state-led initiatives focus on active restoration and reforestation, as well as continuous monitoring.

Practical recommendations for the conservation of biodiversity in the Greater Caucasus. Preserving the biodiversity of the Greater Caucasus requires not only a theoretical understanding but also the implementation of concrete practical measures that are comprehensive and long-term in nature. For example, it is necessary to expand the network of special protected natural areas. Currently, many of the ecosystems in the Greater Caucasus remain insufficiently protected. Expanding the area of nature reserves and national parks and establishing ecological corridors between them helps preserve animal migration routes and maintain genetic-level biodiversity.

Monitoring natural resources will greatly benefit from the integration of modern GIS technologies, remote sensing, and UAVs. Not only is this likely to improve the accuracy of assessments, but it will also speed up the decision-making process. According to UNEP, the digitalization of environmental monitoring significantly enhances the effectiveness of environmental management.

Another key area is the implementation of sustainable natural resource management in forest management and agriculture. Managing mountainous forest ecosystems requires a shift from intensive and often illegal exploitation to selective and certified logging. In agriculture, the adoption of agroecological practices such as crop rotation, minimal tillage, sustainable use of water resources, and reduced use of chemical fertilizers is recommended. Restoration of mountain forests and alpine meadows, which are undergoing degradation due to livestock grazing and climate change, is particularly relevant for the Greater

Caucasus and Azerbaijan. Involving local communities in nature conservation programs, developing community-based tourism and ecotourism, and conducting educational campaigns among the populace will increase the level of public responsibility for the state of the environment.

Fostering transboundary and regional cooperation is important, although not without its own challenges in the South Caucasus. Joint monitoring programs, the exchange of scientific data, and the implementation of international projects are the only ways to comprehensively address the environmental issues and challenges. Overall, the practical recommendations for conserving the biodiversity of the Greater Caucasus are based on a comprehensive approach that includes:

- area-based nature protection,
- sustainable natural resource use,
- ecosystem restoration,
- environmental monitoring,
- education, and
- international cooperation.

Implementing these measures will significantly enhance the resilience of the region's ecosystems and preserve its unique natural heritage for future generations.

15. Conclusion

Based on materials concerning the conservation of biodiversity in the mountain forests of the Greater Caucasus, several general conclusions can be drawn regarding the current state of the issue, the primary threats, and the prospects for addressing them.

The mountain forests of the Greater Caucasus in Azerbaijan constitute one of the country's most valuable natural ecosystems and play a vital role in preserving the biodiversity of the Caucasus region. An analysis of scientific materials and ecological studies has shown that these forest ecosystems are characterized by a high level of biodiversity, a complex spatial structure, and significant ecological resilience.

The study established that the mountain forests of the Greater Caucasus are characterized by distinct altitudinal zonation, a diversity of natural conditions, and a predominance of broad-leaved forests. The primary forest-forming species are beech, oak, and hornbeam, which constitute the basis of the region's forest cover. These forests support the conservation of a wide range of plant and animal species, including rare and endemic ones listed in the Red Book of Azerbaijan.

Forest ecosystems are of particular importance for maintaining ecological balance. They regulate climatic processes, play a role in shaping the water regime, prevent soil erosion, reduce the risk of landslides and mudflows, and ensure the stability of mountain natural complexes.

The materials studied and analyses conducted have shown that the highest concentration of forest resources and biological species is found precisely in the mountainous regions of the Greater Caucasus. At the same time, studies have revealed an uneven distribution of forests, as well as processes of fragmentation and local degradation of natural ecosystems.

The main threats to biodiversity are deforestation, the expansion of agricultural areas, livestock grazing, climate change, and human impact. These factors lead to the disruption of ecosystem structures, the loss of animal habitats, soil degradation, and a decline in the populations of certain species. Studies have also shown that measures to conserve biodiversity are being implemented in Azerbaijan, including the establishment of protected natural areas, reforestation efforts, environmental monitoring, and the use of modern technologies to monitor forest conditions. Thus, preserving the biodiversity of the mountain forests

of the Greater Caucasus is an important environmental task for Azerbaijan. Effective protection of natural ecosystems requires a comprehensive approach that includes state oversight, scientific research, rational use of natural resources, and the fostering of environmental awareness among the public. Preserving forest ecosystems will ensure the region's environmental sustainability and safeguard Azerbaijan's unique natural heritage for future generations

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Manifestation and Forecast of Global Climate Change in Azerbaijan

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Abstract

In the modern era, climate change is considered one of the most serious ecological challenges on a global scale. This problem is even more relevant for Azerbaijan, a country highly dependent on energy resources and with an arid climate. Analysis of long-term meteorological observations shows that a continuous increase in the average annual temperature, a key climate indicator, is being recorded in Azerbaijan. Compared with the period from 1961 to 1990, the average annual temperature has increased by approximately 1.1–1.4°C in recent periods. The acceleration of this increase after the 2000s demonstrates the real regional impact of global warming processes occurring in the climate system. Statistical analyses show that from 1950–2025, the rate of increase in average annual temperature in Azerbaijan was approximately +0.2°C per decade. In recent decades, however, this figure has risen even more in some local regions (for example, in the Central Aran zones), reaching +0.3–0.35°C/10 years. Long-term observations (1950–2025) also confirm a significant imbalance in both the total amount of precipitation and its seasonal distribution. A nationwide decrease in the average annual precipitation of approximately 5% to 12% is observed. Projection matrices show that by 2050, the probability of an increase in average annual temperature in Azerbaijan in the range of a minimum of 1.5°C to a maximum of 2.5°C is very high. Against a backdrop of rising temperatures, a decrease in annual precipitation of 2% to 10%, a sharp intensification of moisture deficit to 15–20%, especially during the growing season (spring and summer months), and a 20–30% reduction in mountain snow reserves is predicted.

Keywords: climate change, annual temperature, drought events, projection indicators, water resources, soil degradation

1. Introduction

Global climate transformations are the sum of profound, statistically confirmed changes in the planet's meteorological system that span decades or longer. This process is primarily characterized by a distinct dynamic in the temperature regime, the geography of precipitation distribution, the circulation of air masses, and other important climate parameters. Based on modern academic theory, climate anomalies are a multifaceted and complex global geosystem phenomenon caused by the result of both natural variations and human-generated energy sources. The scientific evidence shows that the climate of the planet is created based on the interactions that exist between the giant geospheres, including the atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere.

The continuous global cycle of matter and energy between these named spheres plays a crucial role in maintaining the climate balance. For this reason, it is incorrect to perceive the process of climate change as simply a warming of the weather; it also signifies a change in the internal structure of global ecosystems, their resilience limits, and the functional characteristics of biomes.

When explaining the scientific nature of the problem in question, special attention is first given to the concept of "global warming." This process is the sharp increase in the concentration of greenhouse gases (CO₂, CH₄, N₂O, etc.) generated by industrial emissions in the upper layers of the atmosphere, and the resulting disruption of the planet's thermal balance. According to the consensus of the international scientific community, the rapid warming recorded since the Industrial Revolution is a direct negative environmental product of industrialization activities (IPCC, 2023).

The main driving force behind the modern climate crisis is anthropogenic (human-caused) factors. This includes oil, this includes the mass burning of fossil fuels such as oil and coal, the increase in emissions released into the atmosphere from industrial smokestacks, the proliferation of internal combustion engine vehicles, agricultural activities, and deforestation. In particular, the traditional structure of the energy sector, based on hydrocarbon resources, has led to the atmospheric concentration of CO₂ exceeding critical limits. Numerous empirical studies prove that the global warming anomalies of recent decades are a direct result of human capital production activities.

In addition, uncontrolled urbanization, land-use change, and agro-industrial waste also indirectly stimulate this degradation. The destruction of the green cover nullifies the biosphere's natural carbon-absorbing capacity, and as a result, the global carbon balance is completely disrupted. At the same time, the regional "heat island effect" created by the expansion of megacities makes the local microclimate more aggressive.

Changes in climate conditions also significantly challenge natural biodiversity and ecosystem stability. Many plant and animal species are losing their habitat areas or becoming threatened with extinction since they are unable to adapt to new climatic conditions genetically and environmentally. Most importantly, highly sensitive marine ecosystems on our planet, such as coral reefs (which are considered to be the cradle of life for oceans), are being destroyed in large numbers because of acidification and warming (Məmmədov, 2019).

In the modern period, the climate change problem represents a complex eco-economic phenomenon for the whole world that has transboundary influence on all institutional and functional sectors of the economic system; these destructive influences can be seen clearly at regional and national levels, especially in the economy. The macroeconomic analysis shows that agriculture, management of water resources, the fuel and energy sector, health care, and the production-infrastructure sector demonstrate the highest vulnerability to climate anomalies. Such sectoral vulnerabilities produce the multiplier effect that directly influences the dynamics of GDP creation, investment attractiveness, and changes in the employment structure (Qasimov & Məmmədov, 2025). In the agriculture sector, the constant growth of annual average temperatures, decrease of regional precipitation, and increase of drought periods lead to serious agricultural productivity instability.

Soil moisture regime disruptions, deviations of vegetation phases from scientific calendar principles, as well as the random increase in the need for irrigation water use, negatively influence the development cycle of important crops (cotton, vine culture, and others). Moreover, an imbalance in traditional agricultural calendars, growing plant protection problems, and soil erosion accelerate the process of desertification of the lands.

Climate change is significantly affecting Azerbaijan's water resources by altering the annual and seasonal flow patterns of rivers, reducing snow reserves in high mountain regions, and increasing evaporation rates. One of the most pressing consequences is the critically low water levels in the Kura–Araz River Basin, which have led to growing shortages in both urban drinking water supplies and

irrigation for agriculture. These changes have made water resource management increasingly complex, particularly because Azerbaijan relies heavily on transboundary rivers. As a result, the country must adopt alternative water management strategies and modern irrigation technologies to ensure long-term water security and maintain a stable internal water balance. In addition, declining reservoir storage capacity presents both operational and structural challenges for effective water management.

Climate change also poses serious challenges for the energy sector. During increasingly frequent summer heatwaves, the widespread use of air conditioning and cooling systems drives up electricity demand, placing additional pressure on the national power grid. At the same time, reduced river flows limit hydropower generation, making energy production less reliable. Together, these factors increase risks to energy security and grid stability, highlighting the urgent need to expand renewable energy sources and strengthen the resilience of Azerbaijan's energy system (Azərbaycan Dövlət Su Ehtiyatları Agentliyi, 2024).

Heat waves and dust clouds in the atmosphere, especially in large urban agglomerations, cause serious consequences for human health in the healthcare and social sectors. Heat stress, the chronicization of cardiovascular and respiratory diseases, as well as the expansion of the ranges of tropical disease vectors, are recorded in medical statistics. The deterioration of air quality due to ecological imbalance is causing a regional increase in respiratory diseases and a rise in the financial burden on the healthcare system (ÜST & Azərbaycan Respublikası Səhiyyə Nazirliyi, 2023). In infrastructure systems, sudden and intense rainfall, floods, and inundation events accelerate the technical wear and tear of transport-logistics corridors and engineering utility lines, increasing material losses. In urbanized areas, the urban heat island effect, caused by the heat capacity of concrete and asphalt surfaces, results in temperatures being felt as higher in urban environments compared to rural areas. This situation requires the engineering-based redesign of green architecture and drainage systems in modern urban planning (Azərbaycan Respublikası Dövlət Şəhərsalma və Arxitektura Komitəsi, 2024). In general, the analysis demonstrates that there exists an interconnectedness between impacts of climate change in various sectors. Hence, the full-scale implementation of adaptation and mitigation strategies is essential for the sustainable development of the country's economy.

Consequences of climate change generate internal inequalities in the socio-economic development equilibrium of regions. Since rural and urban zones have different potentials of adaptation to climate change and access to financial sources, processes of socio-economic stratification are intensifying. Although regions that depend fully on agriculture are highly sensitive to drought and ecological dangers, high population density in cities puts pressure on infrastructure and energy supply. In order to solve this issue, regions need to reconsider their approaches to sustainable development in terms of ecological aspects (İbrahimov, 2025).

Finally, the above-mentioned universal influence of climate change generates new priorities in the country's economic policy. Adaptation of the national economy to climate change, the transition to green energy sources, decarbonization, and international standards for carbon are crucial for the economic programs of the state. This strategy is very important for the country in order to switch to a diversified development model, thus being able to free itself from hydrocarbon dependency.

Theoretical and statistical evidence suggests that climate change affects Azerbaijan's key sectors through complex, interconnected, and multifaceted processes. The continuous temperature rise, a decrease in total precipitation, and the intensification of sudden extreme weather events negatively affect both the current operations and strategic planning of the national economy. Considering the profound penetration of environmental factors into the macroeconomic and social systems through economic mechanisms, the scientific development of national adaptation strategies and the promotion of green technologies in the agricultural and industrial sectors are of special importance to the state. Achieving sustainable economic growth in the future, reducing climate-related risks, and implementing coordinated, integrated eco-economic policies across all sectors of the economy will be essential to addressing these challenges.

2. Materials and Methods

This study employed a combination of research methods, including statistical data analysis, meteorological data analysis, comparative analysis of data from different years, trend analysis, and a systematic review of relevant literature and reports. A systematic approach was adopted to provide a comprehensive understanding of climate variability and the mechanisms through which it affects different sectors. This approach enabled climate processes to be examined as interconnected components of a broader environmental system.

In addition, comparative analysis was used to assess Azerbaijan's climate indicators alongside regional and global climate trends, allowing both similarities and differences to be identified. Statistical methods were also applied to examine changes in temperature and precipitation over time and to evaluate their long-term trends.

The projection of future climate conditions was conducted based on model results from the RCP 4.5 (medium emission) and RCP 8.5 (high emission) scenarios presented by the IPCC. The combined application of these methods has enhanced the objectivity and practical significance of the results obtained.

3. Results and Discussion

A statistical analysis of the dynamics of climate indicators in Azerbaijan clearly shows the general trends of climate changes observed in the country's territory in recent decades. Based on long-term meteorological observations, a continuous increase in the average annual temperature, the primary climate indicator in Azerbaijan, is being recorded. Compared with the 1961–1990 period, the average annual temperature has increased by approximately 1.1–1.4°C in recent periods. The fact that this increase has accelerated more significantly after the 2000s demonstrates the real impact of global warming processes in the climate system at a regional level.

A seasonal analysis of temperature dynamics shows that the highest increase is recorded in the summer season, with this figure rising to approximately 1.5°C. In the winter season, however, the increase is relatively weaker, averaging around 0.8°C (Qasimov & Məmmədov, 2025). This trend leads to a noticeable extension of the warm period, a shift in the vegetation period, and a disruption of the natural rhythm of agricultural activities. At the same time, a 15–25% increase is observed in the number of days with temperatures above 30°C, which proves the intensification of regional heat waves.

