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Application of Innovative Organic–Mineral Technologies in Cotton Agroecosystems: Agrochemical Optimization and Management of Fiber Quality Using Hvi Digital Analytics

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Abstract. *The exceptional role of organic substances in improving soil fertility constitutes one of the main research directions of modern agrochemical science. In this regard, the application of organic–mineral complexes that positively affect the productivity and quality of agricultural crops, the determination of optimal fertilizer rates, and the development of new technologies represent an urgent issue of scientific and practical significance. The intensity of biological processes occurring in the soil directly determines fertility indicators. The activity of microorganisms requires sufficient soil moisture, the presence of organic matter, and a favorable soil reaction. Within the framework of the present study, a technology for the preparation of organic–mineral complexes based on local raw material resources was developed, and these complexes were tested under cotton cultivation conditions.*

Keywords: *meadow-gray soil, cotton, technology, fertility, nitrogen, phosphorus, potassium, physicochemical properties, fertilizer, organic–mineral complex*

Introduction

Beginning in the second half of the twentieth century, chemicalization became the main direction in the development of world agriculture. Although this approach resulted in a significant increase in agricultural productivity (Akhundova, 2022, pp. 55–62), in the long term it also created a number of serious problems affecting the soil ecological environment. Among these problems, the deterioration of the physical and chemical properties of soils, the depletion of humus reserves, and environmental pollution should be particularly noted. The exceptional role of organic substances in improving soil fertility has been emphasized in numerous studies (Abbasov et al., 2021).

At present, the application of organic fertilizers in agricultural production has become a priority issue (Mammadov et al., 2024). Furthermore, the use of organic–mineral complexes has been shown to improve both crop productivity and product quality. At the same time, determining optimal fertilizer application rates and developing innovative fertilization technologies remain important scientific and practical challenges (Alosmanov et al., 2022). In addition to increasing the availability of essential nutrients in the soil, these organic wastes also have a positive effect on the productivity of agricultural crops (Akhundova & Salimova, 2019, pp. 214–218).

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P.B. Zamanov (2015, pp. 42–47) reported that there are up to 40 types of waste suitable for use as organic fertilizers, with total reserves exceeding 22 million tons. In recent years, following the transition to a market economy, the prices of mineral fertilizers have increased significantly, while the shortage of organic fertilizers in the republic has become even more acute. Therefore, evaluating local waste and raw material resources for use as organic fertilizers is of great importance from both economic and environmental perspectives. The application of organic fertilizers makes it possible to considerably reduce the application rates of mineral fertilizers, providing both ecological and economic benefits. The use in agriculture of widely distributed non-metallic mineral resources in Azerbaijan, such as volcanic mud, oil shale, and other natural materials, has become an important scientific priority as an alternative source of fertilizers (Mammadov et al., 2024). Previous studies demonstrated that organo-mineral complexes prepared from oil shale, plant residues, and industrial wastes had a more favorable effect on cotton growth and productivity than conventional fertilizers (Mammadov & Khalilov, 2003).

Chemical analyses of organic fertilizer resources in Azerbaijan showed that they contain approximately 170 thousand tons of pure nitrogen, 77 thousand tons of pure phosphorus, 221 thousand tons of potassium, 6 million tons of organic matter, and 5 million tons of ash. According to the State Statistical Committee of the Republic of Azerbaijan (2021), 129.9 thousand tons of mineral fertilizers were imported into the country, including 95.7 thousand tons of nitrogen fertilizers and 2.7 thousand tons of potassium fertilizers. During the same year, 88.0 thousand tons of mineral fertilizers (calculated as 100% active substance) were applied to agricultural crops. Cotton was cultivated on 100,590 ha, with an average yield of 28.6 centners ha^{-1}. In recent years, cotton cultivation under monoculture conditions, the absence of crop rotation, the unbalanced application of mineral fertilizers, and the extremely low use of organic fertilizers have led to the deterioration of the water-physical and biological properties of soils, as well as a decline in their natural fertility. Therefore, improving the physical, mechanical, and agrochemical properties of these soils, together with maintaining a balanced humus content, is essential for obtaining the planned high cotton yields.

Methods

The study was conducted under cotton cultivation on irrigated meadow-gray soils located in the Bilasuvar and Saatly districts of the Mughan-Salyan region of Azerbaijan. Agrochemical analyses of the collected soil samples were performed using generally accepted analytical methods. To determine the agrochemical characteristics of the experimental field, soil samples were collected from the 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil layers using the envelope sampling method. Soil pH (measured in a water suspension) was determined using a potentiometer. Total humus content was determined according to the Tyurin method, total nitrogen by the Kjeldahl method, total phosphorus according to the Ginzburg method, and total potassium according to the Smith method. The following analyses were also performed: exchangeable ammonium nitrogen ($N–NH_4$) according to Konev, nitrate nitrogen ($N–NO_3$) according to the Grandval–Lajoux method, available phosphorus (soluble in 1% ammonium carbonate) according to Machigin, and exchangeable potassium according to the Protasov method modified by Huseynov. The technology for preparing the organo-mineral complex was developed and evaluated in a field experiment established within the Azadkend municipality of the Saatly district. The experiment included four treatments with four replications. The area of each experimental plot was 100 m^2. Field experiments were conducted in accordance with generally accepted agronomic practices (Dospekhov, 1985). Ammonium nitrate (33.4%) was applied as the nitrogen fertilizer, ammophos (51%) as the phosphorus fertilizer, and potassium sulfate (52%) as the potassium fertilizer. The organo-mineral complex was applied in combination with these fertilizers. In the agrochemical analyses of soil samples, total nitrogen was determined by the I.V. Tyurin method, exchangeable ammonium ($N–NH_4$) Exchangeable ammonium nitrogen ($N–NH_4$) was determined by the D.P. Konev method, nitrate nitrogen ($N–NO_3$) by the Grandval–Lajoux method, total phosphorus by the A.M. Meshcheryakov method, available phosphorus by the M.P. Machigin method, total potassium by the P.K. Smith method, and exchangeable potassium by the P.V. Protosov method. Phenological observations, including main stem height, number of bolls per plant, and raw cotton mass per boll, were carried out on 20 marked plants from each treatment according to the methodology described by Dospekhov (1973). Biometric measurements were performed during the squaring (flower-bud formation), flowering, and boll formation stages. The BO-440 Aghgizil cotton variety was used in the field experiments (Aslanov & Valiyeva, 2014). Cotton fiber quality parameters were determined in accordance with international standards using the Statex-type High Volume Instrument (HVI), a high-precision and high-speed fiber testing system. According to the international classification, the following 12 quality indicators were evaluated: Mean Length (ML), Upper Half Mean Length (UHML), Uniformity Index (UI), Short Fiber Index (SFI), Fiber Strength (Str), Elongation at Break (Elg), Micronaire (Mic), Fiber Fineness (Fin), Reflectance (Rd), Yellowness (+b), Leaf Grade, and Color Grade (CG).

Results

The principal physical and chemical properties of the irrigated meadow-gray soils in the experimental field located in the Bilasuvar district were analyzed in accordance with previously published methodologies (Mammadov, 2007; Salayev, 1991). The obtained results are presented in Tables 1 and 2.

Table 1

Agrochemical indicators of irrigated meadow-gray soils of the Mughan–Salyan region

Depth (cm)	Total N (%)	Hydrolyzable N (mg/kg)	N-NH_4 (mg/kg)	N-NO_3 (mg/kg)	Total P (%)	Water-soluble P (mg/kg)	Available P (mg/kg)	Total K (%)	Water-soluble K (mg/kg)	Exchangeable K (mg/kg)	pH	Humus (%)
0–20	0.14	85	7.20	11.50	0.15	7.20	18.5	2.85	38.5	285.40	7.60	2.35
20–40	0.11	68	5.80	9.20	0.13	5.40	14.2	2.52	31.2	238.60	7.65	1.82
40–60	0.09	52	4.50	7.10	0.11	3.80	10.5	2.24	24.8	192.30	7.72	1.42
60–80	0.07	38	3.40	5.40	0.09	2.50	7.30	1.98	18.5	152.80	7.78	1.08
80–100	0.05	28	2.60	4.10	0.07	1.60	4.80	1.75	13.2	118.50	7.85	0.82

Table 2

Selected physicochemical properties of meadow-gray soils

Depth (cm)	Dry Residue (%)	$CaCO_3$ (%)	Total Exchangeable Bases (meq/100 g)	Exchangeable Ca (meq/100 g)	Exchangeable Mg (meq/100 g)	Exchangeable Na (meq/100 g)	<0.001 mm (%)	<0.01 mm (%)
0–20	0.45	7.7	24.3	14.5	8.3	1.5	35.88	83.12
20–40	0.52	9.8	24.7	15.1	7.0	2.6	37.36	84.56
40–60	0.68	11.2	22.8	13.2	7.2	2.4	36.90	85.00
60–80	0.85	13.6	20.1	10.9	7.4	1.8	32.64	80.72
80–100	0.92	12.1	18.7	11.0	6.2	1.5	28.32	72.18

Table 3
Technological properties of votton fiber

No.	Treatment	Mean Length (mm)	Upper Half Mean Length (mm)	Uniformity Index (%)	Fiber Strength (g/tex)	Elongation (%)	Micronaire	Fineness (m/tex)	Reflectance (Rd, %)	Yellowness (+b)	Color Grade (CG)	Leaf Factor (%)	Short Fiber Index (%)
1	Control	26.7	27.4	97.3	27.4	6.8	5.0	168	63.6	18.5	21-1	–	<3
2	N120P120K120 Background	25.5	27.9	95.0	26.4	7.0	5.0	176	63.0	16.9	21-1	–	<3
3	Organic–Mineral Complex	25.3	26.7	94.8	27.1	7.0	4.9	159	62.7	16.8	21-1	–	<3
4	Silt + Sand	25.3	27.6	91.1	25.8	6.7	5.1	187	64.5	17.3	21-1	–	<3

As shown in Table 1, the total nitrogen content in the upper soil layer (0–20 cm) of the study area was 0.13%, decreasing progressively with depth to 0.03% in the 80–100 cm layer. This trend can be explained by the accumulation of organic matter primarily in the upper soil horizons. The content of hydrolysable nitrogen followed the same pattern, decreasing from 82 mg kg^{-1} in the 0–20 cm layer to 26 mg kg^{-1} in the 80–100 cm layer (Mammadov, 2007). Among the mineral nitrogen forms, exchangeable ammonium ($N–NH_4$) and nitrate nitrogen ($N–NO_3$) in the upper layer amounted to 6.06 and 13.74 mg kg^{-1}, respectively. With increasing soil depth, both indicators decreased proportionally, reaching their lowest values (1.50 and 4.66 mg kg^{-1}, respectively) in the 80–100 cm layer. This decrease is associated with reduced microbiological activity and, consequently, a lower rate of organic matter mineralization in the deeper soil horizons.

Analysis of the phosphorus regime revealed that the total phosphorus content in the 0–20 cm layer was 0.15%, while the water-soluble and available phosphorus contents were 6.70 and 16.8 mg kg^{-1}, respectively. These values gradually decreased with soil depth. Regarding potassium, the total potassium content in the upper layer was 3.17%, whereas the water-soluble and exchangeable forms reached 45.2 and 342.22 mg kg^{-1}, respectively. A similar decreasing trend with depth was observed for potassium (Mammadov, 2007). The soil reaction (pH) became increasingly alkaline with depth, whereas humus content gradually decreased from the surface horizons to the deeper layers (Mammadov, 2007; Salayev, 1991). The data presented in Table 2 characterize the physicochemical properties of the soil. Dry residue increased with depth, calcium carbonate ($CaCO_3$) reached its maximum concentration in the middle horizon, exchangeable calcium predominated among exchangeable cations, and the soil exhibited a heavy clay texture (Mammadov, 2007; Salayev, 1991). Overall, the results presented in Tables 1 and 2 indicate that the studied soils possess relatively low fertility potential due to weak nitrogen and phosphorus regimes, while their heavy clay texture adversely affects soil structure (Mammadov, 2007; Salayev, 1991).

Sowing in the experimental field was carried out during the third ten-day period of April, and seedling emergence was observed during the first ten-day period of May. Phenological observations were conducted on June 30, July 27, and August 30, 2021. During the squaring, flowering, and full maturity stages, plants treated with the organo-mineral complex exhibited greater plant height, a higher number of branches, and more bolls per plant than those in the control and mineral fertilizer treatments (Abbasov & Ibadzade, 2021; Mammadov et al., 2023). The effects of fertilizer application on cotton yield and fiber quality were investigated under irrigated meadow-gray soil conditions in the Saatly district. The production of cotton fiber with high technological quality is of considerable economic importance for the textile industry. According to the analytical results, the Upper Half Mean

Length (UHML), Uniformity Index (UI), and Fiber Strength (Str) corresponded to medium-staple cotton with a high degree of fiber uniformity. Compared with the other treatments, the organo-mineral complex treatment produced superior improvements in cotton fiber quality characteristics (Abbasov & Ibadzade, 2021; Akhundova, 2022).

Discussion

Irrigated meadow-gray soils are among the agriculturally important soil types formed under arid and semi-arid climatic conditions, mainly on alluvial and proluvial deposits (Mammadov, 2007; Salayev, 1991). Although these soils develop under naturally limited moisture conditions, their morphogenetic, physical, and chemical properties change considerably under irrigation.

From a physical perspective, these soils are predominantly loamy to heavy clay loamy, and irrigation affects bulk density, porosity, water-physical characteristics, aggregate stability, and salinization processes (Mammadov, 2007; Salayev, 1991). Chemically, irrigated meadow-gray soils are characterized by carbonate accumulation, relatively low humus content, an alkaline reaction, and varying degrees of salinity. These characteristics are strongly influenced by irrigation water quality and agricultural management practices (Mammadov, 2007). Consequently, the physical and chemical properties of irrigated meadow-gray soils are closely associated with soil-forming factors, irrigation regimes, and anthropogenic activities. Understanding these characteristics provides an important scientific basis for sustainable soil management (Mammadov, 2007; Salayev, 1991).

For normal cotton growth and development, balanced applications of nitrogen, phosphorus, potassium, and essential macro- and micronutrients are required (Akhundova & Salimova, 2019; Aslanov & Valiyeva, 2014). Organic fertilizer resources available in Azerbaijan constitute an important reserve for sustainable agriculture and environmentally sound waste utilization (Zamanov, 2015). Meadow-gray soils belong to the heavy clay soil group and are characterized by relatively low fertility because of their limited organic matter and nutrient contents. The application of organo-mineral complexes improves soil structure, porosity, microbial activity, moisture retention, aeration, nutrient availability, and ultimately enhances cotton growth and fiber quality (Abbasov & Ibadzade, 2021; Alosmanov et al., 2022; Mammadov et al., 2024).