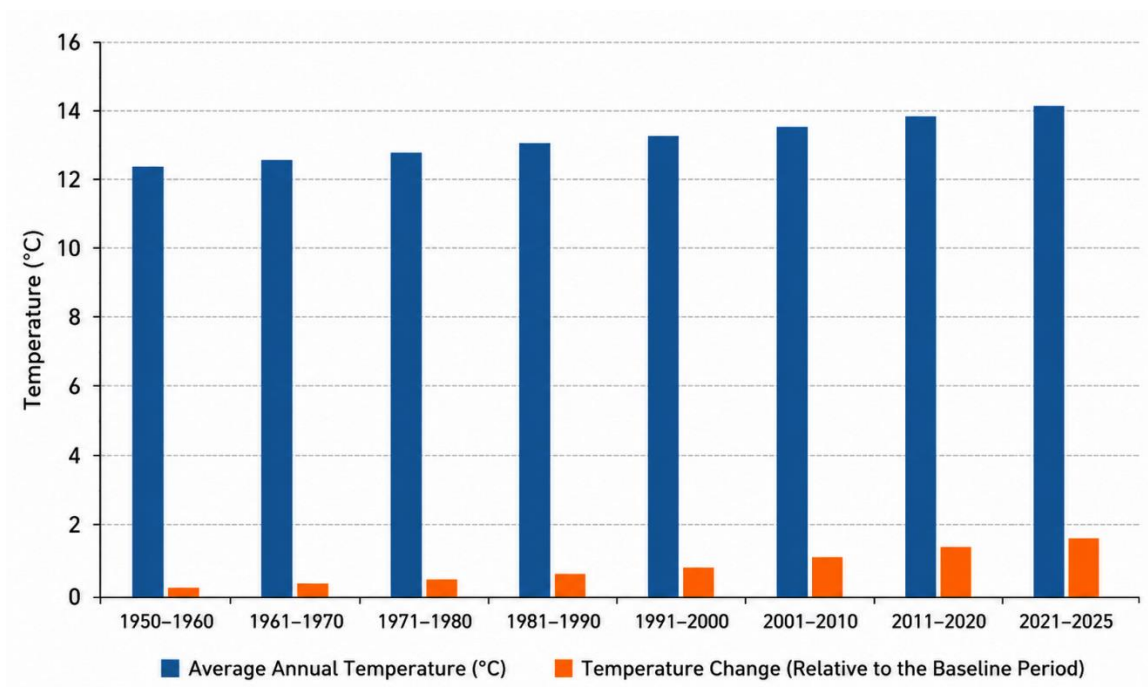


Figure 1. Dynamics of multi-year temperature in Azerbaijan (1950–2025).

Figure 1 shows that long-term meteorological observations in Azerbaijan indicate a clear and continuous increasing trend in the average annual temperature for the period 1950–2025 (İbrahimov, 2024). This is explained not only by large-scale global warming processes but also by the interaction of geographic and human-induced factors in the region.

Analysis of the observation periods chronologically shows several important stages:

From 1950 to 1970, the average annual temperature of the country remained rather constant, showing an average temperature from approximately 12.5 to 13.0°C. This time frame can be called the period of climate stability in the region. Since the end of the 1970s, a rather slow process of warming started becoming noticeable in the graphs.

The temperature increase is clearer in the 1980s and 1990s. During this period, the average annual temperature had already risen to approximately 13.0–13.3°C. The increase in temperature anomalies, particularly during the summer season, is considered the first serious signal of structural changes occurring in the climate system.

However, after the 2000s, the temperature increases in Azerbaijan became faster and more pronounced. According to statistical data, the average annual temperature has increased by approximately 0.6–0.8°C compared to the period from 1991 to 2010. This period is also characterized by an increase in the number of anomalously hot days and a rise in extreme high temperature events.

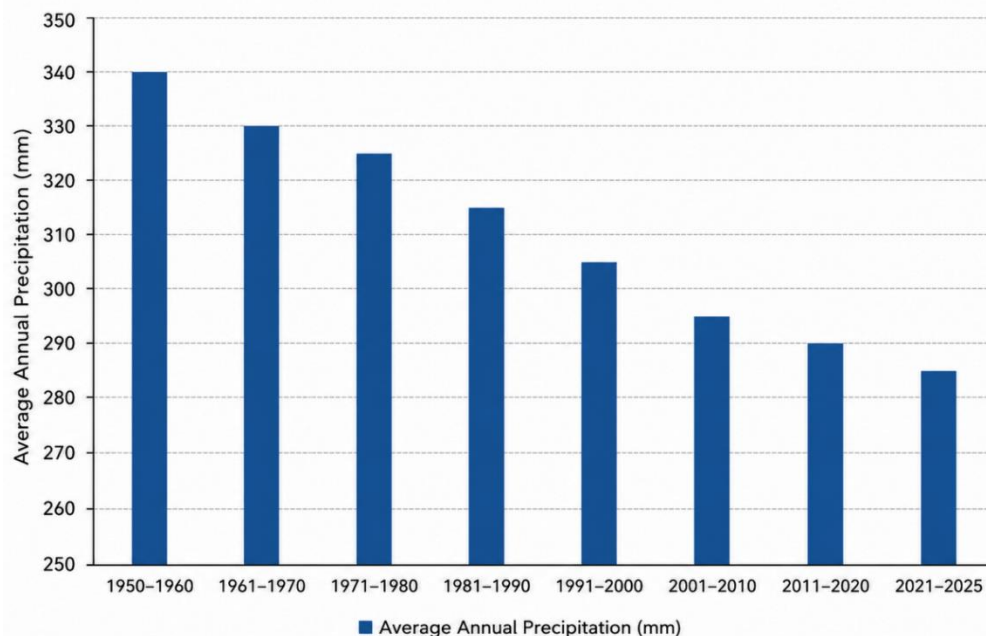


Figure 2. Dynamics of multi-year precipitation in Azerbaijan (1950–2025).

Since 2010, the regional impacts of climate change have reached a new peak. Over the last 15 years, the average annual temperature has increased by approximately 1.1–1.4°C compared to previous baseline periods. Record-high temperatures have been recorded in some years (especially in 2010 and 2020 and the years near them). This trend is accompanied by the intensification of dangerous heat waves and the extension of the natural vegetation period nationwide (Azərbaycan Respublikası Kənd Təsərrüfatı Nazirliyi / ATM, 2023; Quliyev, 2021). Regional analysis indicates that temperature increases are not distributed uniformly across Azerbaijan. Warming is more pronounced on the Absheron Peninsula and in the Kura–Araz Plain, largely due to the combined effects of urbanization and the urban heat island phenomenon. In contrast, mountainous regions have experienced a slower rate of warming, primarily because of the moderating influence of higher elevations (İbrahimov, 2024). These regional differences are driven by variations in microclimatic conditions, moisture availability, and topographic characteristics.

Statistical analyses show that during the 1950–2025 period, the rate of increase in average annual temperature in Azerbaijan was approximately +0.2°C per decade. In recent decades, however, this indicator has risen even more in some local regions (for example, in the central lowland zones), reaching a level of +0.3–0.35°C/10 years.

The statistical analysis of precipitation data in Figure 2, however, reveals a more unstable and fluctuating picture compared to temperature in Azerbaijan. Overall, a decrease in the average annual precipitation is observed across the country, ranging from approximately 5% to 12%, but this variation is sharply different depending on the region's geographical location. In the Absheron and Nakhchivan regions, the decrease in precipitation is pronounced and is estimated at approximately 10–12%, respectively. In the Ganja-Gazakh zone, this decrease is observed at a more moderate pace, while in the Lenkaran-Astara region, thanks to its humid climate type, relative stability and even an increase in specific years are recorded. These variations reaffirm the influence of complex topographical features on the country's climatic diversity.

One of the most sensitive indicators of climate change impacts in Azerbaijan is its precipitation regime. Long-term observations (from 1950 to 2025) prove that there is an obvious disproportionality between the amount of precipitation and its seasonal distribution. While there is a tendency towards a

general decline in the average annual amount of precipitation throughout the country, the dynamics differ during different time intervals:

In the period from 1950 to 1970, the precipitation regime was fairly stable with no sharp deviations in average annual amounts. In this phase, the annual distribution of precipitation was more even and fully conformed to the traditional seasonal rhythm. However, starting from the late 1970s, the variability of precipitation and the duration of drought periods gradually began to increase.

In the 1980s and 1990s, weak decreasing trends in precipitation amounts were recorded, and drought trends began to become more apparent, especially in semi-arid areas such as the Absheron Peninsula and the Kura-Araz Plain. During this period, a decrease of approximately 3–5% in the country's (Vəliyev, 2022) average annual precipitation was reflected in statistical reports.

Changes in the precipitation regime after the 2000s have become more critical. According to statistical analyses, the average annual precipitation across the country has decreased by approximately 5–10% compared to the 1990s. The most concerning aspect is the disruption of the seasonal pattern of precipitation: a relative increase in precipitation (mainly in the form of unstable rain) during the winter months, and a sharp decrease during the summer months, which are vital for agriculture (Qasimov, Ə. N., Məmmədov, 2025). This situation creates a serious imbalance in terms of the natural replenishment of water reserves.

Regional analysis shows that precipitation changes are not evenly distributed across the country. Although the Lankaran–Astara region has experienced relatively stable precipitation patterns, the Absheron Peninsula, the Nakhchivan Autonomous Republic, and the Kura–Araz Plain have seen a marked decline in precipitation, with drought conditions becoming increasingly frequent. In the country's high mountain regions, rising temperatures have reduced snow accumulation and accelerated snowmelt, leading to significant changes in river hydrology and seasonal precipitation patterns.

Overall, statistical analysis indicates that climate change in Azerbaijan has affected not only the total amount of precipitation but also its spatial and temporal distribution (Azərbaycan Respublikası Kənd Təsərrüfatı Nazirliyi / ATM, 2023). These shifts have made the integrated management of surface and groundwater resources more challenging while increasing climate-related risks for the agricultural sector.

4. Conclusion

A long-term analysis of meteorological data from across Azerbaijan shows a significant increase in extreme weather events. In recent years, the frequency of heatwaves has risen by approximately 30–40%, while widespread droughts have become nearly twice as common as in earlier historical periods. At the same time, heavy rainfall events, floods, and flash floods have increased by about 20–25%. These findings show that climate change is affecting not only average climate conditions but also the frequency and intensity of extreme weather events.

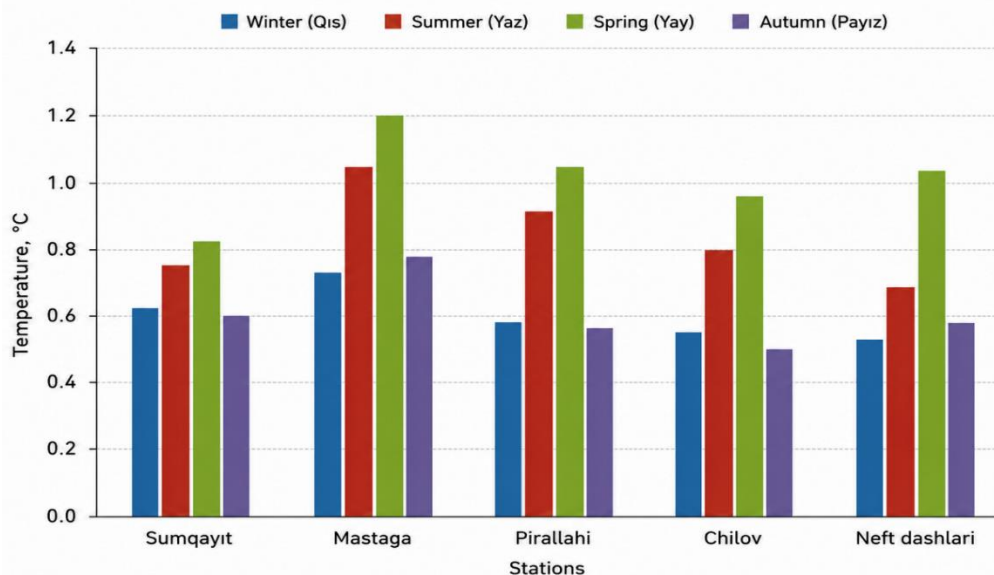


Figure 3. Seasonal Variations in Average Temperature in the Absheron Aquatorium, 1991–2020.

As for the frequency of drought and heat wave phenomena, the Kura-Araz Plain, the Absheron Peninsula, and the lowlands of Nakhchivan have proven to be more prone to these climatic conditions. Flash flooding due to heavy rains, on the other hand, is much more likely to happen in the mountainous and foothill regions, such as Sheki-Zagatala, Guba - Khachmaz, and Mountainous Shirvan. The presence of sharp regional variations in climatic conditions can be explained by the topography of the country and its hydrological conditions.

The presented Figure 3 shows the seasonal average temperature changes at five different stations in the Absheron aquatorium for the period 1991–2020. The highest temperature change was recorded at the Mashtaga station in the summer (approximately 1.2 °C). In the winter and fall, the temperature increase is lower and more stable compared to other seasons, ranging from 0.5 °C to 0.8 °C. Overall, temperature fluctuations are higher at stations closer to land (e.g., Mashtaga) compared to stations in the sea (e.g., Chilov and Neft Dashlari).

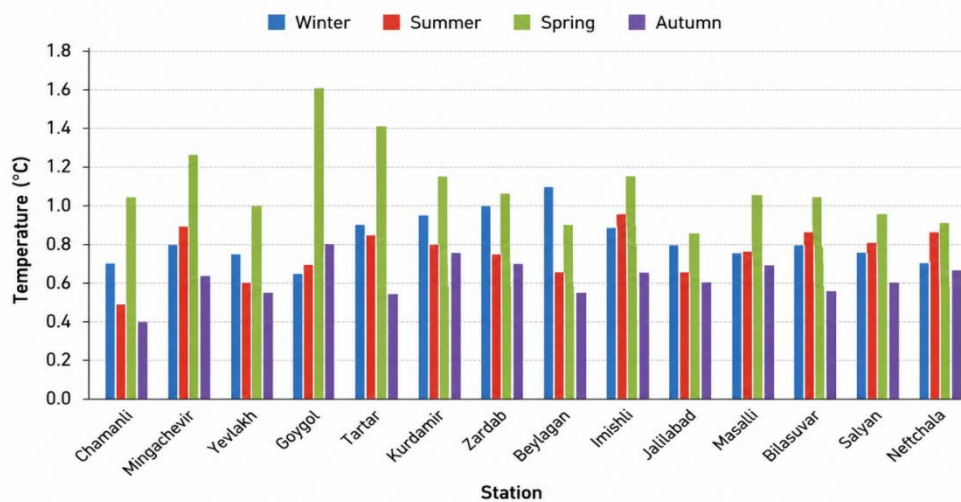


Figure 4. Seasonal average temperature changes in the Kur Intermontane Depression province from 1991 to 2020.

Table 1. Trends in the increase of extreme climate events in Azerbaijan (1950–2025)

Period	Drought events	Floods and inundations	Hot waves	General trend
1950–1960	Mild humidity (Caspian region—Kür-Araz → 10–12 years → 1–2 years of severe drought)	Average annual: 2–4 events (mainly on the southern slope of the Greater Caucasus)	Normal: 3–5 days per year (days with temperatures above 35°C)	Stable climate regime, minimal temperature anomalies ($\pm 0.1^{\circ}\text{C}$)
1961–1970	Stable (In arid zones, total soil moisture is nearly normal, <15%)	On average per year: 3–5 events (localized floods)	Stable: 4–6 days per year (characteristic for the Absheron and Kura-Araz regions)	Sustainable hydrometeorological period, minimal climate risks
1971–1980	Regional dynamics (the regional drought index in the Kura-Araz plain increased by 10%)	Average annually: 5–6 events (Activation in rivers of the Small Caucasus)	Slight increase: 6–8 days per year (in inland districts during summer months)	Regional temperature background rising by 0.2°C to 0.3°C
1981–1990	Moderate regional drought (15–20% decrease in precipitation during the growing season)	On average per year: 7–9 events (in mountainous and foothill zones)	Moderate intensity: 9–12 days per year (Change in the Caspian Sea's thermal regime)	Linear increasing trend in the frequency of climate anomalies
1991–2000	Severe aridification (Hydrological drought covering 25–30% of the country's territory)	On average per year: 12–15 events (Peak in the Talish Mountains and the Greater Caucasus)	High intensity: 14–18 days per year (beginning of the urban heat island effect)	Annual average temperature anomaly between $+0.5^{\circ}\text{C}$ and $+0.7^{\circ}\text{C}$ above normal
2001–2010	Persistent drought (15% reduction in water reserves, 40% expansion of arid zones)	An average of 18–24 events per year (regional floods in May–June)	Critical increase: 20–25 days per year (days of extreme heat stress)	Rapid change in temperature regime (0.9°C increase from the norm)
2011–2020	Extreme aridification (Synoptic drought phases in the Kura-Araz region and Nakhchivan doubled)	On average per year: 28–35 events (Highland River flood activity)	Aggressive trend: 28–32 days per year (record temperature indicators, $>40^{\circ}\text{C}$)	Sharpening of regional Climate risks (Increase from norm by $+1.4^{\circ}\text{C}$)
2021–2025	Decrease in water levels in the Kura River and land aridification	Sudden downpours and flood consequences	Record peak indicator: 35–42 days per year (anomalously long-term)	Maximum ecological and climate security risk (Stress on the national ecosystem)

The most notable feature in the presented graph (Figure 4) is the more pronounced rise in summer temperatures (by 1.4°C – 1.7°C) compared to other seasons at most stations (especially in Goygol and Tartar). While the winter anomaly at the Beylagan station exceeds the summer one, the overall trend indicates that the process of aridification and intensification of summer heat predominates in the region.

Analysis of Table 1 shows that over the last 70 years, the country has transitioned from a stable climate regime to a phase of sharp aridification and aggressive temperature increase. In the initial period, covering the 1950–1970s, the region was characterized by a mild, moderate, and stable climate, with temperature anomalies remaining at a minimal level (between $\pm 0.1^{\circ}\text{C}$ and $+0.3^{\circ}\text{C}$). During those decades, the number of hot days with temperatures above 35°C was a normal 3–6 days per year, while the annual average of flood and inundation events was low, ranging from 2 to 5 incidents.

Spatial analyses prove that changes in humidity are not evenly distributed across the country's geography. While the Lankaran-Astara zone has maintained a relatively stable precipitation regime, a more pronounced aridification of precipitation indicators is observed in the Absheron Peninsula, the Nakhchivan Autonomous Republic, and the Kura-Araz Plain. In high mountain zones, the direct impact of the thermal uplift causes a volume decrease and premature rapid melting of solid precipitation (snow cover and glaciated areas), leading to changes in the multiyear hydrological regime of rivers and the overall precipitation architecture.

According to the overall results of the statistical analyses, in Azerbaijan, precipitation is not only a quantitative indicator, but its configuration in time and space has also undergone a fundamental transformation. This situation has an integrated impact on surface and groundwater resources, management (YSMRI) strategies, complicating them and multiplying ecological risk factors in the agricultural sector. One of the most concerning statistical indicators in recent years is the significant increase in the frequency of extreme meteorological and climatic events. The frequency of severe heat waves has increased by approximately 30–40%, while macro-regional drought events have been recorded at nearly twice the rate compared to previous historical synoptic periods. In parallel, a 20–25% increase in the total number of destructive extreme rainfall, flood, and inundation events is also being recorded. These mathematical indicators prove that climate change is manifesting itself not only in linear average statistical figures but also directly in the intensity of catastrophic and anomalous extreme events (Əliyev, 2024).

In parallel with these processes, significant structural transformations are also occurring in moisture and evaporation indicators across the country. Based on multi-year measurement data from meteorological stations, the average relative humidity has decreased by 3–7%, particularly in arid and semi-arid regions, while annual potential evapotranspiration (evaporation potential) has increased by 10–18%. This downward trend has increased the risk of severe hydrological drought, disrupting the natural hydrological balance, reducing soil moisture availability, and lowering agricultural productivity (Kərimov, 2024).

The period from 2010 to 2025 was marked by even greater variability in precipitation patterns. Although some years experienced localized heavy rainfall events, the overall trend remained negative, with average annual precipitation across Azerbaijan declining by approximately 8–12% compared with earlier reference periods. At the same time, the frequency of anomalous regional precipitation events, i.e., short-term but extremely intense downpours, has increased, which bypasses infiltration into the soil and goes directly to surface runoff, sharply increasing the risks of floods and flash floods.

Overall, mathematical and statistical analyses demonstrate that the observed changes in Azerbaijan's climate indicators are not random but systematic, and are primarily accompanied by regional warming, a degradation in the distribution pattern of precipitation, and an increase in extreme events. These dangerous trends pose serious macroeconomic threats to the country's ecological balance, national water security, and the agro-industrial sector. Consequently, accelerating national adaptation programs for climate change and developing sustainable hydrometeorological monitoring systems with innovative methods emerge as a critical state necessity and strategic goal.

In the context of the consequences of global ecological transformations on a regional scale, Scientific forecast scenarios for the development of climate change in Azerbaijan through 2050 demonstrate that the imbalance in fundamental meteorological and hydrological indicators across the country will continue to increase and that ecological risks will systematically intensify (Azərbaycan Respublikası Ekologiya və Təbii Sərvətlər Nazirliyi, 2024).

According to the mathematical-statistical results of modern climate models applied at international and regional scales, the inevitable increase in temperature by the middle of the century, the destabilization of the precipitation regime with a sharp moisture deficit, and the intensification of destructive extreme natural events are the main macro-trends threatening the stability of the national economy. These changes

are not limited to disrupting regional ecological balance, but also directly place the state's long-term macroeconomic security architecture, demographic sustainability, and social infrastructure formation at risk. Forecast matrices from different Global Climate Models (GCMs) with various emission scenarios, particularly those containing different carbon concentrations, prove that the probability of a rise in average annual temperature in Azerbaijan by 2050 in the range of a minimum of 1.5°C to a maximum of 2.5°C is very high. The uneven distribution of the temperature increase dynamics across the seasons will manifest itself with more pronounced and anomalous thermal spikes, especially during the summer season, resulting in both the frequency and consecutive duration of massive heat waves becoming chronic. Such thermal stress will complicate the functioning of the biosphere and the overall urban environment, creating severe heat stress in the country's arid and semi-arid geographical zones, primarily in the vast Kura-Araz plain, the Absheron Peninsula, and the flatlands of the Nakhchivan Autonomous Republic.

The forecast indicators presented below (Table 2) show that by 2050, the average annual temperature across the country will increase by 1.3°C to 1.8°C under the RCP 4.5 scenario. The projections presented in Table 2.6 show that by 2050, the average annual temperature across the country will increase by 1.3°C to 1.8°C under the RCP 4.5 scenario, and by 2.0°C to 2.7°C under the RCP 8.5 scenario, with extreme temperatures exceeding 45°C in the lowland regions. Against a backdrop of rising temperatures, an annual precipitation decrease of 2% to 10% is projected, a sharp intensification of moisture drought by up to 15-20%, particularly during the growing season (spring and summer months), and a 20-30% reduction in mountain snow reserves. These climate changes will not only increase the risk of flash floods from short-term, intense downpours but will also cause a 15% to 25% reduction in the water reserves of transboundary and inland rivers, accelerating severe water stress, soil erosion, and desertification processes in the country. These negative trends stimulate large-scale land degradation, severely impacting the natural balance of semi-arid regional ecosystems, particularly the Kura-Araz Plain and the Absheron Peninsula. Under such conditions, the implementation of sustainable resource management strategies is inevitable for protecting the country's ecological security and adapting agriculture to climate change (Table 2).

The mathematical trajectory of the precipitation regime in the changing climate parameters -statistical projections also indicate that negative trends are dominant, suggesting a massive reduction of 5% to 20% in total nationwide precipitation by the middle of the century amid a moisture deficit.

This situation will not only fundamentally disrupt the natural moisture balance of soil but will also increase the evaporation and transpiration coefficient from open water surfaces, complicate the natural recovery process of surface water reserves, and maximize the risks of large-scale hydrometeorological drought. The most critical challenge projected in the sphere of water resources is the sharp decline in annual and seasonal flow volumes of rivers, as well as the rapid degradation of permanent snow cover and glaciers located in high-mountain ecosystems that feed the rivers, due to temperature anomalies. Such a negative transformation of the hydrological regime will create a strategic deficit in the drinking water supply of large urban agglomerations as well as in the irrigation systems of the agro-industrial complex, turning the existing resource shortage into a regional crisis against the backdrop of growing overall water demand.

From a geographical and regional perspective, it becomes clear that these ecological changes will not occur with the same intensity across the country but will vary depending on the characteristics of the terrain and microclimate. On the Absheron Peninsula, which has low-lying terrain, severe desertification, salinization, and degradation trends will come to the forefront in the Kura-Araz Plain and the flat parts of the economic regions; the high mountain zones of the Greater and Lesser Caucasus will experience a rise in the snow line to higher elevations and landscape transformation. In the relatively humid Lankaran-Astara zone, a serious structural imbalance will develop in the internal precipitation calendar and moisture regime. A cross-analysis of indicators and the modeled 10% to 25% risk of water loss proves

that the deepening of climate dependency in agricultural planning, water reservoir management, and the resilience of energy grids to peak loads will pose serious institutional and structural challenges.

Table 2. Projected climate change scenarios for Azerbaijan by 2050.

Indicator	Current Scientific Status (Base Period)	Official Projections for 2050 (with Scenario Difference)	Direction and Impact of Change
Average annual temperature	National historical norm ~11.5–12.5°C (in Baku ~14.5°C). An increase of 1.2°C has already been recorded over the last 30 years	RCP 4.5: an increase of +1.3°C to +1.8°C. RCP 8.5: an increase between +2.0°C and +2.7°C.	A continuous increase. The greatest increase is expected in the summer season
Summer temperatures and heat waves	The frequency and duration of heat waves (days of extreme temperatures) have increased.	An increase of 10–14 days in the number of heatwave days, with extreme temperatures exceeding 45°C in some lowland areas	A sharp increase. Increased risk of thermal stress for human health and agriculture.
Total precipitation for the next 30 years	Highly uneven by region (from 200 mm to 1400 mm)	A decrease in annual precipitation of 2% to 10% is projected (with a greater decrease in the Caspian Sea zones).	A moderate decrease. Moisture deficiency will be felt more acutely as temperature increases increase evaporation.
Seasonal distribution of precipitation	Seasonal variability is present.	A sharp decrease in precipitation by 15-20% in the spring and summer months, with a slight increase in some places during the winter.	Seasonal imbalance. In the summer, during the agricultural growing season, moisture drought will intensify.
Extreme events (Floods and torrents)	Increase in mountain stream floods resulting from local downpours.	Although the total amount of precipitation is decreasing, the frequency of short-term, intense downpours is increasing.	Increased risk. An increase in the frequency of flash floods and mudflows in mountainous and foothill regions.
Snow cover in mountainous areas	The retreat of glaciers and the snow line has accelerated in the Greater and Lesser Caucasus.	The retreat of the snow line to higher elevations, a 20-30% reduction in mountain snow reserves.	Rapid decline. Shifting of the spring flood period for rivers and disruption of the water regime.
Surface water reserves (River waters)	Over 70% of Azerbaijan's water reserves are received from outside the country (via the Kura and Aras rivers).	Risk of a 15% to 25% reduction in the water levels of the Kura and Aras rivers, as well as in inland rivers.	Severe water stress, due to both a decrease in flow in transboundary rivers and an increase in domestic water losses.
Soil and Ecosystem Stability	Salinization, erosion, and desertification processes are active.	Expansion of semi-arid and arid zones, acceleration of soil erosion.	Increased risk of degradation. Acceleration of desertification in the Kura-Araz and Absheron regions.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Ecological Aspects of Soil Pollution and Ornamental Planting

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Abstract

The research conducted has determined that soil pollution has a significant negative impact on the development of ornamental trees and shrubs. Comparative analyses have shown that in areas with high anthropogenic impact, the concentration of heavy metals (Pb, Cd, Zn, Cu, and Ni) in the soil increases, while the amount of humus and essential nutrients decreases. These changes cause serious violations in the morphological and physiological indicators of plants. It has been established that in polluted soils, the growth of ornamental plants weakens, the development of the root system slows down, the leaf surface area decreases, signs of chlorosis and necrosis are observed, and photosynthetic activity and overall decorative quality decrease. In contrast, in relatively clean areas, plants demonstrate high vegetative development, normal leaf structure, a strong root system, and stable physiological activity. The results of the research show that the ecological state of the soil is one of the main factors determining the sustainability of urban green systems. The introduction of ornamental plant species that can accumulate heavy metals is considered promising in terms of phytoremediation and can contribute to the improvement of the ecological state of polluted urban areas. The results once again confirm the need to reduce soil pollution, conduct regular ecological monitoring, recultivate contaminated soils, and use pollution-resistant ornamental plant species in urban landscapes. These approaches can serve to increase the ecological stability of urban ecosystems, protect green spaces, and improve environmental quality.

Keywords: urban ecosystems, soil degradation, green spaces, anthropogenic impact, decorative plants, phytoremediation

1. Introduction

In modern times, urbanization, industrialization, and the expansion of anthropogenic activities have turned soil pollution into a serious environmental problem. In urban and industrial zones, the soil cover is polluted with heavy metals, petroleum products, pesticides, and other chemicals. This situation negatively affects the growth, physiological state, and aesthetic appearance of ornamental trees and shrubs. Ornamental plants not only create beauty in the urban environment, but also participate in air purification, microclimate regulation, and preservation of ecological balance. Therefore, the study of the development characteristics of these plants in polluted soils is relevant. In existing studies, the accumulation of pollutants in the soil, their transfer to plant organs, and their effect on photosynthesis and growth processes occupy a central place. However, in the conditions of Azerbaijan, especially in Baku and urban areas exposed to industrial

influence, a comprehensive assessment of the development characteristics of ornamental trees and shrubs in polluted soils still requires separate research.

The main objective of the work is to study the effect of soil pollution on the development of ornamental trees and shrubs, to evaluate their morphological, physiological, and decorative indicators in polluted soil conditions, and to develop scientifically based recommendations for the selection of sustainable plant species. To achieve this goal, the main sources of soil pollution are analyzed, the development indicators of plants in polluted and relatively clean areas are compared, morphological and physiological changes are investigated, the selection of sustainable decorative species and the application of phytoremediation measures are justified.

Soil is an important component of the biosphere; it is an ecosystem where the living and non-living world coexist. Soil is a natural environment where many living organisms coexist. It plays an important role in providing living organisms with water, air, and nutrients. At the same time, it protects against sudden and sharp changes in the environment (Məmmədova, 2024, p. 12). According to Vernadsky, the soil layer represents a unique zone of interaction between the biocosmic substance of nature and living organisms and inert (non-living) matter. He considered the soil to be the "screen" and central link of the biosphere; It is here that the most important geochemical processes that affect fertility and the development of life occur.