Conclusion

1. The study demonstrated that although irrigated meadow-gray and gray-meadow soils of the Yevlakh and Imishli districts contain relatively high total amounts of the principal nutrients, the concentrations of plant-available nutrients remain insufficient. Therefore, balanced fertilizer application is essential for achieving high and high-quality crop yields.
2. The results showed that the contents of nitrogen, phosphorus, and potassium were moderate in the upper soil layer (0–20 cm), low in the plow layer, and very low in the 40–80 cm soil layers.
3. The production and application of organo-mineral complexes prepared from household waste and locally available raw materials are economically efficient and environmentally sustainable. Their use not only reduces environmental pollution but also minimizes the costs associated with waste transportation and disposal.
4. Field experiment results demonstrated that the organo-mineral complex treatment outperformed the other treatments with respect to cotton plant growth, development dynamics, and fiber quality characteristics. Therefore, the combined application of organo-mineral complexes and mineral fertilizers can be recommended as an effective agronomic practice for achieving high and stable crop yields.

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Technological Aspects of the Influence of Mineral and Organic Fertilizers on the Size of Water- Resistant Aggregates of Irrigated Meadow-Forest Soils under Vegetable Agrocenoses

Elnara Mahmudova

Abstract. *This article focuses on the technological optimization of the structure of alluvial-meadow-forest soils in the north-eastern region of Azerbaijan. Under the conditions of the transition to intelligent agriculture (Smart Farming), the water resistance of soil aggregates is considered a key indicator of agroecosystem stability. Experimental results demonstrated that the application of biotechnological vermicompost at a rate of 7 t ha⁻¹ provided the highest content of water-resistant aggregates (>0.25 mm), reaching 71.6%, which significantly exceeded the values obtained under conventional mineral fertilizer systems. Comparative analysis confirmed the technological superiority of organic fertilization in promoting stable soil aggregation and reducing the risk of irrigation-induced soil erosion.*

Keywords: *water-resistant aggregates, vermicompost, agricultural technologies, alluvial-meadow-forest soil, vegetable crops, Smart Farming, sustainable development*

Introduction

Soil structure is one of the most important morphological characteristics determining soil physical quality and agricultural productivity (Lal, 2020). It not only provides a favorable habitat for soil microorganisms but also regulates soil water, air, and nutrient regimes (Kachinsky, 1965). Under conditions of intensive modern agriculture, where anthropogenic pressure on soils continues to increase, evaluating the size distribution and stability of water-resistant aggregates has become an essential component of sustainable soil management. The scientific basis of soil structure formation depends on several major factors, including soil texture, humus content, and vegetation cover. Only an agronomically valuable soil structure can provide plants with adequate water, nutrients, and aeration during critical growth stages. Numerous studies conducted in Azerbaijan have emphasized the importance of preserving the structural stability of agricultural soils (Mamedov, 1961). This issue becomes particularly important when comparing different agroecosystems. Studies carried out in the Mughan region demonstrated that, under cotton–alfalfa crop rotations, the proportion of water-resistant soil aggregates under cotton ranged from 28.4% to 30.5%, whereas under perennial alfalfa stands it increased to 39.7–63.4%. These findings indicate that scientifically based crop rotation systems and balanced nutrient management are effective tools for improving soil structure and enhancing soil stability.

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The aim of the present study was to develop an optimal fertilization strategy for stabilizing the structure of alluvial-meadow-forest soils cultivated with vegetable crops (tomato) through the application of different fertilizer systems (Kachinsky, 1965).

Methods

Study Area and Climatic Conditions

The study was conducted in the north-eastern region of Azerbaijan, within the Shabran District, at the *Svobodnaya Novaya* farm (Hadzhiev & Rahimov, 1977). The study area is characterized by a gently sloping plain dissected by numerous slopes and deep canyon-like valleys, reflecting the active influence of erosion processes. The climate of the region is classified as a moderately warm semi-desert with a pronounced dry summer. The mean annual air temperature ranges from 12 to 13°C, while the average annual soil temperature varies between 12 and 15°C. Annual precipitation ranges from 300 to 600 mm, with the majority occurring during the autumn season. High evaporation rates (600–800 mm $year^{-1}$), together with a radiation balance of 40–50 kcal cm^{-2}, create specific environmental conditions that require careful regulation of the soil water regime (Mammadov & Kuliev, 2002).

Detailed agroclimatic characteristics of the study area are presented in Table 1.

Table 1

Agroclimatic and soil characteristics of the area of studies

Parameter	Value / Description
Soil type	Irrigated alluvial-meadow-forest
Relief	Inclined plain with canyons and river valleys
Average annual temp. air	12-13°C
Annual precipitation	300-600 mm (maximum in autumn)
Evaporation	600-800 mm
Radiation balance	40-50 kcal/cm²
Plant cover	Mountain-meadow, forest and semi-desert

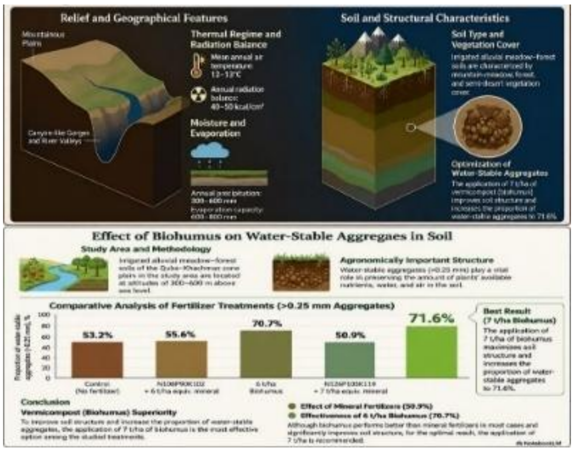

Figure 1

Agroclimatic and soil characteristics of the study area

Object of the Study and Soil Conditions

The object of the study was irrigated alluvial-meadow-forest soils formed on the floodplain terraces of mountain rivers. These soils developed under conditions of continuously disturbed pedogenesis, resulting in considerable variations in their genetic profiles.

Experimental Design

Field experiments were conducted under tomato cultivation following the methodology adopted in the Republic of Azerbaijan (Morphogenetic Profile of Soils of Azerbaijan, 2004). The experimental design consisted of nine treatments, including a control, mineral fertilizer treatments, and different application rates of biotechnological vermicompost. Soil structural composition was evaluated using the wet-sieving method developed by Kachinsky (1965). To ensure the reliability and statistical validity of the experimental results, all treatments were arranged in a randomized block design with three replications. Soil samples were collected from the 0–20 cm layer at the main stages of tomato growth and analyzed under laboratory conditions. The distribution of water-resistant aggregates was determined by the wet-sieving method, and the obtained data were statistically analyzed using analysis of variance (ANOVA). Treatment means were compared at a significance level of $p \leq 0.05$ to determine statistically significant differences among fertilizer treatments. This methodological approach enabled a comprehensive evaluation of the effects of mineral fertilizers and vermicompost on soil structural stability under irrigated vegetable agroecosystems.

Results

The obtained results demonstrated that the optimal technological approach for stabilizing the structure of alluvial-meadow-forest soils under vegetable agroecosystems is the application of vermicompost at a rate of 7 t ha^{-1}. This application rate produced the highest proportion of water-resistant aggregates (71.6%), thereby reducing the risk of irrigation-induced soil erosion and improving the soil water–air regime (Mirzoeva & Geraizade, 2017). In contrast, high application rates of mineral fertilizers without supplementary organic amendments resulted in the deterioration of the physical properties of irrigated soils. The effects of different fertilizer application rates on the proportion of water-resistant soil aggregates are presented in Table 2.

Table 2

Influence of fertilizer systems on the size of water-resistant soil aggregates

Experience option	Contribution rate	>7 mm	1-3 mm	Total >0.25 mm (%)	<0.25 mm (%)
Control (without fertilizer)	-	6.1	15.2	53.2	46.8
N108P90K102 + biohumus equivalent (6 t/ha)	Mixed	1.7	16.9	55.6	44.4
Biohumus (6 t/ha)	Org. (Bio)	5.4	17.3	70.7	29.3
Biohumus (7 t/ha)	Optimal	7.3	20.1	71.6	28.4
N126P105K119 + biohumus equivalent (7 t/ha)	Min.	-	16.8	50.9	49.1
N36P30K34 + biohumus (5.0 t/ha)	Integrated	4.1	22.5	66.2	33.8

Influence of fertilizer systems on the size of water-resistant soil aggregates

In the control variant, the amount of water-resistant aggregates was 53.2%. The maximum result was recorded when applying 7 t/ha of vermicompost — 71.6% , where the most valuable fraction 1–3 mm was 20.1%. The mineral system (N126P105K119) led to a decrease in water resistance to 50.9%.

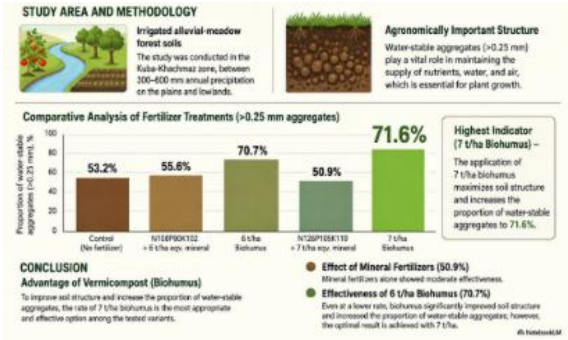

Figure 2

Impact of biohumus on water-stable aggregates in soil

Discussion

The results obtained in this study provide important insights into the aggregation processes occurring in irrigated alluvial-meadow-forest soils under different fertilization systems. The structural condition of the soil is closely related to the biochemical effects of the applied fertilizers (Chen et al., 2023; Edwards, 2019). The technological superiority of vermicompost can be explained by its ability to function as a natural biological binding agent. Unlike mineral fertilizers, vermicompost enriches the soil with humic substances and organic compounds that promote the formation of stable organo-mineral complexes. This process is particularly important in the Shabran region, where sloping terrain increases the susceptibility of soils to water erosion. Consequently, the improved stability of water-resistant aggregates contributes directly to reducing the risk of irrigation-induced soil degradation. A comparison with previous studies conducted in the Mughan region highlights the specific characteristics of alluvial-meadow-forest soils. While the maximum proportion of water-resistant aggregates under alfalfa reached 63.4% in earlier studies, the application of vermicompost in the present investigation increased this value to 71.6% under intensive tomato cultivation. These findings indicate that biologically based soil amendments may provide greater improvements in soil structural stability than traditional crop rotation systems alone.

The adverse effect of high application rates of mineral fertilizers, reflected by the lower proportion of water-resistant aggregates (50.9%), confirms that excessive chemical fertilization may accelerate the dispersion of soil colloids and contribute to structural degradation (Hasanov, 2013). Within modern Smart Farming systems, such information can be used to optimize fertilizer application rates and minimize the physical degradation of irrigated soils. Furthermore, the proportion of agronomically valuable aggregates (1–3 mm), which reached 20.1% under the optimal vermicompost treatment, provides a favorable balance of capillary porosity under the arid climatic conditions of the Shabran region (Mammadov, 2022; Smith et al., 2021).

The improvement in aggregate stability observed following vermicompost application is also important from the perspective of sustainable land management and climate-resilient agriculture. Water-resistant aggregates increase soil infiltration capacity, reduce surface runoff, improve resistance to soil compaction, and enhance the efficient use of irrigation water. In regions with limited water resources and increasing climatic variability, such as the north-eastern region of Azerbaijan, the application of organic soil amendments represents an effective strategy for maintaining long-term soil fertility and agroecosystem stability. Therefore, integrating vermicompost into fertilization programs should be considered not only as a means of improving soil structural quality but also as an essential component of environmentally sustainable agricultural technologies.

Conclusion

The results of the present study demonstrate that both organic and mineral fertilizers significantly influence the structural stability of irrigated alluvial-meadow-forest soils under vegetable agroecosystems. Among the tested fertilization treatments, the application of vermicompost at a rate of 7 t ha^{-1} proved to be the most effective, increasing the proportion of water-resistant aggregates (>0.25 mm) to 71.6%, which substantially exceeded the values recorded for both the control treatment and mineral fertilizer treatments. The findings confirm that vermicompost promotes the formation of stable soil aggregates through the accumulation of organic binding agents and humic substances. As a result, soil physical properties are improved, the risk of irrigation-induced erosion is reduced, and the soil water–air regime is optimized. In contrast, intensive mineral fertilization without adequate organic matter inputs resulted in lower aggregate stability and a tendency toward soil structural degradation. From a technological perspective, integrating vermicompost into fertilization programs represents an effective strategy for sustainable soil management in irrigated vegetable production. The obtained results support the implementation of biologically based fertilization technologies within modern Smart Farming systems to improve soil quality, enhance irrigation efficiency, and promote the long-term sustainability of agricultural ecosystems in the north-eastern region of Azerbaijan. Further long-term studies under different crop rotation systems and climatic conditions are recommended to evaluate the persistence of these positive effects and to optimize integrated fertilizer management strategies.

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Development of an Accessible Remote Method for Monitoring Landslide Processes

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Abstract. *Remote methods for studying and monitoring exogenous processes have been used since ancient times. In the 18th century, the determination of the size and spatial position of objects was done through their drawn images in central projection, which were obtained using a camera obscura from elevated places and ships. The next stage in the development of remote methods was the invention of photography, the photographic lens, and the stereoscope. Photographs of the landscape, taken from a bird's-eye view using balloons and kites, received high cartographic recognition. Currently, drones equipped with cameras are effectively used for studying and monitoring the development of landslide processes. However, even this method has its drawbacks. Thus, it is virtually impossible to fix a drone with photographic equipment in a stationary position for an extended period at a chosen high near-distance observation point. The authors have proposed a simplified method of photogrammetric surveying for near-distance research on large landslide processes. The method involves using various flying vehicles instead of aerial photography. Periodic photography is carried out from elevated points of seismic-resistant high-rise buildings and structures (television towers, chimneys, high masts, and high-voltage power line towers) located outside the landslide-prone area. The method, in comparison to aerial photography, is significantly simpler, cheaper, and allows for more accurate information about the dynamics of landslide, erosion, and abrasion processes due to the possibility of conducting multiple surveys from stationary points over different periods. First of all, we achieve the effect of stationary, relatively inexpensive research on the development of the landslide process over a long period, during which periodic photography of the designated area or object on the landslide slope surface is carried out automatically according to a set program. The method can also be implemented using two or more cameras installed on two or more seismic-resistant high-rise structures located in the vicinity of the large landslide area under study. The equipment installed on the elevated structures can be equipped with automatic systems programmed for emergency response to the rapid development of the landslide process and alerting operators via mobile or satellite communication networks. The development is distinguished by its relative affordability, accuracy, and accessibility.*

Keywords: *landslide, periodic photography, high-rise buildings, method, landslide process*

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Introduction

The primary goal of all human achievements is improving the quality of life. However, it is evident that the world is becoming neither safer nor cleaner due to the growing global population and increasing anthropogenic and technogenic pressure on the environment. This can be attributed to ongoing social and geo-environmental changes, insufficient funding, as well as the attitudes of people toward one another and toward the environment.