Soil is not only one of the environmental factors, but also the main, most stable component of terrestrial ecosystems at all organizational levels, up to the biosphere. Soil is a component of the biosphere, a natural-historical body, the result of long-term interactions between rocks, climate, relief, and biota, and has the property of productivity (Məmmədov, 2007, p.9). Productivity is the main property that distinguishes soil from all other natural formations. Soil is a complex, multifunctional, open, four-phase structural system located in the surface layer of weathered rocks; it is a complex function of rocks, organisms, climate, relief, and time and has the property of productivity.

Rapid industrialization, urbanization, and intensive agricultural activities have led to rapid changes in soil ecosystems. The most serious consequence of anthropogenic impacts is soil pollution (Wang & Mulligan, 2019, p. 17). Soil pollution not only leads to a decrease in fertility but also to a general disruption of the ecosystem and causes harmful substances to directly threaten living organisms and human health through the food chain. As a result of the activities of industrial enterprises, a large amount of chemicals and waste enter the soil, which leads to changes in the soil ecosystem.

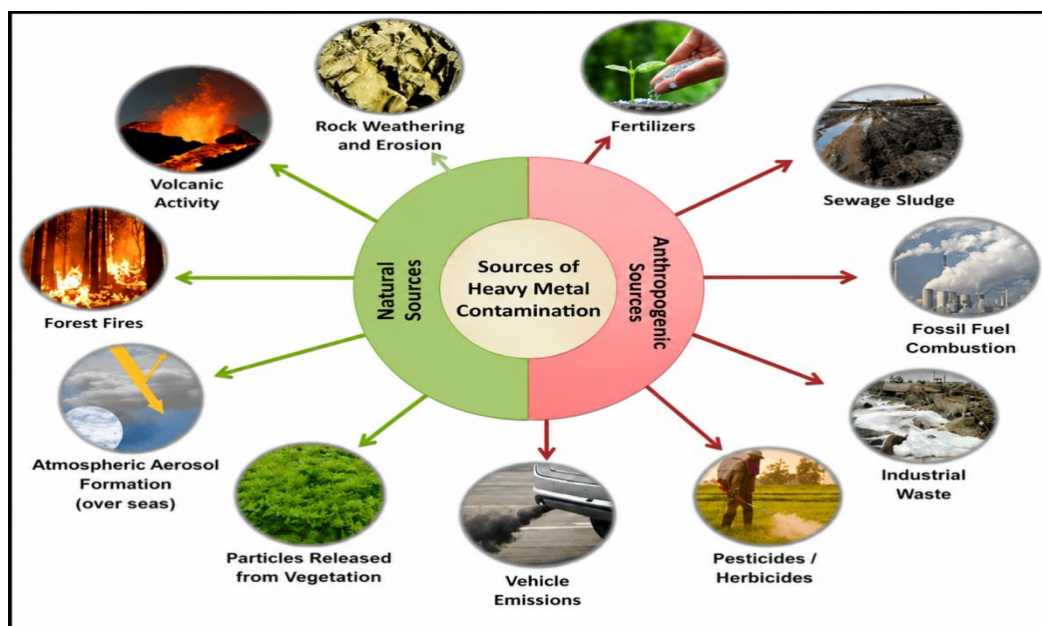


Figure 1. Natural and anthropogenic sources of soil pollution.

Figure 1 shows the main sources of soil pollution with heavy metals. Here, pollution sources are divided into two groups: natural and anthropogenic. Volcanic activity, rock erosion, atmospheric aerosols, particles released from vegetation, and forest fires are considered natural sources. Fertilizers, pesticides and herbicides, industrial waste, vehicle emissions, sewage sludge, and fossil fuel combustion are anthropogenic sources. As a result of these processes, heavy metals accumulate in the soil, weaken its ecological state, and negatively affect plant development. This process also leads to a decrease in organic matter in the soil and harmful substances entering the soil layers and groundwater. As they enter the soil layers, these substances are absorbed by plants, which both weakens plant development and enters the food chain, posing a threat to living organisms. Pollutants are absorbed from the soil layers by plants through the root system and accumulate in their seeds. The accumulation of harmful substances in plant seeds affects the normal development process of plants, weakens their growth, and disrupts their physiological processes. It is difficult to estimate the area of land that is contaminated each year; for this reason, there is no accurate global data, but the problem is widespread.

2. Migration of Heavy Metals in Soil and Their Toxicity to Plants

The term "heavy metals" was first used in 1817 by the German chemist Leopold Gmelin; he classified the chemical elements known at that time into three groups: non-metals, light metals, and heavy metals. Heavy metals enter the soil through wastewater discharged from industrial enterprises, causing pollution and degradation. Heavy metals include lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), zinc (Zn), nickel (Ni), and chromium (Cr) (Kabir, 2015, p. 27). These elements are present in nature in certain quantities, but an increase in the concentration of these elements poses a serious threat to the ecosystem and human health. Heavy metals enter the soil through various sources. Industrial enterprises are also one of the main sources. The chemical industry, metallurgical plants, oil refineries, and the energy sector emit heavy metal-containing waste into the atmosphere. The migration of heavy metals in soil depends on their chemical properties and soil characteristics – pH level, mechanical composition, organic matter content, and cation exchange capacity. In an acidic environment (low pH), the solubility of heavy metals increases, and they become more mobile, migrate to lower layers of the soil profile, and are more easily absorbed by plants (Xəlilov, 2009, p. 22). On the contrary, in an alkaline environment, most of these metals precipitate and become inactive, and their biological availability decreases.

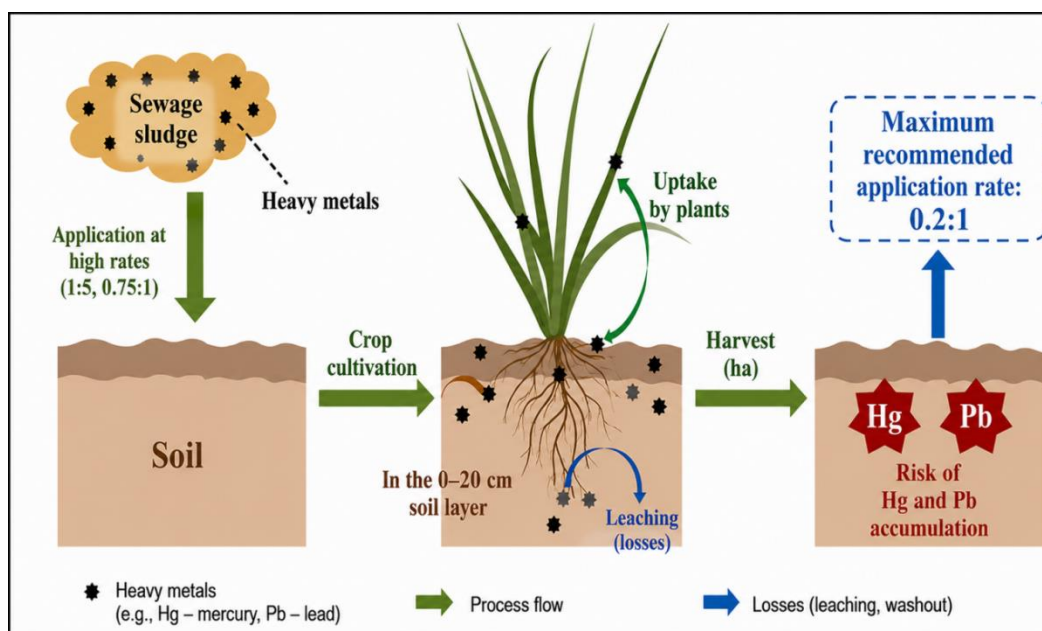


Figure 2. Movement of heavy metals in soil and toxic risk to plants.

Figure 2 shows that heavy metals entering the soil through sewage sludge accumulate in the root zone and are absorbed by the plant. Metal ions accumulate mainly in the 0-20 cm layer of the soil, from where they pass to the roots and accumulate in the tissues of the plant. Some of them leak into the lower layers with water, causing losses and additional pollution. When toxic metals such as Hg and Pb accumulate in the plant, growth, nutrition, and physiological processes are weakened. For this reason, they are widely used in various industrial processes; as a result, despite cleaning measures, the concentration of heavy metal compounds remains quite high in industrial wastewater. Of particular interest are metals that are used in the most extensive and significant quantities in industrial processes and pose a serious threat in terms of their biological activity and toxic properties because of their accumulation in the environment (Alloway & Ayres, 1997, p. 15). Many heavy metals such as iron, copper, zinc, and molybdenum participate in biological processes and are essential trace elements for the activity of plants, animals, and humans in certain quantities.

3. The Impact of Pollution on the Morphological Characteristics of Plants

Pollution of the soil ecosystem by technogenic and anthropogenic factors causes serious changes in both the internal biochemical processes and the external morphological structure of plants. Since plants are immobile organisms, they are directly exposed to the effects of toxic substances in the environment, and therefore their morphological characteristics are considered a visual indicator of the ecological state of the soil (Məmmədov et al., p. 26). The impact of pollutants in the soil environment on plant morphology can be analyzed in several main directions:

a) *Root system deformation*: The organ that first encounters toxic substances in the soil (especially heavy metals and oil residues). As the degree of pollution increases, root growth slows down, the main root shortens, and the branching of lateral roots is minimized. Necrosis (tissue death) occurring at the root tips sharply reduces the plant's ability to absorb water and minerals, which results in the weakening of the plant.

b) *Biometric indicators of aboveground organs*: The growth (height) of plants grown in polluted soil is significantly lower than their counterparts in clean areas. As a result of inhibition (slowing down) of cell division, the phenomenon of "dwarfism" is observed in plants. The diameter of the stem is reduced, the distance between the joints is shortened, and the total green mass (bioproductivity) of the plant is reduced.

c) *Pathologies occurring in the leaf apparatus*: Since the leaves are the center of the photosynthesis process, they are very sensitive to pollution. The following morphological changes are observed in the leaves due to the influence of toxic substances in the soil:

- Chlorosis: Yellowing of the leaf edge because of the breakdown of chlorophyll;
- Necrosis: The formation of brown, black spots on the edges of the leaves or between the veins;
- Epinasty: Folding of the leaves downwards and reducing their area;
- Defoliation: Premature shedding of the leaves as a defensive reaction of the plant.

d) *Impact on reproductive organs*: Soil pollution changes the duration and quality of plant phenological phases (flowering, fruiting). In a polluted environment, plants bloom less often, the pollination process is weakened, and the size of fruits and seeds is reduced. This not only leads to a decrease in current productivity, but also to a limitation of the future recovery of the plant population. Thus, these deviations in the morphological indicators of plants are an important biological test method that allows you to assess the degree of soil pollution. Soil pollution affects the morphological indicators of plants directly and indirectly, seriously disrupting their normal development process.

Pollutants, especially heavy metals, petroleum products, and chemical compounds, accumulate in the soil and enter the body through the root system of plants and cause various morphological changes in growth processes. One of the most observed effects is the weakening of plant height growth. Since the root system is damaged in polluted soil conditions, the absorption of water and nutrients decreases, resulting in a delay

in the development of shoots and stems. This leads to a reduction in the overall size of the plant and poor structural formation. There are also serious changes in the morphology of the leaves. Under polluted conditions, the size of the leaves decreases, their surface area decreases, and their color turns yellow or darkens.

In some cases, necrosis (formation of dead areas) and chlorosis (yellowing due to a decrease in chlorophyll) develop in leaf tissues (Məmmədova, 2024, p. 549). These changes weaken the plant's ability to photosynthesize. Deformation, thinning, and poor lignification (woodiness) are observed in the trunk and branches. This reduces the mechanical resistance of the plant and increases its sensitivity to external influences. In the root system, the development of the main and lateral roots weakens, the number of root hairs decreases, and the total root biomass index decreases. Changes in the flowering process are also observed in ornamental plants because of pollution. The number of flowers decreases, their size decreases, and the decorative quality weakens. In some cases, the flowering period is shortened, and the reproductive ability decreases. In general, soil pollution negatively affects the morphological development of both vegetative (root, trunk, leaves) and generative (flower, seed) organs of plants. As a result of this process, the aesthetic appearance of plants deteriorates, their ecological functions weaken, and their use in urban greening is limited.

Table 1. The effect of soil pollution on the morphological indicators of plants.

Morphological indicator	Changes observed under pollution conditions	Result
Increase in height	Weakening of growth, slowing down of development	Reduction of the overall size of the plant
Stem	Thinning, poor lignification, deformation	Decrease in mechanical strength
Root system	Weakening of root development, reduction of lateral roots	Weakening of water and nutrient absorption
Leaf size	Reduction of leaf surface	Reduction of photosynthesis area
Leaf color	Yellowing (chlorosis), darkening	Decrease in chlorophyll content
Leaf tissue	Necrosis, formation of drying areas	Disruption of the functional activity of the leaf
Flowering	Decrease in the number of flowers, premature wilting	Weakening of reproductive ability
General decorativeness	Fading of color, distortion of shape	Decrease in aesthetic quality

Table 1 shows the effect of soil pollution on the morphological indicators of plants. Changes in the morphological indicators of plants under soil pollution conditions are directly related to the disruption of their physiological and biochemical processes. The data presented in Table 1 show that the polluted environment has a complex negative effect on both the vegetative and generative development of plants. First, the observed weakening in height growth (height) indicates a decrease in the overall growth rate of the plant. This is mainly due to the slowing down of cell division and elongation because of the absorption of heavy metals and other toxic substances in the soil by the roots. As a result, the plant takes on a smaller and less developed form.

4. Specific Ornamental Shrub Species That Accumulate Heavy Metals

Ornamental shrub species that accumulate heavy metals play an important role in phytoremediation and ensuring urban ecological stability. In addition to having an aesthetic function, these plants are distinguished by their ability to absorb and partially neutralize toxic elements (Pb, Cd, Zn, Cu, Ni, etc.) accumulated in the soil. Such ornamental shrub species primarily include willow shrub forms (*Salix* spp.). Willow species can effectively remove heavy metals from the soil due to their rapid growth, extensive root system, and high biomass formation capacity.

Their phyto-extraction potential is highly appreciated, especially in humid and polluted areas. Another important ornamental shrub species is tamarix (*Tamarix* spp.). This plant shows high resistance to salty and polluted soils and can accumulate some heavy metals in its tissues, in addition to sodium and chloride ions. *Tamarix* is also used in the fight against erosion (Singh, 2019, p. 78). Common cranberries (*Berberis* spp.) also accumulate certain heavy metals. Since these plants are used for decorative purposes, especially in urban environments, their ecological function provides an additional advantage. Golden lilac (*Forsythia* spp.) and elm shrub forms (*Cornus alba*) are also distinguished by their moderate metal accumulation capacity. These species mainly participate in the phytostabilization process, limiting the spread of pollutants. In addition, ornamental shrubs such as hibiscus (*Hibiscus syriacus*) and ligustrum (*Ligustrum* spp.) are widespread in urban landscapes and, being relatively resistant to heavy metals, can also be used as bioindicators.