Managing the quality of the surrounding geological environment is difficult to envision without the use of information technologies. In this context, information technologies are understood as a set of methods, production tools, and software-technological resources integrated into a technological chain ensuring the collection, storage, processing, output, and dissemination of information. Management, in turn, is defined as the deliberate and purposeful informational influence exerted by management entities and bodies on people and objects, aimed at directing their actions and achieving desired outcomes (Elias et al., 2003).

For the identification of various types of risks and the prediction of large-scale landslides, the use of Geographic Information System (GIS) methods proves to be highly effective. Since GIS is a complex integrated system, it adheres to all principles of systems analysis. In systems analysis, a system is understood as a set of elements interconnected in such a way as to form a specific integrity and unity. The effectiveness of GIS in the study and prediction of major landslides is determined by its ability to integrate, on the one hand, with geoinformation collection systems (such as remote sensing, geodetic surveying, and monitoring of the surrounding geological and geoecological environment); on the other hand, with information storage systems (including information retrieval systems, databases, knowledge bases, and expert systems); thirdly, with geoinformation processing systems (such as image processing, modeling, and generalization); and finally, with geoinformation visualization systems (including computer graphics, electronic maps, and the creation of three-dimensional video models and scenarios). The fundamentals and current developments in GIS are presented in the monographs by Kapralov et al. (2005), Lurye (2002), Mitchell (2000), Shaytura and Zhurkin (2009), and others.

Remote methods for the study and monitoring of exogenous processes have been used since ancient times. In the 18th century, the dimensions and spatial positions of objects were determined using drawn images in central projection, obtained with the help of a camera obscura from elevated locations and ships. The next stage in the development of remote methods was marked by the invention of photography, the photographic lens, and the stereoscope. Aerial photographs taken from balloons and kites were highly valued for cartographic purposes. Today, drones equipped with cameras are effectively used to study and monitor the development of landslide processes. However, even this method has certain limitations, specifically the difficulty of maintaining a drone with photographic equipment in a fixed position for extended periods at a stationary point suitable for close-range aerial observation. Remote methods for studying geoecological, engineering-geological, and geotechnical processes are addressed in the monographs by Elias et al. (2003), Izrael (1985), Knizhnikov (1997), Revzon (1992), Korsakov and Korchuganov (2009), Shanda (1990), Kuchko et al. (1997), Ries (2006), Kranberg (1998), and others.

The term "monitoring" and its derivatives are widely used across various fields of knowledge. According to Izrael (1985), "Monitoring is a system of observations that allows for the identification of changes in the biosphere under the influence of human activity (monitoring of anthropogenic changes in the environment)." An invaluable contribution to the development of theoretical and practical methods for monitoring geological and natural-technical systems has been made by Bondarik and Yarg (1990), Parabuchev (1992), Epishin and Trofimov (1985), Korolev (2007), Vinogradov (1984), Hansvind and Lebedev (2010), Shubin (2005), Bezuglova and Motuzova (2007), and others.

Methods

Development of a Cost-Effective Method for Monitoring Large-Scale Landslides in Densely Populated Areas and at Critical Engineering Sites

The authors propose a simplified method of photogrammetric surveying for close-range investigation of large-scale landslide processes. Photogrammetric methods for measuring various parameters characterizing landslide, abrasion, rockfall, and other similar processes share a common feature: direct field measurements of objects are replaced by measurements taken from images of those objects. Mathematical processing of the measurement results allows for the calculation of all required parameters. The advantages of photogrammetric methods over traditional geodetic field measurements include a significant reduction in both the volume and duration of fieldwork, the ability to conduct measurements in hard-to-reach areas where other surveying methods are practically infeasible, the detail and objectivity of the resulting data, and the photographic documentation of the studied objects. High-precision measuring instruments are used for the photogrammetric processing of images. Depending on the method of image processing, rigorous photogrammetric methods are divided into two types:

1. Analytical image processing;
2. Processing using universal stereo photogrammetric instruments.

According to the newly developed method, instead of aerial photography using various types of aircraft, periodic imaging is carried out from elevated points on seismically stable high-rise buildings and structures (such as television towers, chimneys, tall masts, and high-voltage transmission towers) located on adjacent stable areas outside the zone of landslide impact or landslide-prone slopes.

These stable high-rise structures must be situated in close proximity to the landslide-prone area under investigation. Specialized photographic or cinematographic equipment is installed at an accessible elevated point on the stable high-rise structure and is temporarily secured there, operating in a pre-set automatic mode. Photo or video imaging is then conducted, focusing either on specific surface zones of the landslide-prone area or on special markers placed at designated surface points of the active landslide or potentially unstable section. Figure 1 shows a landslide slope (1) in the initial stage of development. Outside the landslide slope (1), on an adjacent stable area (2), a tall radio communication mast (3) is installed. This mast (3) is constructed with consideration for the seismic conditions of the area and is seismically stable. At a designated height on the mast (3), photographic equipment (4) is mounted on a special platform and securely fixed. The camera is directed toward the landslide or landslide-prone area under investigation, where special observation markers (5) may be placed as needed.

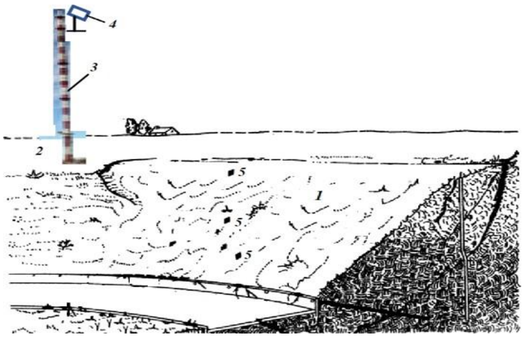

Figure 1

Landslide slope with a tall mast installed on an adjacent stable area, equipped with mounted photographic equipment: 1–landslide; 2–adjacent stable area; 3–tall mast; 4–photographic equipment; 5–observation markers

Variants of the New Method for Monitoring Large-Scale Landslides Using Photography from Stable High-Rise Structures

At a fixed point on a seismically stable high-rise structure, three photo or video cameras can be installed simultaneously to conduct parallel monitoring in the areas of the crown, body, and toe of an active landslide or landslide-prone site. If several stable high-rise structures are present in the vicinity of the active landslide or potentially unstable slope, it is possible to use at least three such structures located in different adjacent zones outside the landslide-affected area for equipment installation. In this case (Fig. ...), photographic equipment for monitoring the crown (2) of the landslide is installed on the first high-rise structure (e.g., a smokestack) (1); equipment for monitoring the body (4) of the landslide is installed on the second high-rise structure (3) (e.g., a multi-story building); and equipment for monitoring the toe (6) of the landslide is mounted on the third high-rise structure (5) (e.g., a power transmission tower). Observation and recording photographic or video equipment may also be mounted on a trolley that can be remotely controlled, moved, and fixed in place along a special metal cable stretched between two stable high-rise structures located in opposite adjacent stable zones of an active landslide or landslide-prone area.

The proposed method can be effectively applied within the landslide forecasting approach developed by Gabibov (2012, pp. 172–173), which studies both pre-landslide and post-landslide processes occurring on landslide-prone slopes. By analogy with earthquake research methods (foreshocks and aftershocks), it has been suggested to refer to pre-landslide slope deformations as *foreslides* and post-landslide deformations as *afterslides* (Gabibov, 2012, pp. 172–173). In the case of cyclic development of landslide processes on unstable slopes, particular interest lies in the transitional phase where afterslides evolve into foreslides. The process remains virtually unexplored and requires a systematic analytical approach. In comparison to traditional aerial photography, the proposed method is significantly simpler, more cost-effective, and enables more accurate monitoring of the dynamics of landslide development due to the possibility of conducting repeated imaging from fixed observation points over different time periods.

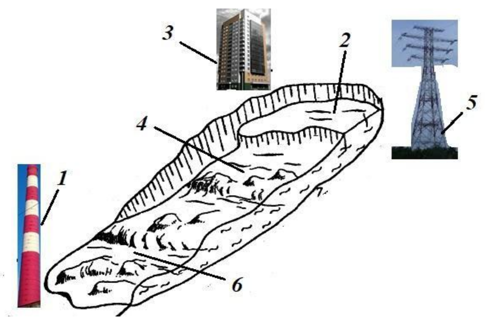

Figure 2

Landslide slope with high-rise structures installed on adjacent stable areas, equipped with mounted photographic equipment: 1–tall smokestack; 2–landslide crown; 3–multi-story building; 4–landslide body; 5–power transmission tower; 6–landslide toe

First, this approach provides the benefit of stationary and relatively low-cost monitoring of landslide progression over extended periods. During this time, periodic imaging of a specified area or surface feature on the landslide slope can be carried out automatically according to a pre-programmed schedule. Photographic equipment installed on high-rise structures can be equipped with automated systems programmed to respond to emergency developments in the landslide process. These systems are capable of sending alerts to operators via mobile or satellite communication networks. The proposed method is characterized by its relative affordability, precision, and accessibility.

Results

The use of Geographic Information System (GIS) methods is highly effective for the identification of various risks and the prediction of large-scale landslides. For the purpose of conducting efficient monitoring of large landslide-prone slopes, it is essential to apply close-range observation methods to the object under investigation. The authors propose a simplified method of photogrammetric surveying for close-range investigation of large-scale landslide processes. According to the newly developed method, instead of aerial photography using various types of aircraft, periodic imaging is carried out from elevated points on seismically stable high-rise buildings and structures located on adjacent stable areas beyond the impact zone of the landslide or landslide-prone slope.

As variations of the proposed method, the following approaches are suggested: installation of three cameras on a single high-rise structure to enable parallel monitoring of the crown, body, and toe zones of the landslide; conducting the same type of observations from three separate nearby high-rise structures; and performing observations using photographic equipment mounted on a trolley moved along and fixed to a special metal cable stretched between two stable high-rise structures located on opposite stable zones of the active landslide area. In comparison to aerial photography, the developed method is significantly simpler, more cost-effective, and enables the acquisition of more accurate information on the dynamics of landslide development, owing to the ability to conduct repeated imaging from stationary points over various time intervals.

Discussion

The proposed method offers an alternative approach to conventional landslide monitoring techniques by combining the advantages of close-range photogrammetry with the stability of fixed observation platforms. Unlike UAV-based surveys, which often require repeated field operations, trained personnel, and favorable weather conditions, the suggested system allows for long-term and continuous observations from stationary locations. This feature is particularly valuable for monitoring slow-moving landslides and detecting subtle deformations that may precede catastrophic failures.

The effectiveness of the method largely depends on the availability and spatial distribution of seismically stable high-rise structures near the landslide-prone area. In urban environments and industrial zones, where such structures are common, the proposed approach may provide a practical and economically feasible monitoring solution. In remote mountainous regions, however, the applicability of the method may be limited unless specially designed towers or support structures are constructed.

Another important advantage of the proposed system is the possibility of automating data acquisition and emergency notification procedures. Integration with mobile communication networks, satellite systems, GIS platforms, and image-processing algorithms may significantly improve the efficiency of landslide early-warning systems. Periodic photographic records obtained from identical observation points also create valuable long-term datasets that can be used for studying the temporal evolution of landslide activity and validating predictive models.

Despite these advantages, several limitations should be acknowledged. The accuracy of displacement measurements may be affected by atmospheric conditions, lighting variations, vegetation cover, and potential movements of the supporting structures themselves. Therefore, regular calibration procedures and verification of the structural stability of observation platforms are essential. Furthermore, additional research is required to quantify the accuracy of the proposed method in comparison with established monitoring techniques such as UAV photogrammetry, terrestrial laser scanning, GNSS observations, and satellite interferometry.

Future investigations should focus on the field implementation of the method in different geological settings and on the development of automated image-processing workflows capable of detecting and interpreting slope movements in near real time. Comparative studies involving multiple monitoring technologies would also contribute to identifying the most effective combinations of methods for specific landslide scenarios.

Overall, the proposed approach represents a promising, accessible, and cost-effective contribution to landslide monitoring practice. By facilitating repeated observations from fixed viewpoints, it has the potential to enhance both scientific understanding of landslide dynamics and the practical management of geohazards in vulnerable areas.

Conclusion

The present study proposes a practical and cost-effective remote method for the long-term monitoring of large-scale landslide processes using stationary photographic equipment installed on seismically stable high-rise structures located outside landslide-prone areas. The proposed method enables repeated observations from fixed viewpoints, providing more reliable information on the temporal dynamics of landslide development than conventional periodic aerial surveys.

The method offers several important advantages, including reduced operational costs, simplified implementation, continuous long-term observations, and the possibility of integrating automated image acquisition with emergency warning systems through mobile or satellite communication networks. The use of multiple observation points or several synchronized cameras further enhances monitoring efficiency and expands the applicability of the proposed approach under different geological conditions.

The developed monitoring concept represents an accessible and reliable alternative to conventional UAV-based surveys, particularly in densely populated areas and around critical engineering infrastructure where permanent monitoring is required. Although further field validation and quantitative accuracy assessment are recommended, the proposed method has considerable potential to improve landslide monitoring, early warning, and geohazard risk management through its simplicity, affordability, and suitability for long-term automated observations.

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Dynamics of Arable Land and Development of Agriculture in Azerbaijan

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Abstract. *The problems related to environmental protection at the international level in recent years and their solutions are presented, and the concept of the "green economy" is discussed in this article. Due to the rapid increase in the world's population, it is reported that, according to UN calculations, the per capita use of the world's natural resources will increase by 70% by 2050. The issue of efficient land use through the effective use of resources in Azerbaijan's agriculture was investigated in the conducted research. It was determined that after 2020, compared to other agricultural crops, the expansion of cotton cultivation areas (7.7% of the total cultivated area) has led to an increase in the ecological load. The total area of fruit and berry orchards was 88.4 thousand ha in 2003, and this indicator reached 222.4 thousand ha in 2022. In other words, it has been determined that the increase in cultivated areas is mainly due to strategic crops such as cereals and legumes. From this point of view, it has been determined that agriculture leads to environmental problems through its negative impacts on sustainable development.*

Keywords: *Azerbaijan's agriculture, "green economy," strategic crops, orchards, ecological capacity*

Introduction

Global economic development, leading to environmental degradation, has created the need to develop new paradigms for sustainable economic growth. The "green economy" is a new model of economic development that includes economic growth, social development, environmental protection, and inclusive development for all. Europe's high-tech economy is considered a leader in the transition to a green economy. Developing countries consider green transformation important but, in many cases, rely on the extraction, processing, and export of raw materials.

These factors make it difficult for these countries to adapt to modern requirements, such as reducing carbon emissions (Blick, 1984; Getmanets & Kudzin, 1979; Mamedov, 2019; Shcherbakov et al., 1983). The "green economy" is an economic system whose main goals are the development of production, environmental protection, and the preservation of the planet's ecology, as well as addressing global problems through the implementation of the "green economy" concept.

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In the conditions of climate change and the transformation of the traditional foundations of economic development, the expansion of the raw material base and opportunities for growth through its widespread application are reduced (Hummatov et al., 2025; Linkina, 1990).

Achieving complete independence in terms of food security is one of the most important goals for Azerbaijan in reaching the level of developed countries. In order to implement this strategy, the existing potential of the country should be evaluated, and the issue should be approached from a scientific-analytical perspective (Mammadov, 2017).

Methods

The conducted research was carried out in accordance with generally accepted methodologies in soil science, ecology, and agrochemistry. The research object covered the agricultural regions of Azerbaijan. The provision of mineral fertilizers for individual crops and the productivity of agricultural plants were determined using the statistical publication *Agriculture of Azerbaijan* (Statistical Publication, 2022, p. 652). The methodological tools were based on *Agrochemical Methods of Soil Research* (Sokolov, 1975).

Results

The analysis of official statistical data showed significant changes in the structure of agricultural land use in Azerbaijan during the last two decades. These changes have directly influenced both agricultural production and the ecological sustainability of the sector. The application of mineral fertilizers remained relatively high during the study period (2018–2022). The total amount of mineral fertilizers varied between 88 and 159 thousand tons, while the average application rate ranged from 47 to 82 kg of active substance per hectare (Table 1). In 2022, 121.8 thousand tons of mineral fertilizers were applied, corresponding to 65 kg ha^{-1}. Cotton cultivation received the highest fertilizer application rate (114 kg ha^{-1}), considerably exceeding cereals (78 kg ha^{-1}), vegetables (72 kg ha^{-1}), orchards (66 kg ha^{-1}), and vineyards (36 kg ha^{-1}). These findings indicate that technical crops, particularly cotton, create a higher agrochemical load on agricultural ecosystems.

The structure of cultivated land also changed considerably during the investigated period. The total cultivated area decreased from 1.738 million ha in 2018 to 1.624 million ha in 2022 (Table 2). Nevertheless, cereals and grain legumes remained the dominant crop group, occupying approximately 986 thousand ha, or about 61% of the total cultivated land, in 2022. Fodder crops occupied approximately 373 thousand ha (23%), while technical crops covered 125 thousand ha (7.7%). Potatoes, vegetables, and melons occupied about 140 thousand ha, representing 8.6% of the cultivated area.

Long-term analysis demonstrated a substantial expansion of perennial plantations. The total area of fruit and berry orchards increased from 88.4 thousand ha in 2003 to 222.4 thousand ha in 2022, representing an increase of approximately 2.5 times. During the same period, vineyard areas increased from 7.7 thousand ha to 14.8 thousand ha. Consequently, perennial plantations currently occupy approximately 237.2 thousand ha, which represents a considerable share of arable land that could potentially be used for strategic cereal production.

A remarkable increase was also observed in technical crop cultivation. Cotton cultivation expanded from 66.8 thousand ha in 2003 to 132.5 thousand ha in 2018, almost doubling within fifteen years. Tobacco cultivation increased from 2.1 to 3.4 thousand ha, while sugar beet cultivation expanded from 3.6 to 8.6 thousand ha (Table 3). Overall, the cultivated area devoted to technical crops increased by approximately 72 thousand ha during the study period.

Changes in crop structure further demonstrated a gradual shift from strategic food crops toward commercial crops. In 2003, cereals and legumes accounted for 63.7% of the total cultivated land, whereas this proportion decreased to 62.3% in 2018 (Table 4). During the same period, the share of technical crops increased from 7.3% to 9.2%. Although the numerical change appears relatively small, the expansion mainly resulted from cotton cultivation, which requires intensive fertilizer application and irrigation, thereby increasing environmental pressure on agricultural ecosystems.

The obtained results indicate that the present structure of agricultural land use does not fully correspond to the principles of sustainable agriculture and the green economy. The rapid expansion of technical crops and perennial plantations has reduced the proportion of strategically important cereal-producing areas while simultaneously increasing fertilizer consumption and ecological pressure. From the standpoint of food security and environmental sustainability, increasing the share of cereals and legumes through the gradual optimization of technical crop and perennial plantation areas would contribute to a more balanced and environmentally sustainable agricultural production system in Azerbaijan.

Discussion

The era of the "green economy" or "green revolution" led to the intensification of agriculture through the mass use of chemical fertilizers and pesticides, the mechanization of agricultural processes, and the genetic improvement of high-yielding crop varieties. It was characterized by a significant increase in the production of cereals such as maize. However, the negative consequences of this revolution have gradually become apparent, as the overall quality of ecosystems has declined due to adverse environmental impacts (Aydınalp, 2005).

Therefore, the main challenge today is to achieve sustainable agricultural development by preserving the integrity of agroecosystems and obtaining stable, high-quality food products through the application of science-intensive innovative technologies in agriculture. The "second green revolution" will depend on the ideas of a new generation of scientists who approach agriculture from a different perspective (Petersburgsky, 1989).

Digital transformation in agriculture, including the application of artificial intelligence for forecasting the dynamics of abiotic and biotic stress factors, has entered all spheres of human activity. This approach makes it possible to predict the spread of pests, assess the influence of climatic factors on their intensity, and prevent epiphytotic outbreaks.

The application of intelligent equipment capable of independently managing fertilizer and growth-stimulant requirements through satellite observation systems based on artificial intelligence technologies, as well as the application of chemicals against pests and diseases, will significantly contribute to increasing productivity and improving product quality in the future (Petersburgsky, 1989).

The use of beneficial microorganisms developed through genetic engineering, agricultural microbiomes, and biological pesticides elevates agricultural development to a new stage. This approach is economically beneficial because it reduces the costs associated with pesticides and fertilizers. For example, the artificial propagation of microorganisms created through genetic engineering can increase crop productivity, improve resistance to unfavorable climatic conditions, and enhance resistance to pests. The supply of mineral fertilizers to agricultural crops has increased during the last five years (Table 1).

Table 1
Providing mineral fertilizers of agricultural crops, 100% account in active substance

Indicators and plants	Years				
	2018	2019	2020	2021	2022
Total, thousand ton	141	159	152	88	122
Kg / ha of crops	72	82	81	47	65
Grain (without corn)	86	89	88	66	78
Cotton	84	127	131	70	114
Tobacco	141	131	137	67	15
Potatoes	81	81	87	49	46
Vegetables and melon	91	96	98	27	72
Fodder plants	35	26	29	9	11
Gardens	63	64	73	40	66
Vineyards	40	51	54	18	36
Specific weight of planting for fertilized areas	84	80	79	66	72

Source. Statistical database. www.stat.gov.az/source/agriculture/

The amount of mineral fertilizers used in agriculture is increasing every year. If the total application of mineral fertilizers, including NPK and other mineral fertilizers, amounted to 141.3 thousand tons (72 kg of active substance per hectare) in 2018, then in 2022 these indicators were 121.8 thousand tons (65 kg ha^{-1}). If we calculate the equivalent amount of manure applied to all cultivated fields, this indicator corresponds to approximately 871.5 thousand tons of manure, containing about 122 thousand tons of organic matter and mineral nutrients (according to the amount of NPK). Taking the above into account, it is considered necessary to prioritize the development of animal husbandry in all regions. The development of agriculture in this direction will have a positive effect on the gradual reduction in the use of mineral fertilizers by ensuring sustainable agricultural development. Furthermore, increasing livestock production and, consequently, the production of organic fertilizers will positively contribute to the transition toward a "green economy" in agriculture.

The indicators for 2022 (Table 2) show that the total cultivated area of the Republic of Azerbaijan was 1.624 million ha. Approximately 986.0 thousand ha (about 61% of the total cultivated area) were occupied by cereals and grain legumes, while 372.8 thousand ha (about 23% of the total cultivated area) were occupied by fodder crops.

Table 2
Agricultural crops in Azerbaijan (th. ha)

Indicators	Years				
	2018	2019	2020	2021	2022
Total cultivated area	1738	1717	1631	1645	1624
Cereals and pulses (total)	1083	1072	989	999	986
Including wheat	679	670	588	572	547
Including legumes	26	17	43	10	12
Technical plants (total)	159	130	122	122	125
Potatoes, melons, and vegetable crops (total)	150	148	144	145	140
Fodder plants (total)	346	367	376	379	373

Source. Statistical database. www.stat.gov.az/source/agriculture/

In the cultivated areas, technical crops accounted for 125.2 thousand ha, while potatoes, vegetables, and melons occupied 140.3 thousand ha, totaling 265.5 thousand ha. Thus, 16.3% of the total cultivated area was occupied by technical crops, potatoes, vegetables, and melons. Taking the above into account, we consider it appropriate to increase the area under cereals and legumes by 265.5 thousand ha through the gradual optimization of areas occupied by technical crops, vegetables, melons, and potatoes, which constitute 16.3% of the total cultivated area, in order to strengthen the sustainable development of agriculture.

On the other hand, the area of fruit and berry orchards in the country was 88.4 thousand ha in 2003, and this indicator increased to 222.4 thousand ha in 2022, according to the State Statistical Committee (Agriculture of Azerbaijan, 2022). The corresponding figures for vineyards increased from 7.7 thousand ha in 2003 to 14.8 thousand ha in 2022, while fruit and berry orchards increased from 88.4 thousand ha to 222.4 thousand ha. Thus, 237.2 thousand ha of land occupied by fruit, berry, and grape plantations (222.4 thousand ha + 14.8 thousand ha = 237.2 thousand ha) could more appropriately be used for cereals and legumes. Therefore, we note that during the last 20 years, the area of fruit orchards has increased almost threefold, while vineyard areas have approximately doubled. The gradual conversion of land occupied by fruit, berry, and vineyard plantations to cereals and legumes would have a positive effect on the sustainable development of agriculture. The area under cotton cultivation was 66.8 thousand ha, tobacco occupied 2.1 thousand ha, and sugar beet covered 3.6 thousand ha in 2003, with a total technical crop area of 72.5 thousand ha. By 2018, these indicators had increased to 132.5 thousand ha, 3.4 thousand ha, and 8.6 thousand ha for cotton, tobacco, and sugar beet, respectively, demonstrating a significant increase in the cultivated area compared with 2003 (Table 3).

Table 3

Plantation areas of agricultural crops, th. ha

Agricultural plants	2003	2013	2015	2016	2017	2018
Cotton	66.8	23.5	18.7	51.4	136.4	132.5
Tobacco	2.1	1.2	1.4	2.4	3.2	3.4
Sugar beet	3.6	5.5	4.9	7.1	13.9	8.6

Source. Statistical database. www.stat.gov.az/source/agriculture/

This increase amounted to 65.7 thousand ha for cotton, 1.3 thousand ha for tobacco, and 5.0 thousand ha for sugar beet. It was determined that the total increase in the cultivated area of technical crops reached 72.0 thousand ha in 2018. The total cultivated area under technical crops was 144.5 thousand ha in 2018. Thus, using 144.5 thousand ha of arable land currently occupied by technical crops for cereals or legumes is considered more favorable from the viewpoint of food security. According to the 2003 data, cereals and legumes accounted for 63.7% of the cropping structure, while technical crops accounted for 7.3%. However, different results were obtained in 2018. Thus, the cultivated area of strategic crops (cereals and legumes) decreased by 1,400 ha and reached 62.3% of the total cultivated area. The area under technical crops increased by 2,000 ha in 2018 compared with 2003 and reached 9.2%, which is considered unfavorable from the standpoint of food security (Table 4).

Table 4
The structure of cultivated areas, %

Agricultural plant groups	2003	2013	2015	2016	2017	2018
Cereals and legumes (total)	63.7	63.8	60.1	61.3	58.7	62.3
Technical plants	7.3	2.5	2.4	4.5	10.8	9.2
Fodder plants	15.5	23.5	27.0	24.2	21.4	19.9
Potatoes, vegetables and melon plants	13.5	10.2	10.5	10.0	9.1	8.6

Source. Statistical database. www.stat.gov.az/source/agriculture/

From this point of view, it is considered more appropriate to expand the cultivated areas of cereals and legumes as strategic agricultural crops at the expense of technical crops. In 1998, 2,032 collective farms and state farms were reformed. As a result of the reform, land shares were distributed to 869,268 families. In addition, in cities and towns where land reform has not been carried out, as well as in summer cottage areas and garden plots, land has been used to a certain extent for the production of fruit and vegetable crops as household plots.

Conclusion

The following activities are considered essential for the sustainable development of agriculture:

- Scientific and practical support for the transformation processes in agriculture and rural habitats; systematic interdisciplinary research for sustainable development; and personnel training.
- Development of methodologies for program formation in agriculture and its sectors at the state, regional, and municipal levels.
- State measures for the resocialization of research methods in the agricultural economy and the reassessment of the agricultural, recreational, cultural, and gastronomic potential of rural areas in Azerbaijan, thereby increasing the value of agricultural products.
- Research on food trade and scientific research expeditions within the framework of rural heritage study programs.

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Establishment and Development Prospects of the Land Cadaster Database in the Qazakh District within the Context of Technical Research

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Abstract. *This article examines the establishment of a land cadaster database within the territory of the Qazakh District, emphasizing its legal, economic, and environmental significance, as well as the application of digitalization and GIS technologies. The study analyzes the classification of land categories, cadaster registration of state-owned and special-purpose lands, the implementation of satellite and drone-based monitoring systems, and the prospects for integration with electronic government platforms. The research substantiates the strategic importance of a digital cadaster system for improving land administration and ensuring sustainable land resource management.*

Keywords: *land cadaster, GIS technologies, land administration, digital mapping, satellite monitoring, NDVI index, land resources, Qazakh District*

Introduction

The establishment of a land cadaster database within the territory of Qazakh District constitutes a fundamental mechanism for the legally, economically, and environmentally efficient management of land resources (Dale & McLaughlin, 1999; Williamson et al., 2010). Land distribution across the district has been carried out in accordance with the Land Code of the Republic of Azerbaijan and the Law "On the State Land Cadaster," whereby lands are classified into state, municipal, and private ownership categories. State-owned lands account for approximately 26–28% of the total land fund and mainly include forest and water reserves, specially protected areas, defense territories, and infrastructure-designated lands. In particular, the territories surrounding the Aghstafachay Reservoir and Jandargol Lake represent a significant component of the state land fund.

Cadaster registration of state-owned lands is conducted through a unified GIS-based system incorporating data on land category, parcel size, legal status, land-use type, and environmental indicators (Burrough & McDonnell, 1998; Longley et al., 2015). This system enables the precise delineation of land boundaries, the prevention of illegal land use, and the enhancement of environmental monitoring processes. Special-purpose lands, constituting approximately 6–8% of the total land fund, include defense facilities, energy and transport infrastructure, melioration systems, and industrial zones (Dale & McLaughlin, 1999; Williamson et al., 2010).

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The principal challenges associated with this category involve legal ambiguities, insufficient boundary demarcation, coordinate inconsistencies, and weak data integration among various governmental institutions. In particular, archival documents and outdated topographic maps inherited from the Soviet period are often incompatible with modern GPS measurements, which negatively affects the accuracy and reliability of cadaster data (Longley et al., 2015).