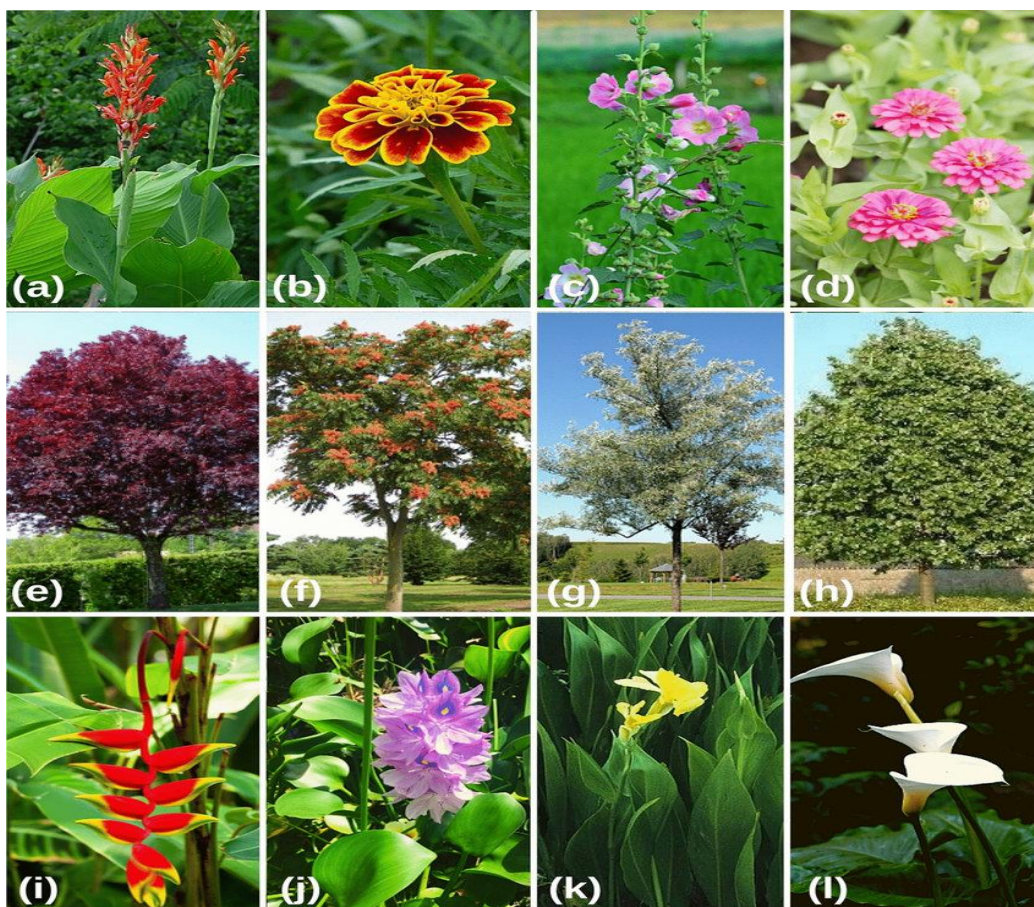


Figure 3. Ornamental plant species that accumulate heavy metals. **A.** *Canna* (*Canna* sp.); **B.** *Marigolds* (*Tagetes* sp.); **C.** *Lavatera* (*Lavatera* sp.); **D.** *Zinnia* (*Zinnia* sp.); **E.** *Plum blossom, decorative form* (*Prunus cerasifera* 'Atropurpurea'); **F.** *Ailanthus altissima*. **G.** *Poplar white* (*Populus alba*); **H.** *Linden* (*Tilia* sp.); **I.** *Heliconia rostrata*; **J.** *Eustoma grandiflorum*, formerly *Lisianthus russellianus*; **K.** *Lily of the valley* (*Hemerocallis* sp.); **L.** *Calla* (*Zantedeschia aethiopica*)

Figure 3 shows ornamental plant species that can accumulate heavy metals. These plants help restore soil by accumulating heavy metal ions in their root, stem, and leaf tissues in contaminated soils. The advantage of ornamental species is that since they are not used for food, the risk of pollutants entering the food chain is lower. *Cornus alba* (elm shrub forms) not only creates aesthetic value with its red decorative stem but also participates in the immobilization of elements such as Ni and Pb in heavy metal-laden soils. *Hibiscus syriacus* (shamama rose) creates conditions for both visual landscape enrichment in urban environments and the formation of a bioindicator role by demonstrating a certain degree of tolerance to metals such as Cd and Zn. *Ligustrum* spp. (privet) and *Viburnum opulus* (blackthorn) act as effective phytosequestrators in the accumulation of heavy metals with their dense leaf cover and high biomass formation capacity, and perform an ecological buffer function, especially in roadside and industrial impact zones.

In the research conducted to study the impact of soil pollution on the development of ornamental trees and shrubs, areas exposed to various degrees of anthropogenic impact in urban and suburban ecosystems were selected. Relatively less polluted green areas were taken as the object of the study to compare them with zones of Baku city with high industrial and transport load. This approach allowed us to comparatively assess the impact of changes in soil ecosystems on the morphological and physiological indicators of ornamental plants.

The research areas were defined in three main categories:

- Highly polluted zone - mainly areas along highways, close to industrial enterprises;
- Moderately polluted zone - inner-city parks and green areas;
- Relatively clean zone (control area) - areas far from the city, with weak anthropogenic impact.

Soil samples were taken from a depth of 0–20 cm in selected areas, and an average sample was formed for each area. During laboratory analyses, the main physicochemical indicators of the soil were determined: pH, humus content, total nitrogen, phosphorus and potassium content, as well as the concentration of heavy metals (Pb, Cd, Zn, Cu, Ni). The analysis conducted showed that as the level of pollution increased, significant changes occurred in the chemical composition of the soil (Məmmədova, 2024, p. 104). In highly polluted areas, the pH of the soil tended to become more alkaline, which weakened the ability of plants to absorb nutrients. While the pH in the control areas was relatively neutral (6.5–7.2), in areas exposed to industrial and transport impacts, this indicator varied within the range of 7.5–8.1. A decrease in the amount of the humus layer was also observed. Especially in highly polluted areas, the increase in the rate of decomposition of organic matter and the deterioration of the soil structure led to a decrease in the humus reserve. This weakens the water-holding capacity and aeration properties of the soil. The following table (Table 2) presents the summarized results of the soil analyses.

Table 2. Main mechanisms of the phytoremediation method.

Indicators	Highly contaminated zone	Moderately contaminated zone	Control zone
Ph	7.8	7.2	6.8
Humus (%)	2.1	3.4	5.2
Total Nitrogen (%)	0.09	0.14	0.21
Phosphorus (mg/kg)	42	58	76
Potassium (mg/kg)	110	145	190
Pb (mg/kg)	78	42	18
Cd (mg/kg)	1.9	1.1	0.4
Zn (mg/kg)	165	98	60
Cu (mg/kg)	74	46	25
Ni (mg/kg)	58	33	15

Table 2 shows the main mechanisms of the phytoremediation method. The results obtained show that there is a direct relationship between the level of soil pollution and the concentration of heavy metals. In particular, the high accumulation of elements such as lead (Pb), zinc (Zn), and copper (Cu) proves the intensive impact of industrial and automobile emissions on the soil. The accumulation of these elements in the soil disrupts the ion balance in the root system of plants and limits the absorption of nutrients. At the same time, the reduction of humus and basic nutrients weakens the biological activity of the soil.

This situation negatively affects the vegetative development of ornamental trees and shrubs, slows down their growth, and causes changes in the leaf structure. The indicators obtained in the control zone indicate that the soil has relatively stable and favorable conditions for plant development. Here, the low content of heavy metals and the balanced distribution of nutrients ensure the normal development of ornamental plants. Thus, soil analyses prove that anthropogenic pollution is one of the main factors that severely alters the chemical and biological properties of the soil, limiting the development potential of ornamental plants (Alloway & Ayres 1997, p.58).

5. Comparative Analysis of Plants Growing in Polluted and Clean Areas

A comparative analysis of ornamental trees and shrubs growing in polluted and relatively clean areas shows that the degree of anthropogenic loading of the soil has a direct and complex effect on both the morphological and physiological state of plants. Since plants develop in clean or minimally polluted areas in optimal ecological conditions, normal growth dynamics are observed in their vegetative and generative organs. In such areas, the width of the leaf surface, the amount of chlorophyll, the intensity of shoot formation, and the development of the root system are at a high level.

The soil's richness in humus, balanced distribution of nutrients, and low concentration of heavy metals maintain the physiological processes of plants stably and maximize photosynthetic activity. On the contrary, several stress symptoms are observed in ornamental trees and shrubs growing in polluted areas. As a result of the accumulation of heavy metals in the soil, ion exchange in the root system is disrupted, which limits the absorption of water and minerals. As a result, physiological disorders such as reduced growth, reduced leaf area, chlorosis, and necrosis occur in plants. High concentrations of elements such as lead (Pb), cadmium (Cd), and zinc (Zn) reduce the activity of enzymatic processes, creating metabolic imbalances at the cellular level (Guerriero et al., 2016, p.21)

Comparative analysis shows that while in clean areas the growth of plant biomass is stable and continuous, in polluted areas this indicator significantly decreases. At the same time, differences are also evident in the reproductive development stage; in clean areas the flowering and fruiting process proceeds at a normal rhythm, but in polluted areas this process is either delayed or weakly expressed. From an ecological point of view, although it is observed that some species demonstrate a certain degree of adaptability in polluted areas, this adaptation is not long-term and stable. On the contrary, in clean areas, the genetic potential of plants is fully realized, and the decorative qualities of the species are preserved at the maximum level.

Thus, based on the comparative analysis, it can be concluded that soil pollution is one of the main ecological factors limiting the development of ornamental tree and shrub plants, and this effect is manifested in a complex manner both in morphological changes and in the weakening of physiological processes.

Table 3 presents comparative indicators of plants in polluted and clean areas. As can be seen from the table, as the level of environmental pollution increases, a significant deterioration is observed in all the main morphological and physiological indicators of ornamental trees and shrubs. In clean areas, plants develop in accordance with their genetic potential, demonstrating high decorative and ecological qualities.

Although signs of adaptation are observed in plants in moderately polluted areas, this adaptation is not completely stable and creates certain limitations in the development process. In highly polluted areas, both vegetative and generative development of plants is seriously weakened because of the toxic effects of heavy

metals, which significantly reduce their decorative value (Əliyev, 2021, p. 38). As a result, the data in the table prove that soil pollution is one of the main ecological factors that has a complex negative impact on the development of ornamental plants.

Table 3. Comparative indicators of plants in polluted and clean areas.

Indicators	Clean areas	Moderately polluted areas	Highly polluted areas
Vegetative development	Strong and stable growth	Moderate development	Weak, slow development
Leaf size	Large and normal shape	Relatively small	Small, deformed
Leaf color	Dark green, stable chlorophyll	Light green	Signs of yellowing and chlorosis
Root system development	Deep and widespread	Moderate development	Superficial and weak
Photosynthetic activity	High	Medium	Low
Flowering intensity	Abundant and timely	Partially reduced	Weak and delayed
Fruiting	Normal and productive	Partially reduced	Very weak or absent
Stress symptoms	Not observed	Mild stress symptoms	Severe stress, necrosis, and chlorosis
Biomass growth	High and stable	Medium	Low and unstable

The results of the conducted research show that soil pollution is one of the main ecological factors that has a serious and multifaceted impact on the development of ornamental trees and shrubs. Comparative analyses conducted in areas with different levels of pollution have proven that the accumulation of heavy metals (Pb, Cd, Zn, Cu, Ni) in the soil causes significant changes in both the morphological and physiological indicators of plants.

Ornamental plants growing in clean areas are characterized by high vegetative activity, normal leaf structure, stable chlorophyll content, and a strong root system. In these areas, the soil is rich in humus, and the balanced distribution of nutrients ensures optimal plant development. As a result, the process of biomass growth, flowering, and fruiting proceeds normally and stably.

On the contrary, in polluted areas, plants experience a weakening of development, a decrease in leaf size, physiological disorders such as chlorosis and necrosis, as well as general signs of stress. High concentrations of heavy metals limit the functional activity of the root system, weaken the absorption of nutrients, and reduce photosynthetic activity. This leads to a decrease in the decorative quality of plants.

Based on a comparative analysis, it was determined that as the degree of pollution increases, the adaptation capabilities of plants are limited and their vital activity weakens. Although certain signs of adaptation are observed in moderately polluted zones, this process is not sustainable in highly polluted areas, and sharp declines in plant development occur.

The results of the study also show that the quality of the soil environment plays a decisive role in the development of ornamental plants, and the sustainability of urban greenery is directly related to the ecological state of the soil. Therefore, it is necessary to reduce soil pollution, carry out reclamation measures, and plan green areas on a scientific basis.

In general, the results obtained confirm that ecologically clean soil conditions are one of the main conditions for the healthy development of ornamental trees and shrubs, and the implementation of complex ecological measures in this direction plays an important role in the sustainable development of urban ecosystems.

6. Conclusion

Based on the results of the study, the implementation of the following proposals is considered appropriate to reduce the negative impact of soil pollution on the development of ornamental trees and shrubs and ensure the sustainability of urban ecosystems. First, it is important to take comprehensive measures to reduce the main sources of soil pollution in the urban environment. Limiting emissions from vehicles, applying environmentally friendly technologies in industrial enterprises, and proper waste management can significantly reduce the heavy metal load on the soil.

Expansion and proper planning of urban green systems are of great importance. Creating protective green belts along highways and industrial zones, as well as increasing the area of parks and gardens, can partially prevent the spread of pollutants and improve the microclimate. It is necessary to implement measures for the reclamation and restoration of contaminated soil. Increasing the humus layer, using organic fertilizers, and improving the structure of the soil restore its biological activity, creating more favorable conditions for plant development.

Widespread application of phytoremediation technologies. Planting plant species that can accumulate heavy metals in contaminated areas allows for natural soil purification. This method is considered efficient from both an ecological and economic perspective. It is important to apply a scientific approach to the selection of ornamental plant species. The predominance of pollution-resistant and stress-tolerant species in landscape design increases the viability of plants and ensures the sustainability of green areas.

The establishment of ecological monitoring systems and strengthening of regular control can be indicated. Continuous monitoring of the chemical composition of the soil, heavy metal concentration, and plant development indicators allows for early detection of problems and taking operational measures.

Finally, increasing environmental awareness among the population is also of great importance. Educational measures on environmental protection, care for greenery, and proper waste management can contribute to the formation of an ecological culture and the improvement of the overall ecosystem.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Evaluation of Correlation and Regression Relationships Between Soil Solution Electrical Conductivity and Major Ion Concentrations

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Abstract

Since the electrical conductivity (EC) of soil solutions directly reflects the total concentration of dissolved ions, it is considered one of the most reliable and widely used indicators for assessing the salt content in the soil. EC parameters, acting as a comprehensive indicator of the content of soluble salts, are closely related to many physicochemical properties of the soil, including food mobility, plant water supply, soil fertility, and long-term productivity of agricultural systems. In this context, identifying ions that directly influence fluctuations in electrical conductivity is fundamental to understanding salinization dynamics, evaluating the effectiveness of Reclamation measures, and developing sustainable soil management strategies. The presented research work was carried out with the aim of studying the degree of influence of the main dissolved cations (Na^+ , Ca^{2+} , Mg^{2+} , K^+) and anions (Cl^- , SO_4^{2-} , HCO_3^-) on the electrical conductivity of the soil solution. Pearson analysis was used to determine the intensity of the correlation between EC and individual ions. To determine the relative weight and significance of each variable, the multidimensional linear regression method and standard regression coefficients were used. The combined use of these statistical methods allowed an in-depth analysis of the Ionic factors that control EC changes and the correct separation of large and small factors that affect soil salinization. Statistical analysis showed that the elements with the strongest positive correlation with electrical conductivity are sodium (Na^+) and chloride (Cl^-). This situation also confirms that these two ions play a dominant role in the accumulation of soluble salts in the studied soils. Although significant positive correlations were also recorded with calcium (Ca^{2+}), magnesium (Mg^{2+}) and sulfate (SO_4^{2-}) ions, their final effect on EC was poor compared to sodium and chloride. Conversely, potassium (K^+) and bicarbonate (HCO_3^-) ions showed both low standard regression coefficients and relatively weak correlations. This result shows that in modern research conditions, the ratio of these ions in EC oscillations is very limited. In general, the results obtained more clearly reveal the mechanism of influence of the ionic composition of the soil solution on its electrical conductivity and prove that the main driving forces that determine salinity in the studied medium are sodium and chloride. The study also confirms the effectiveness of multidimensional statistical methods when interpreting the chemical properties of soils and looking for the most informative indicators of salinization. In conclusion, we can say that this study provides an important scientific framework for improving the assessment of salinity, developing Reclamation methods and managing irrigation, and supporting the sustainable use of saline arable land. In addition, the presented analytical base can be used in future studies as a useful tool for monitoring soil quality and predicting the risks of salinization in various environmental and agricultural conditions.