Methods

The study is based on GIS-based spatial analysis, remote sensing data, and cadastral documentation (European Space Agency, 2015; USGS, 2019). Satellite imagery from Sentinel-2 and Landsat, together with drone-based topographic surveys, was used to update and verify land boundaries. GIS technologies were applied to integrate spatial and legal datasets into a unified geodatabase. This system enables land classification, parcel identification, and environmental monitoring (Burrough & McDonnell, 1998; Longley et al., 2015). Spatial analysis techniques were used to evaluate land-use distribution, ownership structure, and ecological indicators (Haining, 2003).

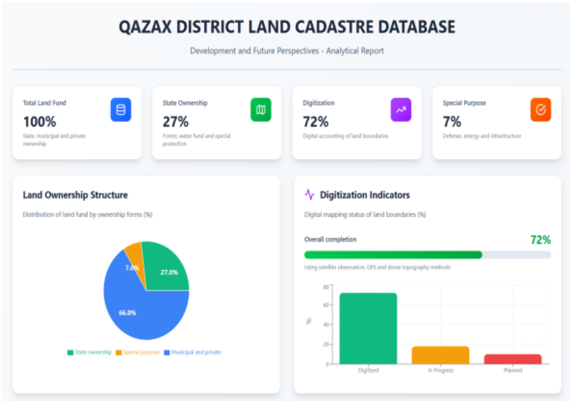


Figure 1

Land cadastre database of the Qazakh District

Results

In recent years, more than 70% of land boundaries have been digitized through the application of digital cartography, satellite observation technologies (Sentinel-2 and Landsat), and drone-based topographic surveying methods. Although this approach has significantly improved the accuracy and transparency of the cadaster system, the comprehensive integration of spatial and legal data remains a priority area for further development (European Space Agency, 2015; USGS, 2019; Weng, 2012).

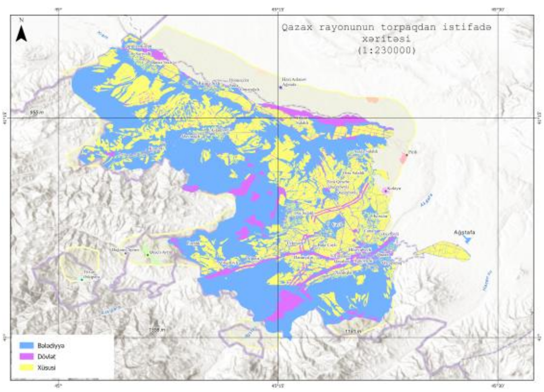


Figure 2

Analysis of land ownership structure in the Qazakh District

The cadastral map presented in Figure 2 illustrates the distribution of land ownership categories within the territory of the Qazakh District. According to the spatial analysis, municipal lands occupy the largest share of the district and are widely distributed throughout both lowland and foothill areas. Private lands are concentrated mainly in agricultural zones and settlement surroundings, reflecting the dominant role of agriculture in the local economy. State-owned lands are primarily located in environmentally sensitive territories, water protection zones, infrastructure corridors, and areas designated for strategic public purposes. The spatial distribution of ownership categories demonstrates the importance of maintaining an up-to-date cadastral database for effective land administration. Digital mapping allows authorities to identify ownership boundaries accurately, reduce land-related disputes, and improve the management of state and municipal assets (Dale & McLaughlin, 1999; Williamson et al., 2010). The integration of ownership information with GIS technologies further enhances transparency and supports sustainable land-use planning (Burrough & McDonnell, 1998; Longley et al., 2015).

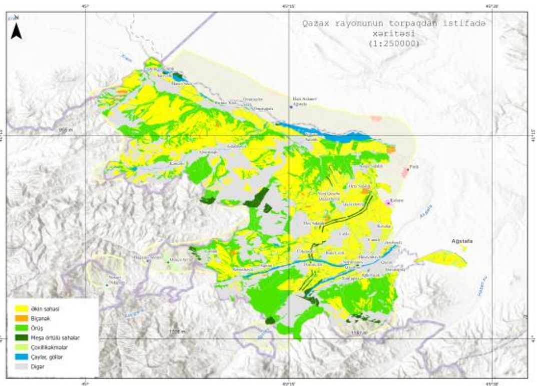


Figure 2

Spatial distribution of land use types in the Qazakh District

Land Use Analysis Based on GIS Mapping. Figure 3 presents the land-use structure of the Qazakh District derived from GIS-based spatial analysis. Agricultural lands constitute the dominant land-use category, with extensive areas occupied by arable fields and pasturelands. These territories form the foundation of the district's agricultural production and significantly contribute to regional economic development. The map also indicates the presence of forest-covered areas, perennial plantations, water bodies, and other land-use categories. The spatial distribution of these resources highlights the diversity of land functions within the district and emphasizes the necessity of balanced land management practices. GIS-based land-use mapping provides valuable information for assessing environmental conditions, monitoring land degradation processes, and planning future agricultural development. Furthermore, the integration of satellite imagery and remote sensing data into the cadastral database enables continuous monitoring of land-use changes. Such an approach supports evidence-based decision-making and contributes to the sustainable utilization of natural resources in the Qazakh District.

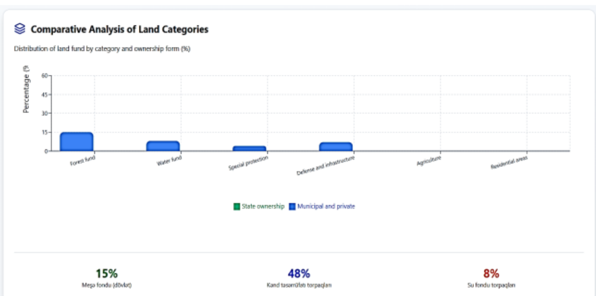


Figure 3

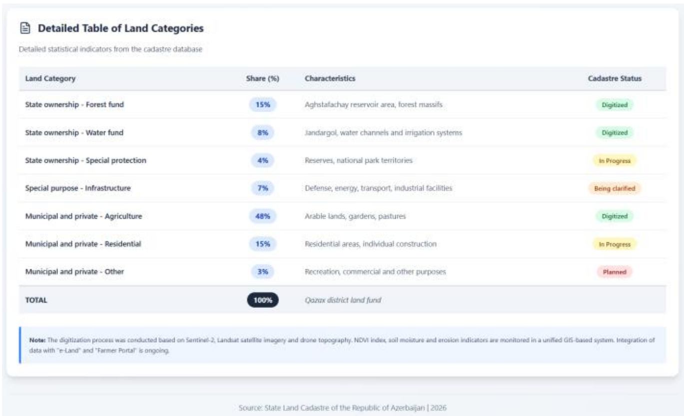
Comparative analysis of land categories in the Qazakh District

Discussion

Application of GIS Technologies in the Land Cadaster System

The implementation of Geographic Information Systems (GIS) has become one of the most significant factors in the modernization of land cadaster databases. GIS technologies facilitate the collection, storage, analysis, and visualization of spatial information related to land resources (Burrough & McDonnell, 1998; Longley et al., 2015). Within the territory of the Qazakh District, the application of GIS enables the integration of cadastral maps, satellite imagery, topographic surveys, and legal documentation into a unified digital environment.

One of the primary advantages of GIS-based cadaster systems is the ability to update land information in real time (Weng, 2012). Through geospatial databases, specialists can identify changes in land use, detect unauthorized occupation of land parcels, and monitor environmental conditions more efficiently than with traditional paper-based systems. In addition, GIS technologies support decision-making processes by providing analytical tools for land-use planning, agricultural development, infrastructure expansion, and environmental protection. The creation of digital cadastral layers also contributes to reducing administrative costs and increasing institutional efficiency. Landowners, municipal authorities, and governmental agencies gain faster access to reliable information, thereby minimizing bureaucratic procedures. Furthermore, GIS technologies improve transparency in land management by ensuring that spatial information is accessible and verifiable. For the Qazakh District, where agricultural production constitutes an important component of the local economy, GIS applications can significantly improve land productivity assessments and resource allocation (FAO, 1993). The integration of remote sensing data with cadastral records allows for the identification of suitable agricultural zones, the monitoring of crop conditions, and the evaluation of environmental risks affecting land resources (Mather & Koch, 2011; Smith & Jones, 2010).



Detailed Table of Land Categories

Detailed statistical indicators from the cadastre database

Land Category	Share (%)	Characteristics	Cadastre Status
State ownership - Forest fund	15%	Aghstafachay reservoir area, forest massifs	Digitized
State ownership - Water fund	8%	Jandargol, water channels and irrigation systems	Digitized
State ownership - Special protection	4%	Reserves, national park territories	In Progress
Special purpose - Infrastructure	7%	Defense, energy, transport, industrial facilities	Being clarified
Municipal and private - Agriculture	48%	Arable lands, gardens, pastures	Digitized
Municipal and private - Residential	15%	Residential areas, individual construction	In Progress
Municipal and private - Other	3%	Recreation, commercial and other purposes	Planned
TOTAL	100%	*Qazax district land fund*	

Note: The digitization process was conducted based on Sentinel-2, Landsat satellite imagery and drone topography. NDVI index, soil moisture and erosion indicators are monitored in a unified GIS-based system. Integration of data with "e-Land" and "Farmer Portal" is ongoing.

Source: State Land Cadastre of the Republic of Azerbaijan | 2026

Figure 4

Detailed table of land categories in the Qazakh District

Future development of agricultural lands should be oriented toward digital integration, agroecological mapping, bonitet zoning, and the automation of land valuation processes. Through satellite- and drone-based monitoring, the assessment of NDVI indices, soil moisture levels, and erosion indicators will transform the land cadaster from a purely legal registry into an analytical and predictive management system. At the same time, the integration of land-related data with electronic government platforms such as “e-Torpaq,” the “Farmer Portal,” and other digital governance systems will enhance transparency in land circulation processes while optimizing taxation and subsidy mechanisms (Mather & Koch, 2011). In conclusion, the establishment and modernization of the land cadaster database in the Qazakh District are of strategic importance in terms of strengthening legal reliability, increasing economic efficiency, and ensuring environmental sustainability. As a result of digitalization and enhanced institutional coordination, land administration within the district is expected to evolve into a more systematic, transparent, and scientifically grounded management model (Dale & McLaughlin, 1999; Williamson et al., 2010).

Conclusion

Socio-Economic Benefits of a Digital Land Cadaster

The establishment of a comprehensive digital land cadaster database generates substantial socio-economic benefits for both governmental institutions and local communities. Accurate cadastral information contributes to the development of an effective land market by ensuring legal certainty in property ownership and facilitating secure real estate transactions. As a result, investment opportunities increase, and land-related disputes are significantly reduced. From an economic perspective, the availability of reliable cadastral data improves the efficiency of land taxation systems. Local authorities can calculate land taxes more accurately, while state institutions can better assess land values and manage public assets. Digital cadastral systems also support agricultural subsidy programs by enabling the verification of land ownership and land-use patterns. Environmental sustainability represents another important benefit of modern cadastral databases. By integrating ecological indicators, soil quality assessments, and monitoring data, decision-makers can identify environmentally sensitive areas and implement appropriate conservation measures. Such an approach supports sustainable land management principles and contributes to the long-term protection of natural resources (FAO, 1993; Williamson et al., 2010). In the context of regional development, the digitalization of land administration strengthens cooperation among governmental agencies, municipalities, and private stakeholders. The use of interoperable databases and electronic services accelerates information exchange and enhances the quality of public services. Consequently, the land cadaster evolves beyond its traditional registration function and becomes an essential component of modern territorial governance and sustainable development policies.

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Comparative Analysis of Soil Temperature-Moisture Regime and Hydrothermal Potential (HTP) in Different Ecosystems

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Abstract. *In the brown mountain-forest soils of the Greater Caucasus, the formation features of the hydrothermal potential of the soil environment under different ecosystems (forest, xerophytic forest, and meadow) were studied. The research was aimed at determining the regularities of temperature and moisture changes along the profile in the 0–20 cm soil layer. The impact of vegetation cover on the dynamics of soil temperature and moisture, and consequently on the formation of hydrothermal potential, was evaluated. The purpose of the study was to identify the influence of vegetation cover on the formation of the hydrothermal potential of the soil environment and to assess the functional characteristics of soil cover under various ecological conditions. The obtained results are significant for the study of soil processes in mountain-forest ecosystems, the evaluation of soil fertility, and the improvement of ecological monitoring systems.*

Keywords: *hydrothermal potential (HTP), temperature regime, moisture regime, brown mountain-forest soils, forest ecosystem, meadow, xerophytic forest*

Introduction

The diversity of hydrothermal regimes in ecosystems composed of different plant formations is undeniable, since the moisture requirements of herbaceous, shrub, and tree species are closely related to their biomass, the shape of leaves, and the size and structure of the evaporative surface of their vegetative organs. Therefore, the coexistence of different ecosystems is possible under conditions where soil environments with varying degrees of moisture supply exist within the annual cycle. In other words, within the hydrothermal limits of the soil environment, the theoretical basis for the formation of any ecosystem with specific vegetation cover is the natural harmony between the hydrothermal regime and the plant's requirements.

Daily, seasonal, and global fluctuations of temperature indicate that the inflow of energy into the soil occurs in a variable regime. This requires evaluating processes according to the potential and duration of energy entering the soil. Since the rise in temperature during the day is accompanied by the loss of soil surface moisture, the opposite process—soil moistening—is asynchronously related to cooling (Suleymanov et al., 2011). It should be noted that these processes manifest more sharply in areas with high continentality, while in other regions they are observed on a relatively smaller scale. In mountainous areas, these features are permanent due to differences in vegetation cover across relief exposures, making their study and explanation scientifically significant and relevant.

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Thus, 95–99.5% of the energy spent on soil formation is used for evaporation and total transpiration. Consequently, the efficiency of energy entering the soil directly depends on the degree of soil moistening; in other words, the soil's thermal regime is closely linked to its moisture regime. The most general regularities of soil distribution on Earth are determined by the combined influence of moisture and temperature. Recently, the main direction in the development of soil science and soil physics has been the study of elementary areas and polypedons using methods based on quantitative indicators (Shikhalibeyli, 1956).

In nature, without fundamental changes in the hydrothermal regime, which is a limiting factor in soil formation, there cannot be a change of vegetation (reforestation, afforestation, desertification), processes that occur continuously, in close correlation with the first (Hasanov, 1979, 1981; Suleymanov, 2009). To determine the dependence of soil cover on hydrothermal conditions, various coefficients have been used. This was done to identify correlations between the thermal and moisture regimes of different soil types. The coefficients expressing these relationships are called hydrothermal coefficients (Alizade, 2025; Dobrovolsky & Urusevskaya, 2004). From the above, it can be concluded that all processes occurring under the influence of climatic factors are limited by soil moisture and temperature indicators. In this case, the use of soil moisture and temperature as limiting factors is theoretically acceptable. Studying the relationship between soil moisture and temperature and the elementary soil processes and microprocesses involved in soil formation is one of the main problems facing modern soil science (Suleymanov, 2009a, 2009b). In the soil–plant system, water plays a regulatory role. The volume of water and the energetic state of moisture in the soil environment determine the rate of soil–biological processes, soil development, and phyto-climatic ratios (Suleymanov, 2009).

The formation of the soil temperature regime is influenced by many factors: vegetation cover, snow cover, lithological composition, humus content, etc. Since the amount of solar radiation flux depends on slope exposure, the structure and density of the vegetation layer and the length of the growing season determine the living conditions of soil fauna (Shulgin, 1957; Elizbarashvili et al., 2010; Eyubova, 2010). The aim of the study is to determine and provide a comparative characterization of the hydrothermal potential (HTP) of soil profiles in different ecosystems and landscape elements of the brown mountain forest soils of the southern slope of the Greater Caucasus, using modern digital mobile devices.

Methods

The object of research is selected from the southern slope of the Big Caucasus, an area with brown mountain-forest soils. Administratively, the territory is subject to the Ismayilli region. The area is situated at an altitude of 700–850 m and above. The location terrain is favorable for the development of deciduous relict forests and grass and trees and shrubs, and is closely correlated with the distribution of hydrothermal resources and the spatial and temporal position of the relief elements. The characteristics of the areas where mountain-forest brown soils are received in separate areas, the development of herbaceous, xerophytes, deciduous, and mesophyll's forests (Fig. 1). To identify existing differences, it is necessary to use a parameter, giving the opportunity to evaluate digital local deviations from the statistical indicators and exceptions. From the point of view of the above, an acceptable option is the hydrothermal potential of the soil medium-HTP, proposed by the author, expressing the dialectical integrity of natural processes, or reversible processes occurring in the soil environment in native under different ecosystems in the space-time format.

Figure 1
General view of systems and elements of the landscape mountain-forest brown soils

Theoretically, it is possible to redistribute climatic factors under the effective influence of local requirements (Suleymanov et al., 2010; Suleymanov, 2012). HTP provides an overview of reversible processes in the soil environment, but the genetic function of the parameter does not allow a clearer differentiation of reference for studies of meso-level terrain.

Results

The hydrothermal potential (HTP) of brown mountain forest soils varied considerably among the three investigated ecosystems, reflecting differences in vegetation cover, soil temperature, and moisture regimes. The obtained results demonstrate that vegetation significantly modifies the redistribution of heat and moisture within the soil profile, resulting in distinct hydrothermal conditions. In the mesophytic forest ecosystem, soil temperature increased gradually with depth from 10.21°C at 5 cm to 25.41°C at 20 cm. Soil moisture also showed a consistent increase from 20.33% to 43.76% along the profile. Consequently, HTP values increased from 58 snr in the upper layer to 548 snr at 20 cm depth, with a weighted average value of 385 snr for the 0–20 cm soil layer. The structural coefficient (Kst) remained relatively stable, varying between 0.6 and 0.8.

In the xerophytic forest ecosystem, the soil temperature exhibited an opposite pattern, decreasing with depth from 39.3°C in the upper layer to 21.2°C at 30 cm. In contrast, soil moisture increased substantially, reaching 58.4% at 20 cm depth. Water reserves also increased markedly below 10 cm, indicating the accumulation of subsurface moisture. The hydrothermal potential ranged from 187 to 742 snr within the 0–20 cm profile, while the average HTP reached 485 snr, representing the highest value among the investigated ecosystems. Under meadow vegetation, soil temperature gradually decreased from 27.73°C to 22.00°C with increasing depth, whereas soil moisture increased from 18.14% to 38.64%. The maximum HTP value (465 snr) occurred at a depth of 10–15 cm rather than at 20 cm, indicating a different vertical distribution of hydrothermal resources compared with forest ecosystems. The weighted average HTP for the meadow ecosystem was 362 snr. Comparison of the three ecosystems revealed clear differences in the distribution of hydrothermal potential throughout the soil profile. The annual average HTP values followed the order:

Xerophytic forest (485 snr) > Mesophytic forest (385 snr) > Meadow (362 snr)

The amplitude of HTP variation also differed among ecosystems, amounting to 555 snr in xerophytic forest soils, 490 snr in mesophytic forest soils, and 298 snr in meadow soils. These differences indicate that vegetation cover strongly regulates the redistribution of soil heat and moisture and consequently controls the formation of hydrothermal potential. Polynomial regression analysis showed that the HTP curves of all ecosystems had similar sinusoidal patterns despite differences in absolute values. The regression models demonstrated excellent agreement with the observed data (R^2

≈ 1.0), confirming the reliability of the calculated hydrothermal potential and its suitability for describing the hydrothermal state of brown mountain forest soils under different vegetation covers.

Discussion

The results of the study on the role of vegetation cover in the formation of hydrothermal potential show that the HTP formed in the forest understory brown mountain forest soils differs from the potential existing in other landscape elements. Distinguishing features include the rate, character, direction, and stages of soil-forming processes, which depend on the vegetation cover shading the soil in arid regions, the slope of the relief, and its exposure—local factors that must be taken into account. Table 1 presents the three-year average statistical indicators of fertility, moisture, and HTP elements that form the forest understory brown mountain forest soil type. The main indicator of the landscape is the slope direction, which is north and northwest, with an inclination of ≥ 19.4°. Research carried out in the experimental area (directly measured in field conditions using digital devices) shows that forests are distributed on slopes with an inclination greater than 19°, starting from elevations of 780–800 m.

Table 1
Annual average statistical indicators of HTP and K_{st} formed in forest-understory brown mountain-forest soils

Depth, cm	Soil temperature, °C	Moisture, %	Water content, mm	HTP, snr	K_{st}	Humus, %
3	11,73	20,33	6,46	76	0,6	7,53
5	10,21	22,93	5,64	58	0,6	7,53
10	22,77	38,31	18,64	424	0,8	4,84
15	24,50	41,12	20,33	498	0,8	-
20	25,41	43,76	21,59	548	0,8	-
0-20 cm	20,95	36,1	16,67	385	0,8	4,30

The average statistical value of soil temperature (at the 20 cm layer) fluctuates between 10.21–25.41 °C. In general, it shows an increasing tendency and is synchronous with moisture. Other soil parameters and indicators along the profile have the character of an increasing function, with the only exception observed in the distribution of humus, which corresponds to the general theory of fertility. The HTP formed in forest understory brown mountain forest soils has a fluctuating interval of 58–548 snr across the calculated layers, with the maximum value at a depth of 20 cm and the minimum at a depth of 5 cm. The average statistical limit of the ecosystem is equal to 385 snr. Table 2 presents the three-year average statistical indicators of fertility, moisture, and HTP elements that form the forest understory brown mountain forest soil type.

From the table, it is clear that, unlike the forest ecosystem, under xerophytic forest cover the soil temperature decreases along the profile from top to bottom. This decrease is slightly more than 18 °C. The temperature range is 21.2–39.3 °C. In the 0–20 cm layer, the average statistical temperature determined by the weighted average method is equal to 30.2 °C. Moisture along the profile has the character of an increasing function, varying within the interval of 23.4–58.4%. Moisture reserves are very small in the upper layers; below 10 cm they amount to 15–20 mm, while at depths of 20 cm a sharp increase is observed. This situation indicates the occurrence of "verxovodka" (near-surface intra-soil flow), which causes transformation and sliding in the landscape.

Table 2

Annual average statistical indicators of HTP and K_{st} formed in xerophytic forest soils

Depth, cm	Soil temperature, °C	Moisture, %	Water content, mm	HTP, snr	K_{st}	Humus, %
3	39.3	23,4	7.43	292	0.2	-
5	34.9	25,3	5.36	187	0.2	4.84
10	31.8	28,4	15.04	478	0.5	3.76
15	27.6	32,2	17.05	471	0.6	-
20	24.0	58,4	30.92	742	1.3	-
30	21.2	58,1	61.53	1304	2.9	-
0-20 cm	30.2	35,8	17,40	485	0,6	4,30

Under xerophytic forest cover, the HTP formed in brown mountain-forest soils fluctuates within the boundaries of 187–742 snr across calculated layers, with the maximum value at a depth of 20 cm (742 snr) and the minimum at a depth of 5 cm (187 snr). The average statistical limit of the ecosystem is equal to 485 snr. Compared to forest-understory brown mountain-forest soils, the HTP formed in this landscape element is 100 snr higher. This means that the forest ecosystem assimilates HTP more rapidly within a shorter time interval, so the residual potential is fixed at a lower level.

Table 3 presents the distribution by depth of HTP and soil indicators formed under mixed grass (belonging to the wormwood-ephemeral family) vegetation cover. As seen from the table, the three-year average statistical indicators of soil temperature and moisture respectively have decreasing and increasing functional characteristics. The fluctuation of soil temperature in the 20 cm soil layer has a lower boundary of 22.0 °C, amounting to 5.7 °C, while the dynamics of moisture have an upper boundary of 38.64%, amounting to 20.5%. Moisture reserves below the 10 cm soil layer increase threefold compared to the upper layer. The reason for the low moisture in the upper layer is that the root system of herbaceous plants is mainly distributed at this depth and uses the incoming water reserves. The average statistical limit of the ecosystem is equal to 362 snr. The interval of HTP variation is 146–465 snr, with the lowest value observed in the upper layers and the highest value at a depth of 15 cm. As can be seen, the HTP formed in the meadow-understory soil environment differs from forest and xerophytic forest ecosystems mainly in terms of the depth at which the maximum potential is located. While in other areas the maximum HTP was located at a depth of 20 cm, under meadow cover it is established at a different point.

Table 3

Annual average statistical indicators (3-year) of HTP and K_{st} formed in meadow-understory brown mountain-forest soils

Depth, cm	Soil temperature, °C	Moisture, %	Water content, mm	HTP, Snr	K_{st}	Humus, %
3	27,73	18,14	5,76	160	0,2	3,85
5	26,02	23,78	5,62	146	0,2	3,23
10	24,34	38,47	19,09	465	0,8	-
15	23,21	38,64	19,13	444	0,8	-
20	22,00	35,43	17,46	384	0,8	-
0-20 cm	24,15	33,2	15,35	362	0,7	3,32

In Figure 2, the HTP curves formed in the soil environment of different ecosystems constituting the landscape are presented. Analytical analysis of the quantitative indicators of the HTP parameter shows that the annual average value of brown mountain-forest soils, determined by the weighted average method, fluctuates within the closed interval [362÷485]. The HTP value for meadow ecosystems varies within [146÷465 snr], in xerophytic forests within [187÷742 snr], and in mesophytic forests within [58÷548 snr]. The fluctuation amplitude is respectively equal to 298, 555, and 490 snr.

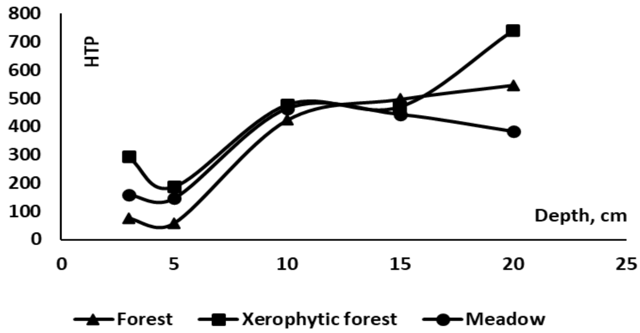

Figure 2
Comparison of HTP curves formed in the soil environment of different brown mountain-forest ecosystems

The general comparison shows that the curves have an arbitrary form with a sinusoidal character. The fact that the regression equations of the curves, which possess three maxima and two minima, have approximation coefficients at the maximum level indicates that the adequacy of the equations carries functional significance.

The following equations respectively express the polynomial curves characterizing the soil environments (0–20 cm) of meadow, xerophytic forest, and mesophytic forest ecosystems:

$$y = 0{,}1849x^4 - 8.5113x^3 + 127{,}49x^2 - 652{,}87x + 1148{,}6 \quad (1)$$

$$y = 0{,}1522x^4 - 6{,}8408x^3 + 104{,}1x^2 - 591{,}62x + 1302{,}4 \quad (2)$$

$$y = 0{,}1013x^4 - 4{,}8981x^3 + 79{,}01x^2 - 437{,}83x + 838{,}46 \quad (3)$$

In the brown mountain-forest soil type, the approximation coefficient of the equations being equal to one indicates that the adequacy of the mathematical models is at the maximum level. The synchronicity of the polynomial curves, their having the same amplitude, and the close correlation of quantitative indicators show that they fall within the HTP limits of the brown mountain-forest soil type. As a conclusion of the research, it should be noted that the determination of HTP makes it possible to record and monitor, in a point-based multiparametric format, the dynamics of the potential existing in the soil—namely, the sum of moisture and temperature—within any arbitrary soil layer and genetic horizon in space and time, through a digital parameter that meets the requirements of the “soil-moment” principles. According to N.R. Suleymanova, HTP represents a methodological approach that is “fair both to the natural world, to the interactions between humans and nature, and in general to the process of understanding,” in line with V.R. Volobuyev’s emphasis on a systematic approach in comprehending natural processes (Volobuev, 1981).

Conclusion

1. In different landscape elements of the Greater Caucasus brown mountain-forest soils, under various vegetation covers (mesophytic and xerophytic forests, meadow), the elements of the soil hydrothermal potential (HTP) and the structural coefficient of the potential (Kst) have been determined at the elementary area level in a micro-caten format.

2. It has been established that the annual average statistical natural hydrothermal potential (HTP) limits of brown mountain-forest soils fluctuate within the closed interval of 362–485 snr, and the HTP formed in brown mountain-forest soil environments developed under meadow, mesophytic, and xerophytic forest ecosystems has been determined respectively at 362, 385, and 485 snr.
3. The differences in HTP under various vegetation covers (23, 123, 100 snr) are regulated by the water demand of the plants forming the ecosystem, the density of vegetation cover, the level of transpiration, the slope of the relief, and finally the exposure, thereby identifying local features that correct the influence of abiotic factors.
4. As a conclusion of the research, it should be noted that the determination of HTP provides the opportunity to record and monitor, in a point-based multiparametric format, the dynamics of soil moisture within any arbitrary soil layer in space and time, through a digital parameter that meets the requirements of the "soil-moment" principles.