Keywords: soil salinity, Pearson correlation, multiple linear regression, standardized regression coefficient, soil reclamation, sustainable land management

1. Introduction

Soil is one of the most complex natural systems in which physical, chemical and biological components interact continuously, creating a dynamic and heterogeneous environment (Weil, Brady & Weil, 2017). As the main life-supporting environment for soil plants, soil provides them with water and essential mineral nutrients necessary for plant growth and development. In addition to its agricultural function, it also regulates numerous ecosystem processes, promoting food circulation while maintaining biological activity and environmental stability.

Among the various components of the soil, the soil solution occupies a central place, since it most often serves as the medium through which physico-chemical, biochemical, and biological reactions take place. The soil solution, which acts as a link between the solid soil and the plant roots, controls the transport, transformation, and availability of solutes. Therefore, its composition and physicochemical properties largely determine the mobility of nutrients, their assimilation by plants, and the overall fertility of the soil. Thus, differences in the chemical composition of the soil solution provide valuable information about the state of the soil and its environmental activity (Abrol et al., 1988).

A careful assessment of the properties of the soil solution is necessary to determine soil fertility, increase irrigation efficiency, and apply sustainable soil management methods. In modern agricultural conditions, which are characterized by intensive agriculture, increased food demand, and climate uncertainty, this importance has increased significantly. As a result, the study of the chemical composition of soil Solutions has become a key component of soil quality monitoring and environmental assessment programs around the world (Rengasamy, 2010).

One of the most serious environmental threats facing arable land in modern times is the constant increase in the level of salinization. The negative effects of climate change, limited access to freshwater resources, and the expansion of irrigated agricultural areas have further accelerated salt accumulation in many regions (Corwin, 2021). The problem in question is especially acute in arid and semi-arid regions, where the concentration of soluble salts in the soil layer increases against the background of strong evaporation and insufficient rainfall (FAO, 2021). The systematic accumulation of salt over time changes both the physical structure and the chemical composition of the soil. In this case, the strength of the aggregate decreases, the integrity and permeability of the pores decrease, and, as a result, the water-air balance in the soil deteriorates. Such structural changes make it difficult for the roots to absorb water, worsen the absorption of nutrients and, as a result, lead to a decrease in crop yield. In the long term, continuous salinization aggravates soil degradation, has a direct impact on the sustainability of agricultural ecosystems and reduces the long-term productivity potential of arable land to zero. In many irrigated regions, the poor condition of drainage networks and improperly selected irrigation methods stimulate the processes of secondary salinization and mineralization of the soil. This situation creates additional barriers to sustainable land management and significantly increases the risk of non-renewable degradation. Among the various indicators used to assess the level of salinization, the electrical conductivity of the soil solution is still considered one of the most informative and practical parameters (Corwin & Lesch, 2005). Since the EC indicator directly reflects the total concentration of dissolved ions, it allows you to quickly determine the degree of salinization of the soil. Therefore, it is regularly used in agriculture, irrigation planning, and environmental monitoring. However, although high EC values indicate a high total salt concentration, this measurement alone does not allow determining the degree of exposure to individual ions that determine electrical conductivity (Hillel, 2003). The ratio of each ion to its electrical conductivity; the ionic charge depends on a number of physicochemical factors, such as the hydration radius, electrical conductivity, and transport properties in the soil solution (Tan, 2011). Therefore, the effect of ions on the measured EC value cannot be estimated as a single unit. In this context, the assessment based solely on electrical conductivity, without considering the ionic composition, can be aimed at facilitating the interpretation of salting processes. To obtain more complete and accurate results, EC measurements should be combined with quantitative analysis of the main dissolved ions in the medium. It also allows for a more objective characterization of geochemical processes in the soil. In general, the chemical composition of the soil

solution is dominated by sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+) cations. Chlorides (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-) ions are the main anions (Rhoades et al., 1999). The concentration of these ions, the equilibrium mechanisms, and the interaction between them largely determine the severity and type of disinfection, as well as the dynamics of the development of these processes (Sparks, 2019). The interaction of these ions not only controls the chemical balance of the soil but also plays a leading role in the formation of bonds between plants and soil (Essington, 2015). Disinfection of the soil by deactivation is a key factor in the formation of the soil-plant environment.

Increased concentrations of sodium and chlorides are usually associated with a predominance of neutral or chloride forms, which primarily affects osmotic conditions and limits the water absorption of plants (Munns & Tester, 2008). On the contrary, excessive concentrations of bicarbonate contribute to salinization, increasing the share of exchangeable sodium in the composition of the soil adsorption complex. As sodium accumulation increases, clay particles collapse, soil aggregates lose their stability, infiltration decreases, and the destruction of the structure becomes more pronounced (Naida & Sumner, 1998; Sposito, 2008).

Recent advances in soil science have contributed to the widespread use of multidimensional statistical methods for studying complex chemical relationships in soil. Pearson correlation analysis is widely used to determine the direction and strength of linear relationships between AB and individual dissolved ions, allowing researchers to identify statistically significant relationships. However, the correlation analysis itself cannot determine the independent contribution of each variable when several ions act on its electrical conductivity at the same time (United States Salinity Laboratory Staff, 1954).

Because of this, multiple linear regression has become an important analytical tool for measuring the individual and combined effects of dissolved ions on the EC. This method allows you to divide the contribution of each predictor and consider the interaction between variables. In addition, the standardized regression coefficients (Beta) facilitate the direct comparison of the variables measured in different units of measurement and allow the identification of the ions that have the greatest impact on electrical conductivity.

The integration of these complementary statistical methods provides a more reliable and complete interpretation of the chemical composition of the soil solution, which is better than all other methods that consider it separately. This approach to analysis contributes to a deeper understanding of the mechanisms of ion interaction, identifies the dominant factors controlling the development of salinization, and reinforces predictive models that describe changes in the chemical properties of soil in various environmental and agricultural conditions. Thus, a comparative statistical assessment of base cations and anions is a highly effective approach to the study of mechanisms for determining electrical conductivity (Qadir et al., 2014). From the point of view of Basic Soil Science, such studies make a fundamental contribution to a more detailed understanding of Ionic interactions and internal processes that regulate the chemical balance of the soil. From a practical point of view, the results provide valuable scientific data to optimize irrigation management, improve land reclamation strategies, and promote sustainable use of land resources. In conclusion, it should be noted that the data obtained from a comprehensive statistical analysis allow for a more accurate diagnosis of soil salinization, allow for improved monitoring systems, and provide a solid foundation for the scientific management of agricultural lands subject to salinization (Visconti et al., 2010). The purpose of the study, the main goal of the presented scientific research, is to comprehensively assess the influence of the main cations and anions present in the soil solution on the formation of electrical conductivity (EC) using modern statistical methods. Within the framework of the study, the goal was set to compare the relative contribution of individual ions to the EC indicator, determine the strength and direction of these connections using correlation and regression analysis, and identify dominant Ionic components that are directly responsible for changes in electrical conductivity. In addition, the study provides for the control of the statistical significance of these dependencies, the identification of the main factors that control soil salinization, and the creation of scientific foundations for the interpretation of hydrochemical processes that regulate the distribution of salts through the accumulation of ions in the soil solution. The expected results will contribute to a better understanding of soil salinization processes and will contribute to the development of better regional assessment strategies, monitoring soil salinization and sustainable soil management.

To achieve the set goal of the study, the following tasks are intended to be performed:

- to determine the basic cation and anion composition of the soil solution and evaluate their concentrations;
- to analyze the patterns of change in electrical conductivity of soil solution;
- to evaluate the strength and direction of linear relationships between electrical conductivity and base ions based on Pearson correlation analysis;
- to build a multiple linear regression model for complex evaluation of factors affecting electrical conductivity;
- to determine the level of relative influence of each ion on the EC indicator using standardized Beta coefficients;
- to analyze the obtained statistical results comparatively and substantiate their scientific and practical significance in terms of assessing the level of salinity of soils.

2. Materials and Methods

Research area and sampling

The study was carried out in an area with semi-desert conditions, where salinization processes were observed. The selection of soil samples was carried out on the basis of the principle of a systematic grid; the sub-samples taken at each observation point were homogenized, and medium-mixed samples were prepared. Samples were taken from 0-20 CM and 20-40 CM layers of the soil profile; the ionic composition and electrical conductivity of the soil solution at these depths were comparatively studied.

Laboratory analysis

At the laboratory stage, a soil solution was prepared from soil samples according to the standard methodology, and its main physicochemical indicators were determined. The following parameters were determined during the analysis:

- electrical conductivity (EC, dS / m);
- Na⁺ (mmol/L)
- Ca²⁺ (mmol/L)
- Mg²⁺ (mmol/L)
- K⁺ (mmol/L)
- Cl⁻ (mmol/L)
- SO₄²⁻ (mmol/L)
- HCO₃⁻ (mmol/L)

The EC indicator was measured at a temperature of 25°C using a portable conductometer (Allison & Richards, 1954). United States Salinity Laboratory Staff, 1954). The concentration of IONS was determined by Standard titrimetric and photometric methods.

Statistical analysis methods

The data collected were analyzed by the following statistical methods:

- 1) Descriptive statistics. The average value, standard deviation, minimum and maximum indicators were calculated.
- 2) Pearson correlation analysis. The strength of the linear relationship between the variables is determined by the formula:

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}$$

3) Multiple linear regression model: The dependence of EC on ions was assessed by the following model:

$$EC = \beta_0 + \beta_1 Na^+ + \beta_2 Ca^{2+} + \beta_3 Mg^{2+} + \beta_4 K^+ + \beta_5 Cl^- + \beta_6 SO_4^{2-} + \beta_7 HCO_3^-$$

4) Standardized Beta ratios: The Relative Strength of the action of ions on the EC was determined.

5) Coefficient of determination (R²): The explanatory power of the model was assessed. Software used for statistical analysis:

- IBM SPSS Statistics 26
- Microsoft Excel 2019

3. Results and Discussion

Descriptive statistical results

During the study, the statistical indicators of the basic ions and electrical conductivity (EC) measured in the soil solution were as follows. High dispersion of EC and Na⁺ and Cl⁻ indicators indicates an uneven distribution of salinization in the area (Table 1).

Table 1. Descriptive statistics of soil solution indicators.

Parameter	Mean	Min.	Max.	Standart Deviation
EC (dS/m)	4.82	1.10	12.60	2.91
Na ⁺	28.4	6.2	75.0	18.7
Ca ²⁺	12.6	3.1	34.8	8.9
Mg ²⁺	9.8	2.0	25.4	6.1
K ⁺	2.4	0.5	6.8	1.5
Cl ⁻	30.7	5.4	82.1	20.2
SO ₄ ²⁻	18.3	4.0	49.5	11.6
HCO ₃ ⁻	7.9	1.2	21.3	5.4

Correlation analysis

Pearson correlation results show the strength of the connection between ions and EC. The change in EC is formed mainly by the action of Na⁺ and Cl⁻ ions (Table 2).

Table 2. Correlation coefficients between EC and ions.

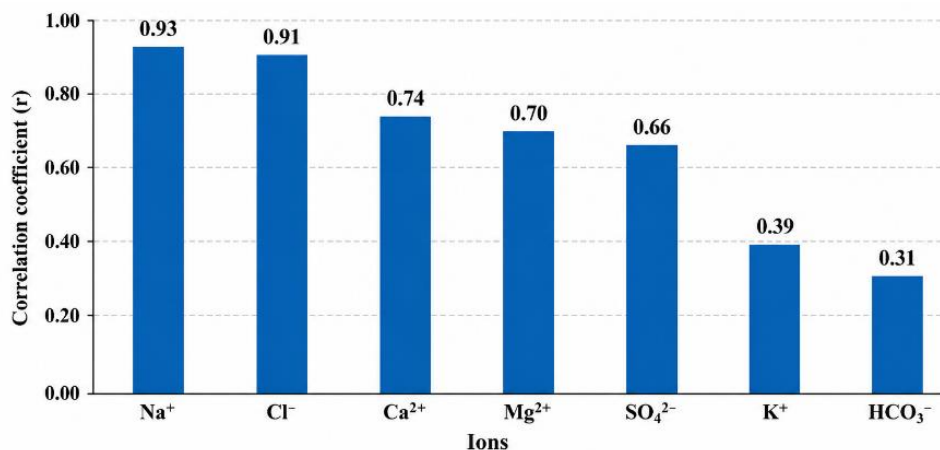
Parameter	Correlation Coefficient (r) with EC	Correlation Strength
Na ⁺	0.93	Very strong
Cl ⁻	0.91	Very strong
Ca ²⁺	0.74	Strong
Mg ²⁺	0.70	Medium
SO ₄ ²⁻	0.66	Medium
K ⁺	0.39	Weak
HCO ₃ ⁻	0.31	Weak

Regression model results

Multiple regression analysis yielded the following results:

Table 3. Standardized Beta ratios.

Variable	Standardized β Coefficient	Relative Effect
Na^+	0.41	The highest
Cl^-	0.38	High
Ca^{2+}	0.21	Medium
Mg^{2+}	0.18	Medium
SO_4^{2-}	0.15	Medium
K^+	0.09	Weak
HCO_3^-	0.07	Weak



The graph shows the strongest positive correlation of EC with Na^+ and Cl^- ions. Ca^{2+} , Mg^{2+} and SO_4^{2-} ions show a moderate correlation. K^+ and HCO_3^- ions show a weak correlation.

Figure 1. Correlation coefficient (Pearson r) between electrical conductivity (EC) and ions.