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Soil Fertility Indicators of Forest Ecosystems in the Shaki District of the Southern Greater Caucasus Slope

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Abstract. *Forest ecosystems of the Sheki district on the southern slope of the Greater Caucasus play an important role in biodiversity conservation, regulation of water resources, and prevention of soil erosion. The fertility indicators of forest soils in the Sheki district, one of the main forested areas of the southern slope of the Greater Caucasus, were evaluated. During the study, soil samples were collected from different altitudinal zones of the area, and their physicochemical properties, including humus content, pH, total nitrogen, available phosphorus, exchangeable potassium, and soil texture, were analyzed. The results of the research showed that the forest soils of the region possess relatively high organic matter reserves and favorable physical properties. The observed variations in soil fertility indicators were mainly associated with altitude, vegetation cover, and relief conditions. The obtained findings contribute to a better understanding of the formation characteristics of soil fertility in mountain forest ecosystems and provide a scientific basis for sustainable forest management.*

Keywords: *forest soils, soil fertility, humus, nutrients, Greater Caucasus, Sheki district, Azerbaijan*

Introduction

The forest soils of the southern slope of the Greater Caucasus are an important component of mountain ecosystems, influencing forest productivity, biodiversity conservation, and soil fertility (Mammadov, 1998; Mammadov & Khalilov, 2002)**.** The diverse climatic conditions and rich forest vegetation of the southern slope of the Greater Caucasus have contributed to the development and enrichment of brown mountain-forest and dark brown mountain-forest soils in the region (Mammadov, 1998; FAO, 2022; Mammadov & Khalilov, 2002). In this respect, the Sheki district occupies a significant position due to its extensive forest resources and complex topography (Mammadov, 1998; FAO, 2022)**.**

Soil fertility is formed through the complex interaction of physical, chemical, and biological factors (FAO, 2019; Khar'kina, 2017; Kovda, 2011)**.** The assessment of fertility indicators enables the determination of soil quality and provides insight into the processes of forest soil formation within mountain forest ecosystems (FAO, 2022; Khar'kina, 2017; Soil Atlas of the Republic of Azerbaijan, 2007)**.** Therefore, the study of the fertility characteristics of forest soils in the Shaki district is of great importance from both scientific and practical perspectives (Huseynova, 2007; Mammadov & Khalilov, 2005).

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Methods

The study area covers the Shaki district located on the southern slope of the Greater Caucasus. The region is characterized by mountainous terrain, elevations ranging from approximately 500 m to over 2,500 m above sea level, and a moderately humid climate. The dominant vegetation consists of broad-leaved forests composed mainly of Oriental beech (Fagus orientalis), Georgian oak (Quercus iberica), Caucasian hornbeam (Carpinus caucasica), and other tree species. The predominant soil types in the study area are brown mountain-forest soils and dark brown mountain-forest soils. These soils provide favorable conditions for the development of forest ecosystems and are distinguished by their high biological activity (FAO, 2022; Mammadov & Khalilov, 2002). Studies conducted to assess the fertility indicators of soils in the Sheki district on the southern slope of the Greater Caucasus have revealed significant changes in the upper and lower boundaries of forest distribution. The lower forest boundary has been consistently exposed to anthropogenic impacts. In the past, the mountain-forest soils of the region were predominantly covered by low-growing oak forests and, to a lesser extent, hornbeam–oak forests (Baghaee et al., 2020; FAO, 2019; Khar'kina, 2017). The forests of the region play an important role in soil conservation and the protection of water resources. However, parts of these forests have been cleared by local populations and converted into agricultural lands. Owing to the favorable conditions for the completion of the growing season of agricultural crops in the plains and foothill zones of the Shaki district, cultivated areas have expanded onto former forest lands (Huseynova, 2007; Mammadov & Khalilov, 2002).

The gradual destruction of forests, which were once rich in vegetation, has led to the weakening of water resources and the intensification of soil erosion on sloping terrains. Consequently, a dual challenge has emerged: on the one hand, there is a growing need to ensure the conservation and sustainable development of forests, while, on the other hand, the demand for agricultural production and the cultivation of crops remains an important socioeconomic issue (Mammadova, 2022; Mammadov & Khalilov, 2005).

Results

Five representative soil profiles established within the forest ecosystems of the Sheki district were analyzed to evaluate the fertility status of mountain forest soils. The investigated soils included leached brown mountain-forest soils, carbonate brown mountain-forest soils, forest-derived brown soils, and steppe-affected brown mountain-forest soils distributed under different vegetation communities and elevation zones. The results demonstrated considerable variation in soil fertility indicators among the investigated profiles and soil horizons (Table 2). Humus content ranged from 0.85% to 4.48%. The highest humus concentration was recorded in the surface horizon (0–11 cm) of Profile 5 (4.48%), whereas the lowest value (0.85%) occurred in the 62–90 cm layer of Profile 1. In all soil profiles, humus content gradually decreased with increasing soil depth, reflecting the accumulation of organic matter mainly within the upper horizons.

Soil reaction varied from pH 7.5 to 8.4, indicating neutral to slightly alkaline conditions throughout the study area. The lowest pH value (7.5) was observed in the 12–27 cm horizon of Profile 3, while the highest value (8.4) occurred in the deeper horizons of Profile 1. Vertical changes in soil reaction were relatively small, although a slight increase in alkalinity with depth was observed in most profiles. Exchangeable calcium was the dominant basic cation in all investigated soils. Calcium concentrations ranged between 6.0 and 30.0 meq/100 g soil, with the highest value recorded in the surface layer of Profile 5 and the lowest in the 45–62 cm horizon of Profile 1. Exchangeable magnesium varied from 5.0 to 19.5 meq/100 g soil, following a distribution pattern similar to that of calcium. The highest magnesium content was also measured in Profile 5, whereas the minimum value occurred in the middle horizon of Profile 1. Exchangeable sodium content remained consistently low in all investigated soils, ranging between 0.4 and 1.7 meq/100 g soil. These values indicate the absence of sodium accumulation and confirm that salinity is not a limiting factor for forest soil fertility in the study area. The total amount of exchangeable bases varied considerably among soil profiles, ranging from 11.5 to 49.7 meq/100 g soil. The highest value was determined in the surface horizon of Profile 5, while the minimum value occurred in the 45–62 cm layer of Profile 1. Surface horizons generally contained greater amounts of exchangeable bases than subsurface layers. Comparison of the five soil profiles showed that Profiles 4 and 5 possessed the highest fertility indicators owing to their greater humus content and higher concentrations of exchangeable calcium and magnesium. In contrast, Profile 1 exhibited comparatively lower fertility values, particularly in the middle horizons, where both humus content and total exchangeable bases reached their minimum levels. The obtained results indicate that soil fertility in the forest ecosystems of the Sheki district is strongly influenced by soil depth and environmental conditions. Surface horizons consistently exhibited higher organic matter accumulation and greater nutrient reserves than deeper soil layers. Overall, the investigated mountain forest soils demonstrated favorable fertility characteristics suitable for sustaining natural forest vegetation.

Discussion

The main objective of the study was to analyze and assess the current condition of the soils within the high-mountain landscape–soil complexes of the Greater Caucasus and to identify the characteristics of their transformation under the influence of anthropogenic factors. Accordingly, comprehensive information was obtained on soil cover structure, vegetation cover, ecological conditions, relief, hydrographic features, climate, and other environmental characteristics of the study area (Huseynova, 2007; Kovda, 2011; Soil Atlas of the Republic of Azerbaijan, 2007).

Table 1
Coordinates of the soil profiles established in the Shaki District on the southern slope of the Greater Caucasus

Soil profiles	Latitude	Longitude	Elevation m²
Soil Profile 1: Bideiz Village	41°0.7'58.29"	47°19'25.89"	727
Profile 2. Bash Gunchut Village	41°9'54. 32"	47°19'15. 14"	871
Profile 3. 5 km north of Kish Village	41°15'33. 74"	47°12'18.50"	761
Profile 4. Bash Shabalyd Village	41° 18' 10.07"	47°6'18. 84"	732
Soil Profile 5: 10 km East of Shin Village	41° 22'18. 11"	47°4'42. 09"	1260

The natural conditions and other characteristics of the Shaki district indicate that the soil-forming processes in the region occur under highly complex conditions. The sharp variations in relief, along with corresponding changes in climate and vegetation zones, as well as the influence of parent materials and the hydrographic network, have contributed to the complexity of soil development in the area (Kovda, 2011; Mammadova, 2022; Mammadov & Khalilov, 2002). On steeper slopes, shallow soils are formed, while well-developed soils are found in areas with gentler slopes. In the plain areas, the diversity of alluvial deposits, together with the varying influences of climate, vegetation cover, surface and groundwater conditions, creates a complex system of soil formation (FAO, 2022; Mammadov, 1998).

1. Brown mountain forest soils
2. Forest-derived brown soils
3. Carbonate-rich brown mountain forest soils
4. Steppe-affected mountain brown soils

These soil types are distributed in the northern part of the district, in the high-mountain zone around the villages of Bash Layski, Oxud, Bash Gunchut, and Oraban. The total area covers 404.45 hectares (Huseynova, 2007). These areas are predominantly used under forest cover. The soils have developed under beech–hornbeam forests in the middle forest belt and represent a transitional stage toward brown forest soils. In the upper layer, a fresh forest litter is present, beneath which a 2–3 cm humus layer is formed, which is a characteristic feature of these soils (Huseynova, 2007; Mammadov & Khalilov, 2002). The relief of the area consists of sloping mountainsides and dissected slopes divided by valleys. The natural vegetation includes oak, hornbeam, hawthorn, alder, wild strawberry, raspberry, and other widely distributed plant species. The soil-forming parent materials consist of eluvial and eluvial–deluvial deposits. The soil cover is of medium depth to shallow (Huseynova, 2007; Soil Atlas of the Republic of Azerbaijan, 2007). In the areas where brown mountain-forest soils are distributed, both leached and weakly leached soils are present. In some places, forest litter has been washed away in patches, leaving individual roots exposed. The morphological characteristics of these soils can be clearly observed from the description of the soil profiles (Huseynova, 2007).

Profile 1. Located 10 km east of Bideiz village, which belongs to the forestry area of the Sheki district, in a low-mountain zone. The vegetation cover is very rich, including mixed stands of ash, yew, maple, hornbeam, wild grape, blackberry, willow, walnut, apple, and pear trees, as well as shrub species such as cornel, medlar, hawthorn, rosehip, and barberry (Huseynova, 2007). The profile depth is 97 cm.

The soil is a steppe-affected brown mountain-forest soil

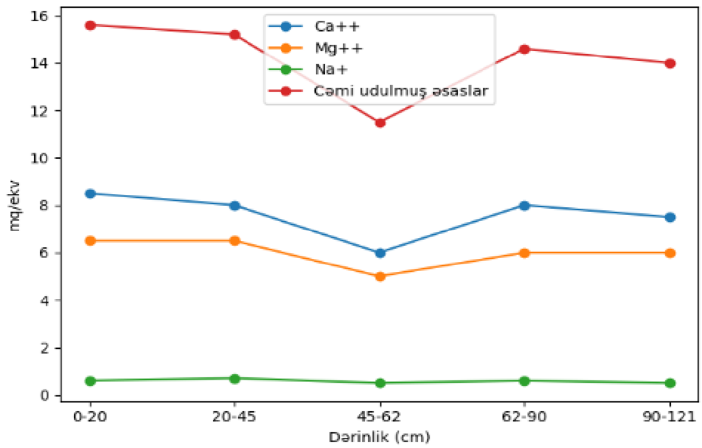
A second soil profile was established 7–8 km north of Bash Gunchut village. Hornbeam (Carpinus caucasica) dominates the vegetation in this area. Other plant species include walnut, ash, sea buckthorn, plum, rosehip, blackberry, cornel (dogwood), medlar, wild cherry, willow, and elm (Huseynova, 2007). The profile depth is 80 cm. The soil is classified as steppe-affected brown mountain-forest soil. A soil profile was established in the middle-mountain zone, 5 km northeast of Kish village. The soil-forming and parent materials consist of deposits that have undergone complete weathering of the original rock. The mesorelief is characterized by a middle-mountain landscape, while the microrelief is a west-facing slope. The vegetation cover includes hornbeam, sporadic oak, chestnut, maple, dogwood, rosehip, blackberry, goat willow, plum, wild cornel, occasional walnut, and herbaceous plants such as shepherd's purse, sorrel, red clover, sage, yellow clover, thistle, wormwood, yarrow, and others (Huseynova, 2007). The profile depth extends below 31 cm. The soil is classified as carbonate brown mountain-forest soil. A fourth soil profile was established in the natural forest area of the Shaki district, in the Bash Shabalyd village, located in the middle-mountain zone on a southeast-facing slope. The area has a slightly inclined relief, and the elevation ranges around 1100 m above sea level (Huseynova, 2007). The vegetation consists of hornbeam, oak, occasional beech, maple, plum, willow, and elm. The forest stand is well preserved, with only isolated signs of logging. Forest litter is present. The profile depth is 56 cm.

The soil is classified as leached brown mountain-forest soil

The fifth soil profile was established in a mountainous area 10 km east of Shin village, on the left bank slope of the Shin River in the middle-mountain zone. The profile depth is 36 cm. The land use type is natural forest. The vegetation cover includes hornbeam, oak, chestnut, maple, dogwood, rosehip, blackberry, walnut, hazelnut, and various herbaceous plants such as shepherd's purse, sorrel, red clover, sage, yellow clover, thistle, wormwood, yarrow, and others (Huseynova, 2007).

The soil is classified as carbonate brown mountain-forest soil

The natural conditions of the Shaki district, along with other characteristics, indicate that soil-forming processes in the region occur under highly complex conditions. The sharp variation in relief, together with corresponding changes in climate and vegetation zonation, as well as the influence of parent materials and the hydrographic network, has contributed to the complexity of soil development in the area. Shallow soils are mainly found on steep slopes, while well-developed soils are distributed in areas with gentler slopes (Kovda, 2011; Mammadova, 2022; Mammadov & Khalilov, 2002). In the southern slope of the Greater Caucasus, soil data for the mountainous and foothill zones of the Shaki district have been collected. These data are aimed at the efficient use of soil resources, refinement of land use classification, implementation of land reform activities, increasing productivity, and ensuring soil conservation. Within the landscape complexes of the area, soil fertility indicators of high- and low-mountain soils have been analyzed using GIS-based approaches, including the collection of large-scale geospatial data, processing of the collected information, spatial analysis, comparison, and systematization of the overall dataset (Huseynova, 2026; Soil Atlas of the Republic of Azerbaijan, 2007). One of the factors influencing soil fertility with increasing elevation above sea level is altitude. In high-mountain areas, greater accumulation of humus, better development of soil structure, and relatively higher levels of nutrient elements have been observed. These features are explained by lower temperatures in these regions and the slower rate of organic matter mineralization (Khar'kina, 2017; Kovda, 2011).



Fiqure 1

Variation of exchangeable base content with soil depth

The graph shows that the total amount of exchangeable bases is the lowest in the 45–62 cm layer. Calcium (Ca) and magnesium (Mg) constitute the main share and exhibit similar trends throughout the profile. Sodium (Na^+) remains relatively stable but at a very low level. Overall, the total exchangeable bases are higher in the upper and lower layers, while they decrease in the middle horizon. In the studied area, the humus content in forest soils ranged from 0.85% to 4.48% across the soil profiles. The highest humus content was recorded in the upper layer (0–11 cm) of the profile given in the table, reaching 4.48%, while the lowest value, 0.85%, was observed at a depth of 62–90 cm in Profile 1. In general, all soil profiles showed a decreasing trend of humus content with depth, which is associated with the accumulation of organic residues mainly in the surface horizons (Khar'kina, 2017; Kovda, 2011). The soil reaction (pH) varied between 7.5 and 8.4. These values indicate that the soils have a neutral to slightly alkaline reaction. The lowest pH value (7.5) was recorded in the 12–27 cm layer of the profile given in the table, while the highest value (8.4) was observed in the 45–62 cm and 90–121 cm layers of Profile 1 (FAO, 2022; Mammadov, 1998).