Figure 1 compares the correlation strength of the major ions with electrical conductivity (EC):

- Strongest correlation: Na^+ and Cl^-
- Moderate correlation: Ca^{2+} , Mg^{2+} , and SO_4^{2-}
- Weakest correlation: K^+ and HCO_3^-

The results obtained indicate that the electrical conductivity (EC) of the soil solution is governed by a complex system of dissolved ions. However, the statistical analyses demonstrated that sodium (Na^+) and chloride (Cl^-) ions are the dominant factors influencing EC. These findings suggest that:

- Soil salinity is primarily associated with the accumulation of sodium chloride (NaCl)-type salts.
- Although calcium (Ca^{2+}) and magnesium (Mg^{2+}) contribute to maintaining soil structural stability, their influence on EC is comparatively limited.
- Potassium (K^+) and bicarbonate (HCO_3^-) play secondary roles in determining the electrical conductivity of the soil solution.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Sustainable Municipal Solid Waste Management in the City of Baku: Contemporary Challenges and Innovative Solutions

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Abstract

Because of population growth, rapid urbanization, expanding consumption habits, and intensive economic activity, there has been a steady increase in the generation of municipal solid waste, making its effective management one of the key challenges for the sustainable development of modern cities. Against the backdrop of increasing anthropogenic impact, traditional approaches to waste management are no longer capable of ensuring a stable level of environmental protection, resource efficiency, or adherence to the principles of the circular economy. In Baku, this issue has become relevant due to the city's rapid social and economic development, population growth, and the need to upgrade the existing waste management system in line with current international environmental standards. The aim of this study is to conduct an all-round assessment of the current state of the municipal solid waste management system in Baku, identify the principal environmental, organizational, and technological challenges, and develop innovative solutions aimed at increasing the overall effectiveness of the system. This research includes an analysis of the waste management infrastructure, the regulatory and legal framework, the best international practices, and advanced technological approaches, with particular emphasis on the principles of the circular economy, resource conservation, and the digitalization of waste management processes. The results of the study are expected to identify priority directions for advancing the municipal solid waste management system in Baku, substantiate the feasibility of implementing innovative organizational and technological solutions, and provide scientifically grounded recommendations directed at decreasing the environmental impacts of waste, growing resource efficiency, and facilitating the transition toward a sustainable waste management model consistent with the United Nations Sustainable Development Goals.

Keywords: Baku city, solid waste, recycling, innovative technologies, waste management system.

1. Introduction

Over the last 10 years, rapid population growth, accelerated urbanization, industrialization, and increasing levels of consumption have become the principal factors of the continuous growth in municipal solid waste (MSW) generation worldwide (Kaza et al., 2018; UNEP, 2019). According to current projections, global municipal solid waste generation is expected to increase from 2,1 billion tons in 2020 to 3,8 billion tons by 2050, representing an increase of nearly 56%. Although recycling and waste treatment technologies have improved, only about 62% of the produced waste is recycled, used to generate energy, or placed in properly managed landfills. The last 38% is still disposed of in ways that can harm the environment (ISWA, 2024; Hoornweg & Bhada, 2012; Chen, 2020). This trend significantly hinders the

achievement of sustainable development aims and requires the transition to more effective waste management models based on the principles of the circular economy, resource efficiency, and environmental sustainability.

Improper trash utilization can cause a lot of problems for the environment, people's lives, and their money. When we throw out trash in landfills or dump it wherever, it releases more greenhouse gases and pollutes the air, soil, and groundwater. It also makes things less clean and can spread diseases. Experts think that the amount of greenhouse gases from trash could increase a lot by 2050, from about 1300 million tons in 2015 to almost 2400 million tons. This shows that we really need to get better at managing our waste. If we do better, we can reduce pollution, use our resources more effectively, and help cities grow in a way that lasts.

This problem is very important for quickly developing countries because the number of people is growing, which means more consumption and a lot more trash. Azerbaijan is a good example. In 2023, it was recorded that the country produced 4086.1 thousand tons of waste, which is more than 3985.1 thousand tons in 2022. This is the highest amount for this year. Since 1995, when only 247 thousand tons were generated, waste has increased more than sixteen times. This shows that the current waste management system is under pressure and needs to be modified. Most of Azerbaijan's trash comes from Baku, the main city for government, business, and the economy. In Baku, there are a lot of people, buildings, businesses, and services. Because so many people live there, the city is growing, and people's needs are becoming more, so the amount of trash keeps going up. This makes it harder to collect, move, sort, recycle, and get rid of all the waste efficiently. Despite improvements lately, like building better waste management facilities and starting to separate trash at the source, there are still environmental, organizational, and technical problems. These problems are preventing Azerbaijan from managing waste sustainably and moving towards a system where resources are reused.

High population density, intensive urban development, territorial expansion, and increasing consumption patterns have resulted in a continuous increase in municipal waste generation, placing greater demands on the efficiency of waste collection, transportation, sorting, recycling, and final disposal. Although considerable progress has been achieved in recent years through the development of modern waste management infrastructure and the introduction of selected elements of source-separated waste collection, several environmental, organizational, and technological challenges remain, limiting the implementation of sustainable waste management principles and the transition toward a circular economy (EC, 2020; Zhang et al., 2024; 10, Tamiz Shahar JSC, 2023).

Contemporary scientific literature places considerable emphasis on improving municipal solid waste management systems through the adoption of innovative recycling technologies, the digitalization of waste management processes, the application of Life Cycle Assessment (LCA), and the implementation of circular economy principles. However, comprehensive studies evaluating the sustainability of the municipal solid waste management system in the city of Baku, while considering contemporary international approaches and the potential for implementing innovative solutions, remain limited (Chen et al., 2020; Kirchherr et al., 2017; Geissdoerfer et al., 2017; Pires et al., 2011; Wilson et al., 2015).

2. Research Aim and Objectives

The aim of this study is to evaluate the current municipal solid waste management system in Baku, identify its main ecological, organizational, and technological problems, and propose practical solutions to improve its efficiency. The study also considers ways to make waste control more sustainable and support the principles of the circular economy. These research objectives will be achieved through the following:

1. Analyze the current condition of solid waste management in Baku and the major trends in its evolution;
2. Investigate the existing methods of collecting, transferring, grading, recycling, and ultimately disposing of municipal solid waste and the factors affecting its effectiveness;

3. Explore how municipal solid waste management can be organized in an environmentally friendly and economical way and what the challenges of this management are from an organizational perspective as well as from an economic perspective.
4. To analyze current international methodologies for effectively managing municipal solid waste and to explore how modern technologies can support the sustainable management of municipal solid waste and become applicable for solid waste management in Baku.
5. To develop the system of managing municipal solid waste on the example of "Baku" through the development of a wide range of recommendations, which will be based on scientific principles and will consist of innovative methods of managing municipal solid waste, following the principles of the circular economy and resource efficiency, as well as the principles of sustainable development.

The aim of this study is to examine the current waste management system in Baku, identify its main environmental, organizational, and technological problems, and suggest practical solutions to improve its efficiency. The study also focuses on ways to make waste management more sustainable and support the principles of the circular economy.

3. Materials and Methods

This study performs a comprehensive assessment of the municipal solid waste management system in Azerbaijan's capital, Baku, covering not only environmental and organizational factors but also technological and legal/regulatory factors. Besides being aligned with the latest international principles for evaluating the sustainability of municipal solid waste management systems, this research methodology also adheres to the methodologies for assessing waste management systems according to the circular economy.

The study information base used official statistical data published by the State Statistical Committee of the Republic of Azerbaijan, the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, the Organization for Economic Cooperation and Development, the World Bank, the International Solid Waste Association, as well as legislative and regulatory documents governing municipal solid waste management in Azerbaijan (OECD, 2025; Gosudarstvennyi komitet statistiki Azerbaidzhanskoi Respubliki, 2024; The World Bank, 2020; Gosudarstvennyi komitet statistiki Azerbaidzhanskoi Respubliki, Helms & Nixon, 2010). In addition, scientific publications indexed in the Scopus and Web of Science databases were analyzed, with an emphasis on sustainable waste management, resource efficiency, the circular economy, and the implementation of innovative waste treatment technologies (Kirchherr et al., 2017; Geissdoerfer et al., 2017; Pires et al., 2011; Zaman, 2015; Ferronato & Torretta, 2019; EUA, 2023).

To reach the research goal, a mix of complementary methods was used. First, an in-depth review of scientific literature helped capture current approaches to municipal solid waste management, highlighting key trends shaping the sector, and detecting gaps in existing studies. Then, a comparative analysis assessed Baku's waste management system by looking at how it stacks up against practices in European Union countries and other nations that have successfully embraced sustainable waste strategies. Statistical methods allowed the exploration of patterns of waste generation, tracked vital performance indicators, and identified major developments within the system. By using official data, the research was able to measure the volume of waste produced and uncover factors that affect how well the current management system functions. A SWOT analysis was employed to evaluate the internal and external factors that affect the development of the municipal solid waste management system in the city of Baku. This approach facilitated the identification of the system's strengths and weaknesses, as well as the opportunities for its improvement and the potential risks associated with its future development.

To develop practical recommendations, we applied a systems approach, clearly examining how waste is generated, collected, transported, sorted, recycled, and ultimately disposed of. The results were analyzed through the lenses of sustainable development, the circular economy, resource efficiency, and environmental sustainability (Kirchherr et al., 2017; Geissdoerfer et al., 2017; MacArthur, 2013; Ferronato & Torretta, 2019; Khan et al., 2019; Zhang et al., 2015). By combining these research methods, we get a

clear, overall picture of the Baku municipal solid waste management system. This type of approach helped detect main operational challenges and formed a solid scientific foundation for creating evidence-based recommendations. These recommendations focus on modernizing the system by introducing innovative solutions.

4. Results

4.1. Current Status of Waste Generation in Azerbaijan

An important measure of how well a waste management system works is how much waste is produced and how effectively it is recovered or utilized. According to official statistics, Azerbaijan has seen a steady rise in industrial and municipal waste over the last fifteen years. This growth is driven by factors like population growth, fast industrial development, widening cities, more construction, and shifts in how people consume goods (Kaza et al., 2018; ISWA, 2024; OECD; Gürel & Tat, 2017).

Table 1. Waste Generation, Recovery, and Treatment in Azerbaijan, 2009-2024.

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Industrial and Municipal Waste Generated, thousand tonnes	2287,6	2281,5	2789,6	3096,7	2575,6	2386,0	2350,4	3019,7	2754,5	2896,1	3256,0	3452,3	3778,2	3985,1	4086,1	4365,0
Per Capita, kg	256	252	304	333	274	250	247	309	283	295	329	346	377	395	402,4	427,8
Industrial and Municipal Waste Recovered and Treated, thousand tonnes	503,1	476,1	572,3	665,0	537,2	497,3	771,7	796,6	767,3	848,3	713,4	792,1	1563,1	801,9	1139,2	1148,4
Per Capita, kg	56	53	62	72	57	52	81	82	79	85	72	79	156	79	112,2	112,6

As shown in Table 1, the total volume of industrial and municipal waste generated increased from 2287,6 thousand tonnes in 2009 to 436 thousand tonnes in 2024, indicating an almost twofold increase over the study period. The most pronounced growth occurred after 2018, when waste generation increased annually and reached its highest recorded level in 2024. The analysis of per capita indicators reveals a similar trend. While each resident accounted for 256 kg of generated waste in 2009, this figure increased to 427,8 kg by 2024, reflecting the growing anthropogenic pressure on the environment and increasing consumption levels (OECD, Ferronato & Torretta, 2019; Kaza et al., 2018).

A positive trend can also be observed in the recovery and treatment of waste. During the study period, the volume of recovered and treated industrial and municipal waste more than doubled, increasing from 503.1 thousand tonnes to 1,148.4 thousand tonnes. Despite this progress, the rate of increase in waste generation continues to exceed the rate of waste recovery and treatment, indicating the need for further improvement of the national waste management system.

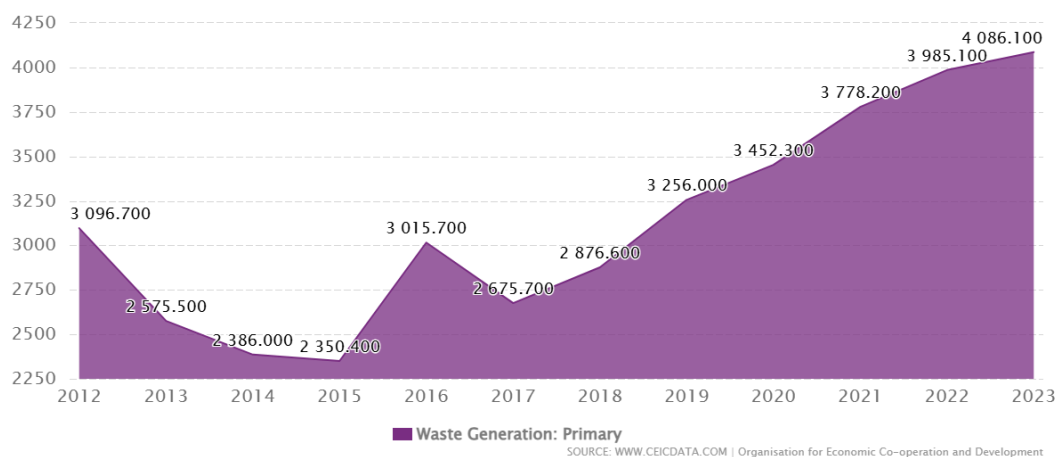


Figure 1. Waste generation figures for Azerbaijan for 2012–2023.

An analysis of the trends shown in Figure 1 [43] reveals a steady increase in waste generation volumes throughout virtually the entire period under review. The most pronounced growth was observed after 2020, which is linked to the recovery of economic activity following the COVID-19 pandemic, an increase in construction volumes, the expansion of industrial production, and rising consumption. In 2023, the volume of waste generation reached 4,086.1 thousand tonnes, which is the highest figure for the period under review.

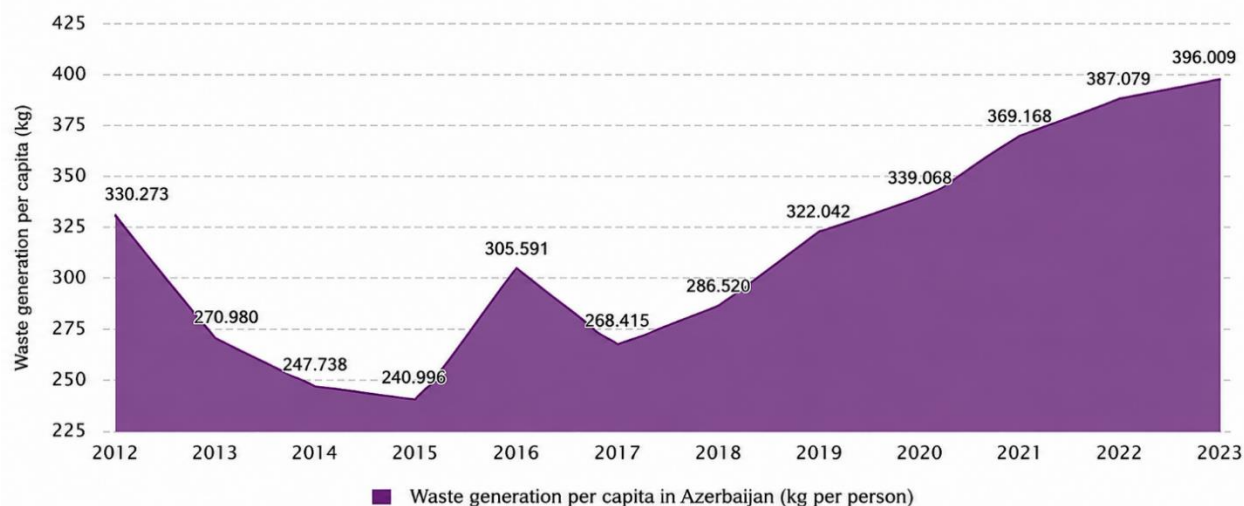


Figure 2. Per capita waste generation figures in Azerbaijan for 2012–2023.

One of the most informative indicators of the efficiency of natural resource use is the volume of waste generation per capita. The data in Figure 2, show a gradual increase in the amount of waste generated per capita. According to information from the Organization for Economic Co-operation and Development (OECD), this figure stood at 396,0 kg per person in 2023, compared with 387,1 kg in 2022. This increase is attributable to rising levels of household consumption, the expansion of urban agglomerations, and changes in the composition of municipal waste generated. Despite positive developments in the field of waste recycling, the rise in per capita waste generation highlights the need to introduce waste prevention measures, raise public environmental awareness, and develop a separate collection system. An important indicator of the environmental efficiency of the economy is the volume of waste generated per unit of gross domestic product.

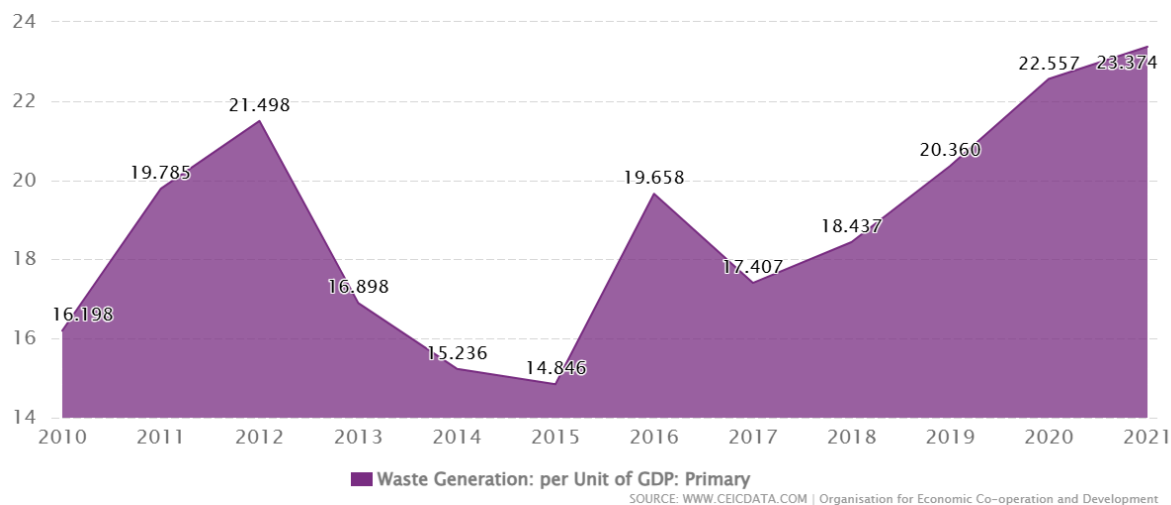


Figure 3. Waste generation rates per unit of GDP in Azerbaijan for 2010–2021.

The data show that waste generation per unit of GDP is changing at a slower rate than the absolute volume of waste. This indicates a gradual improvement in resource efficiency and an increase in economic productivity. At the same time, the persistently high level of waste generation points to the need for further implementation of low-waste technologies, resource-efficient production processes, and the principles of the circular economy [44]. The household sector has a significant impact on the total volume of municipal solid waste generated.

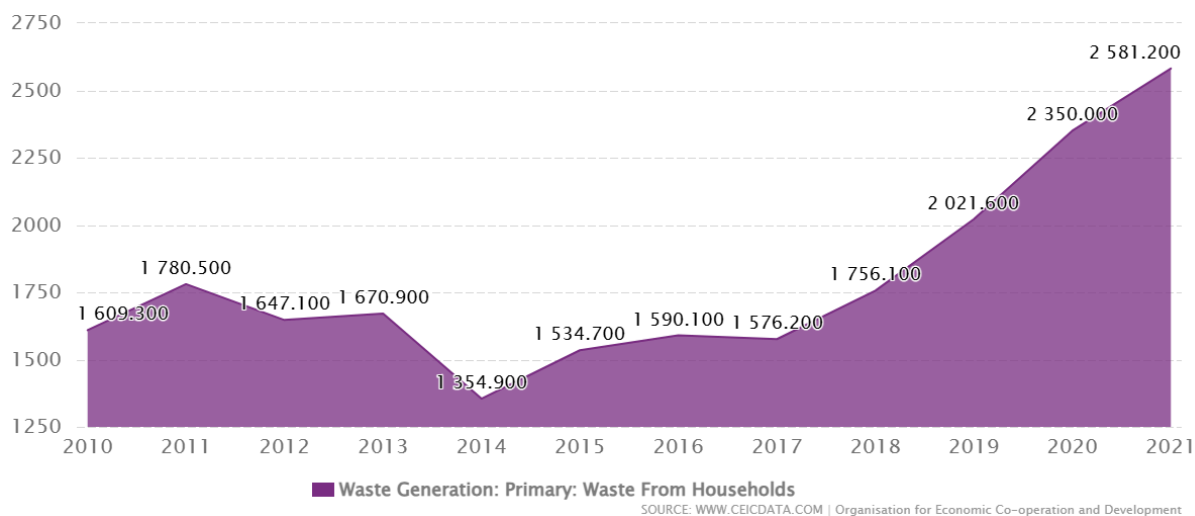


Figure 4. Household waste generation figures in Azerbaijan for 2010–2021.

Analysis of the data shows a steady increase in the volume of waste generated by households. Whilst this figure stood at around 1,3 million tons in 2010, by 2021 it had reached 2,58 million tons. This trend is driven by population growth, rising living standards and the expansion of the consumer market [40, 41, 45, 46]. The findings confirm that the domestic sector remains one of the main sources of municipal solid waste, which necessitates further improvements to the system for its separate collection and recycling.

The Current State of the Municipal Solid Waste Management System in Baku

As more than a quarter of Azerbaijan's population is concentrated in Baku, it is the capital that generates the largest volume of municipal solid waste in the country. In recent years, a range of measures has been implemented in the city aimed at modernizing the waste management system and improving the efficiency of waste collection, transport, sorting, and subsequent recycling.

The most important project is the creation of a new container system for collecting municipal solid waste that gradually covers all 9 administrative districts (Narimanov, Nizami, Nasimi, Yasamal, Khatai, Pirallahi, Surakhani, Binagadi and Sabail) of the city. Systematic observation of the amounts of sorted garbage shows positive dynamics. A good illustration is the case of Binagadi district: after the launch of the project, the amount of sorted waste grew from 6-8 tons/day at start-up to 21-23 tons/day now. This trend demonstrates the high effectiveness of the measures being taken to raise public environmental awareness, improve the logistics system, and enhance the quality of municipal services. To ensure the operation of a modern waste management system, 164 units of specialized municipal vehicles were purchased, enabling a significant modernization of the material and technical infrastructure (UNEP, 2024; ISWA, 2024; Kirchherr et al., 2017; OECD, 2024).



Figure 5. Changes in the volume of household waste in Baku by year (estimate, thousands of tons).

An analysis of trends in household waste generation in the city of Baku reveals a steady upward trend, driven by population growth, the development of urban infrastructure, and rising consumption levels. At the same time, the implementation of measures to improve the waste management system is contributing to a gradual increase in the proportion of waste sent for recycling and energy recovery (Tamiz Shahar ASC, 2024; World Bank, 2020).

According to official statistics, 4.086 million tons of waste were generated in Azerbaijan in 2023, of which 66.6 per cent was solid household waste. Of the total volume of municipal waste, 79.4 per cent was sent to landfill sites, 19.5 per cent was used for energy production, and 1.1 per cent was sold domestically as secondary raw materials. Using trash to generate energy produced 223 million kWh of electricity, an increase of 8.6 percent compared to last year. This shows that we're slowly moving away from just throwing waste away and moving toward a more sustainable way of utilizing it, focusing on saving resources and getting energy back (Kaza et al., 2018; Wilson et al., 2006; EEA, 2023; UNEP, 2024).

Table 2. Generation of specific types of industrial and household waste in Azerbaijan, 2005-2024.

Type of waste	2005	2010	2015	2017	2018	2019	2020	2021	2022	2023	2024
Waste generated during the preparation and processing of meat, fish and other products of animal origin	3,3	3,6	8,7	7,0	5,9	6,3	6,0	6,4	7,8	10,9	12,5
Waste generated during the preparation and processing of fruit, vegetables, cereals, vegetable oils, tea and tobacco	105,0	59,0	37,9	54,1	51,6	49,4	61,5	69,6	113,5	51,5	62,7
Waste from sugar production	x	28,1	-	11,2	13,7	38,5	30,1	8,7	20,1	36,2	25,1
Waste from the processing of dairy products	-	-	0,1	1,0	1,1	1,2	0,5	0,6	0,4	0,8	0,8
Waste from the cotton ginning industry	30,3	4,1	2,9	34,4	64,9	96,4	89,7	87,3	83,5	58,6	53,0
Paper and cardboard waste	0,6	0,6	2,2	5,7	8,9	38,4	38,9	43,8	46,8	55,9	56,1
Recycled textiles	0,4	0,3	0,1	0,1	0,1	0,1	0,0	0,0	0,0	0,0	0,05
Glass containers and cullet	0,3	0,4	0,1	0,1	1,9	2,5	9,6	0,8	1,9	7,2	4,6
Plastics and polymers	0,6	0,3	0,4	2,5	3,2	2,6	2,4	2,3	1,9	1,6	1,6
Waste from mineral extraction, the mining industry, quarries, and the physical and chemical processing of minerals	13,4	3,2	1,3	29,7	4,2	4,7	5,0	4,8	3,5	3,4	7,4
Ferrous metal waste	514,6	303,4	346,3	495,7	468,8	426,4	376,2	367,3	449,0	453,3	506,8
Non-ferrous metal waste	0,4	1,2	0,1	0,5	0,4	0,4	0,8	0,9	0,6	0,7	0,9
Bottom ash	x	x	103,5	98,0	46,7	119,6	69,0	146,6	95,4	107,9	111,7
Wood waste, thousand m ³	4,3	2,4	0,6	22,4	15,5	16,7	12,0	4,7	4,6	4,8	7,4
Household waste, million m ³	7,3	6,7	6,4	6,6	7,3	8,4	9,8	10,8	11,1	11,3	12,6

Table 2 shows the trends in the generation of different types of industrial and household waste in Azerbaijan over the period 2005-2024. The results show significant changes in the composition of waste, driven by the development of industrial production, rising consumption, the better of the waste management system, and shifts in the sectoral structure of the economy.

Among the categories, ferrous metal waste accounted for the highest volume throughout the entire period under review, ranging from 303,4 thousand tons in 2010 to 506,8 thousand tons in 2024. It shows a high concentration of metallurgical and industrial production, as well as significant potential for the further integration of metal waste into the secondary economic cycle (Habitat, 2021; UN, 2015).

The big changes are also observed in the category of paper and cardboard waste. If in 2005 the volume amounted to just 0,6 thousand tons, then by 2024 this figure had increased almost a hundredfold, reaching 56,1 thousand tons. This trend reflects the increase in the consumption of packaging materials, the development of trade and logistics, and the constant improvement of the system for recording and separately collecting waste paper.

A positive trend is also evident for organic waste from the food industry. For instance, the volume of waste generated during the processing of meat, fish and other products of animal origin increased from 3,3 thousand tons in 2005 to 12,5 thousand tons in 2024. Similar trends are observed in waste from the processing of fruit, vegetables, cereals, vegetable oils, tea and tobacco, which is linked to the development of the country's agro-industrial complex and food industry.

Attention should be paid to the growth of household waste. Its volume increased from 7,3 million m³ in 2005 to 12,6 million m³ in 2024. This increase can be linked to population growth, urbanization, changes in consumption habits, and improvements in living standards. The growing amount of municipal waste puts more pressure on the existing systems for waste collection, transportation, treatment, and disposal. Therefore, further development of waste management infrastructure is needed.

The analysis also shows that the waste situation in Azerbaijan is changing not only in terms of the total amount of waste generated, but also in its composition. The growing share of materials such as paper, cardboard, glass, and metals shows that there is good potential for developing separate waste collection and recycling. At the same time, the increase in the size of household and organic waste highlights the need to introduce more sustainable waste management. These methods should include better resource use, circular principles, and modern technologies for waste collection, treatment, and recycling. These types of measures are especially important for large cities and urban agglomerations, including Baku.

5. Conclusion

This research assessed the current municipal solid waste management system in Baku and examined the main ecological challenges related to its development. The results show that population growth, urbanization, economic development, and changing consumption models have increased the amount of waste generated. These changes show the need to improve the existing waste management system and move towards a more effective approach based on better use of resources.

An analysis of statistical data has detected a steady trend of an increase in the total volume of waste in Azerbaijan. In 2023, the volume of waste generation reached 4.086 million tons, with solid household waste accounting for more than two-thirds of this total. At the same time, there was an increase in per-capita waste generation and a rise in the volume of municipal waste, confirming the need to introduce the newest waste prevention mechanisms, enlarge the separate collection system, and increase the recycling rate.

In the research, we can see that, in Baku, in recent years, several significant measures have been implemented to modernize the municipal solid waste management system. The introduction of separate waste collection in nine administrative districts of the city, the update of the fleet of specialized municipal vehicles, the modernization of the Balakhaniy landfill site, and the implementation of the “Integrated Solid Waste Management” project with the support of the World Bank have been important milestones in the development of a new management infrastructure. The positive trend in the growth in the volume of sorted waste indicates a gradual improvement in the system’s operation and a rise in the population’s environmental responsibility.

At the same time, the research findings indicate that the existing waste management model remains heavily reliant on landfill disposal. Despite the increase in energy recovery and recycling, the majority of municipal solid waste continues to be sent to junk yards, which limits the potential for the rational use of secondary material resources and increases the load on the environment.

An analysis of the waste composition has verified that there is significant potential for expanding the recycling of paper, cardboard, glass, metals, plastics, and organic waste. This opens the way for the wider implementation of recycling principles, which aim to maximize the saving of material resources within recycling, reduce the volume of waste sent to the landfill, and improve the efficiency of natural resource use.

The practical significance of the research is based on the development of a set of scientifically grounded recommendations aimed at modifying the municipal solid waste management system in Baku. Priority areas include enlarging the infrastructure for separate waste collection, introducing digital technologies for monitoring waste streams, growing the efficiency of sorting facilities, developing enterprises for the processing of recyclable materials, refining public-private partnership mechanisms, and raising public environmental awareness through educational and information programs.

The main scientific value of this study is that it considers the municipal solid waste management system from several different sides. The study combines statistical data, an assessment of existing waste management infrastructure, international experience, and the principles of sustainable growth and recycling. The recommendations presented in the study can be useful for government agencies, local authorities, and other organizations working in this field. They can be used to improve waste management in Baku and other major cities of Azerbaijan.

Future research can focus on design models to predict the level of municipal waste using artificial intelligence and GIS technologies. It would also be useful to study the environmental and economic consequences of different waste management technologies till the end of their life cycle. Another important area is the assessment of digital waste management systems and their role in the progress of smart and sustainable cities.

Overall, we see that the results that Azerbaijan needs to move towards a new and integrated waste management system. This type of system should focus on recycling, effective use of resources, and new technologies. This approach can help decrease environmental impacts, improve the urban environment, and support the achievement of the Sustainable Development Goals in Azerbaijan.

Author's contribution

The sole author is responsible for conceptualizing, collecting, and analyzing data, and writing and editing the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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