Table 2
Fertility indicators of forest soils in the Shaki district on the southern slope of the Greater Caucasus

Profile No.	Depth, см	Humus %	pH	Structural analysis of exchangeable bases in 100 g of soil, meq/100 g			
				Ca^{++}	Mg^{++}	Na^{+}	Total exchangeable bases
1	0-20	2.75	8.1	8.50	6.50	0.60	15.60
	20-45	2.28	8.3	8.00	6.50	0.70	15.20
	45-62	1.40	8.4	6.00	5.00	0.50	11.50
	62-90	0.85	8.3	8.00	6.00	0.60	14.60
	90-121		8.4	7.50	6.00	0.50	14.00
2	0-8	3.28	8.3	18.00	16.50	1.70	36.20
	8-21	2.36	8.1	15.00	13.50	1.30	29.80
	21-31	1.73	8.2	16.00	13.00	1.20	30.20
3	0-12	4.36	7.6	18.00	14.00	-	32.00
	12-27	3.04	7.5	10.00	8.50	-	18.50
	0-12	1.96	7.9	9.00	8.00	-	17.00
4	0-8	3.91	7.8	14.00	12.00	0.60	26.60
	8-19	3.03	7.9	10.00	6.00	0.40	16.40
	19-36	1.67	7.7	8.00	6.50	0.50	15.00
5	0-11	4.48	8.0	30.00	18.00	1.70	49.70
	11-28	3.17	8.2	26.50	19.50	1.60	47.60
	28-39	1.72	8.3	20.00	16.50	1.40	37.90

The fertility indicators of the forest soils of the Shaki district are presented in the table
Exchangeable bases are dominated by calcium (Ca^{2+}), whose content varied between 6.0 and 30.0 meq/100 g of soil. The highest value was recorded in the surface horizon of Profile 5 (30.0 meq/100 g), while the lowest value was observed in the 45–62 cm layer of Profile 1 (6.0 meq/100 g). The magnesium (Mg^{2+}) content ranged from 5.0 to 19.5 meq/100 g of soil. The highest value was found in the 11–28 cm layer of Profile 5 (19.5 meq/100 g), whereas the lowest value was recorded in the 45–62 cm layer of Profile 1 (5.0 meq/100 g). The sodium (Na^{+}) content remained generally low, ranging from 0.4 to 1.7 meq/100 g of soil. This indicates that there is no risk of soil salinization in the studied area (FAO, 2022). The total amount of exchangeable bases varied between 11.5 and 49.7 meq/100 g of soil. The highest value was observed in the surface horizon of Profile 5 (49.7 meq/100 g), while the lowest value was recorded in the 45–62 cm layer of Profile 1 (11.5 meq/100 g). The high cation exchange capacity indicates a strong ability of the soils to retain nutrient elements (Huseynova, 2007; Mammadov & Khalilov, 2005; Soil Atlas of the Republic of Azerbaijan, 2007). The results show that the studied forest soils are moderately to well supplied with humus, have neutral to slightly alkaline reactions, and are rich in calcium and magnesium. The generally high fertility indicators confirm favorable conditions for forest vegetation development in these soils. In particular, Profiles 4 and 5 can be considered more fertile due to their higher humus content and total exchangeable base values (Huseynova, 2007; Mammadov & Khalilov, 2002). The soil reaction is slightly alkaline in the upper horizons and becomes more alkaline with depth. The pH value ranges from 7.7 to 8.4 within the 0–100 cm soil profile (FAO, 2022; Mammadov, 1998). Typical brown mountain-forest soils have a high cation exchange capacity. In the surface horizons (0–20 cm), the total exchangeable bases range from 15.60 to 49.70 meq/100 g of soil, while in the deeper layers (0–50 cm), they range from 14.00 to 37.90 meq/100 g of soil (Huseynova, 2007; Soil Atlas of the Republic of Azerbaijan, 2007).

Conclusion

The results of this study demonstrate that the forest soils of the Shaki district on the southern slope of the Greater Caucasus possess generally favorable fertility characteristics and provide suitable conditions for the sustainable development of forest ecosystems. The analyzed soil profiles revealed relatively high humus content in the surface horizons, neutral to slightly alkaline soil reaction (pH 7.5–8.4), and high levels of exchangeable calcium and magnesium, indicating a strong nutrient-retention capacity. The study also confirmed that soil fertility indicators vary according to altitude, vegetation cover, relief conditions, and soil-forming parent materials. Humus content and the amount of exchangeable bases generally decrease with soil depth, reflecting the concentration of organic matter in the upper horizons. Among the investigated profiles, Profiles 4 and 5 exhibited the highest fertility due to their greater humus reserves and higher total exchangeable base content. At the same time, the research highlights the influence of anthropogenic activities, particularly deforestation and agricultural expansion, on the degradation of mountain forest ecosystems. These processes contribute to soil erosion, reduced water retention, and the gradual deterioration of soil quality. Overall, the obtained findings provide valuable scientific information on the fertility status of mountain forest soils in the Sheki district and can serve as a basis for sustainable forest management, soil conservation planning, and the rational use of natural resources. The application of modern monitoring methods, including GIS-based spatial analysis, together with effective forest protection measures, will contribute to maintaining soil fertility, preserving biodiversity, and ensuring the long-term ecological stability of the southern slope of the Greater Caucasus.

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Fertility Indicators of Forest Soils in the South-Eastern Part of the Greater Caucasus

Nazaket Ismayilova

Abstract. *This article examines the relationships between forest biogeocenoses and environmental factors on the southeastern slope of the Greater Caucasus, with particular emphasis on the role of soil as a key component in maintaining ecosystem stability and productivity. The study identifies the main ecological parameters influencing the fertility of forest soils and evaluates their significance in the functioning and development of forest ecosystems Based on field investigations and the analysis of soil profiles established under different forest formations, actual and optimal environmental indicators were determined for the construction of ecological fertility models. Special attention is paid to the soil block of the ecological model, which includes the soil profile and the physicochemical properties of soils as major sub-blocks. Diagnostic characteristics of soil horizons, including their thickness, structure, color, degree of compaction, and transition features, were used as indicators reflecting ongoing ecological processes such as soil evolution, degradation, erosion, and the effects of climatic changes. The study presents ecological characteristics of brown mountain-forest and brown forest soils formed under mesophilic beech–hornbeam–oak and xerophilous oak–hornbeam vegetation communities in different altitudinal zones of the region. The proposed soil block of the fertility model provides a scientific basis for the development of ecological passports of forest soils and can be used for monitoring the ecological condition of forest biogeocenoses, assessing the degree of their stability or degradation, and supporting the planning of conservation and restoration measures in mountain forest ecosystems of Azerbaijan.*

Keywords: *ecological fertility model, forest soils, soil profile, ecological passport, forest biogeocenosis, brown mountain-forest soils, beech, hornbeam, oak, Greater Caucasus*

Introduction

When developing ecological fertility models for agricultural crops and forage lands, the factors determining soil fertility and plant productivity are systematized, and zonal models of high soil fertility are created. Advanced farms, zonal experimental stations, and soils of small experimental stations may serve as ecological and agroecological fertility models. Taking the high-fertility model of a particular farm as a standard and applying appropriate agrotechnical and reclamation measures, it is possible, within 15–20 years, to improve and manage the fertility of soils throughout the region (Ismayilova, 2007). As noted above, unlike agroecosystems, forest biogeocenoses possess their own regulatory and management systems. Models intended for monitoring, protection, and restoration of forests reflect either the normal development of forest biogeocenoses (high level) or their degradation (medium and low levels). This approach has also been adopted in our studies.

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When implementing ecological fertility models for agricultural crops and forage lands, fertility models are developed in the form of standards or fertility passports to enhance their practical significance and facilitate monitoring (Ismayilova, 2018).

Methods

The research was carried out on the southeastern slope of the Greater Caucasus within forest ecosystems differing in altitudinal position, vegetation composition, and ecological conditions. The study area included territories of the Basgal, Topchu, Galynja, and Talystan forest districts, where representative soil profiles were established under mesophilic beech–hornbeam–oak and xerophilous oak–hornbeam forest communities. These forest ecosystems occupy both middle-mountain and low-mountain zones and differ in slope exposure, vegetation cover, and edaphic conditions.

The methodological approach was based on the concept of ecological fertility modeling of forest soils, according to which the fertility status of forest ecosystems is assessed through a system of interconnected ecological indicators reflecting the functioning and sustainability of forest biogeocenoses (Mammadova & Ismayilova, 2023). In accordance with this concept, ecological passports of forest soils were developed using information obtained from the main blocks and sub-blocks of the fertility model.

Field investigations included route surveys and detailed soil studies conducted at representative sites selected according to differences in relief, vegetation type, and forest productivity. Soil pits were excavated in typical forest stands, and their locations were chosen to represent the prevailing ecological conditions of the region (Ismayilova, 2025). The forest characteristics of each site, including forest site quality class (bonitet), stand density, average age of stands, crown closure, percentage of live ground cover, slope inclination, and slope exposure, were recorded during field observations.

Morphological descriptions of soil profiles were performed according to conventional pedological methods. The thickness of genetic horizons, their color, structure, consistency, compactness, boundary characteristics, and the presence of mottles or other diagnostic features were determined directly in the field. Particular attention was paid to the characteristics of forest litter and to the sequence and differentiation of soil horizons, as these properties serve as important indicators of the intensity and direction of soil-forming processes occurring within forest biogeocenoses (Mammadova & Ismayilova, 2023).

The soil block of the ecological fertility model was divided into two principal sub-blocks: (1) soil profile characteristics and (2) soil composition and physicochemical properties. The soil profile sub-block included diagnostic morphological features reflecting soil genesis, ecological conditions, and the degree of ecosystem stability. These indicators were used to assess processes such as erosion, degradation, humus accumulation, profile differentiation, and the possible impacts of climatic changes on forest soils (Ismayilova, 2018).

The study utilized data obtained from a series of representative soil profiles. Profiles No. 1, 2, 3, 5, 6, and 7 were examined in the forests of Basgal, Topchu, and Galynja under mesophilic beech–hornbeam–oak vegetation to characterize brown mountain-forest soils of the middle-mountain zone. Profiles No. 3, 4, 5, 8, 9, 12, 13, and 15 were established in the Talystan forestry area under xerophilous oak–hornbeam communities to evaluate the ecological characteristics of brown forest soils formed in the low-mountain zone.

The collected information was subjected to comparative ecological analysis aimed at identifying similarities and differences among the studied forest soil types. Based on the obtained results, actual ecological parameters characterizing the current state of forest ecosystems were determined and compared with optimal conditions associated with stable and productive forest biogeocenoses (Mammadova & Ismayilova, 2023). The identified indicators formed the basis for the development of soil blocks and sub-blocks within the ecological fertility model and for the preparation of ecological passports intended for monitoring, conservation, and restoration of forest ecosystems in the southeastern part of the Greater Caucasus.

Table 1
Soil composition and physico-chemical properties

Indicators	Beech-Hornbeam-Oak Mountain Forest Soils of the Mid-Mountain Zone under Mesophytic Forests			Oak-Hornbeam Mountain Forest Soils of the Low-Mountain Zone under Xerophytic Forests		
	Leached Brown Mountain-Forest Soils	Carbonate Brown Mountain-Forest Soils	Leached Meadow-Brown Mountain Soils	Leached Brown Mountain-Forest Soils	Typical Brown Mountain-Forest Soils	Carbonate Brown Mountain-Forest Soils
Humus content (0–20 cm), %	6.4–9.1	3.8–7.3	7.0–8.2	2.9–6.5	3.8–4.8	1.9–5.4
Humus reserves, t/ha						
0–20 cm	143–170	99–110	150–162	50–97	67–89	49–69
0–50 cm	140–180	180–205	170–200	107–191	111–217	100–151
0–100 cm	190–230	250–280	310–330	187–297	217–401	197–235
			3.0–7.0	3.3–7.1	4.0–6.7	3.5–7.5
Nitrogen (0–20 cm), %	0.28–0.32	0.11–0.38	0.37–0.43	0.15–0.25	0.22–0.23	0.12–0.31
Phosphorus (0–20 cm), %	0.20–0.22	0.23–0.24	0.23–0.30	0.25–0.27	0.27–0.35	0.29–0.41
Potassium (0–20 cm), %	2.1–2.2	2.1–2.2	2.3–2.4	2.3–2.5	2.4–2.6	2.5–2.7
CEC, meq/100 g	20.4–34.7	23.4–29.1	20.1–23.3	29.0–35.0	21.9–40.1	17.6–27.8
pH	6.5	6.5–7.0	5.0–6.0	7.0–7.5	6.1–7.0	6.5–7.2

The investigation confirmed that mesophilic beech–hornbeam–oak forests of the middle-mountain belt and xerophilous oak–hornbeam forests of the low-mountain belt differ considerably in their soil ecological characteristics. These differences are reflected in the structure and development of soil profiles, humus accumulation patterns, vegetation cover, and the influence of topographic factors such as slope exposure and inclination. Consequently, the assessment and management of forest ecosystems require region-specific ecological criteria and fertility indicators.

Based on the developed ecological fertility models, ecological zoning of the southeastern slope of the Greater Caucasus was carried out, taking into account the soil-ecological conditions of both the low-mountain and middle-mountain regions. The identified ecological zones reflect variations in forest productivity, environmental conditions, and the degree of development of forest soils, thereby providing a scientific basis for differentiating management approaches within the region.

The proposed soil blocks and sub-blocks, incorporated into the ecological fertility models, can serve as a methodological framework for the preparation of ecological passports of forest soils (Ismayilova, 2018). Such passports may be effectively applied in long-term ecological monitoring, assessment of forest ecosystem health, identification of degradation processes, and evaluation of the impacts of natural and anthropogenic factors on forest environments. From a practical perspective, the developed models may contribute to improving the scientific basis for forest conservation and sustainable forest management in Azerbaijan. Their application can support decision-making related to the protection, restoration, and rational use of mountain forest ecosystems, while also facilitating the preservation of their ecological functions and biodiversity under changing environmental conditions.

Thus, the ecological fertility models developed for the forest soils of the southeastern slope of the Greater Caucasus constitute an important tool for understanding the interactions between soils and forest ecosystems and represent a valuable approach for ecological assessment and sustainable management of forest resources (Mammadov & Osmanova, 2025).

Results

The investigation demonstrated that the forest soils of the southeastern slope of the Greater Caucasus differ considerably according to vegetation type, altitudinal zone, and ecological conditions. The analyzed physicochemical properties indicate distinct patterns of soil fertility between the mesophilic beech–hornbeam–oak forests of the middle-mountain belt and the xerophilous oak–hornbeam forests of the low-mountain belt (Table 1). The highest humus content was recorded in leached brown mountain-forest soils developed under mesophilic beech–hornbeam–oak forests, where values ranged from 6.4 to 9.1% in the upper 20 cm of the soil profile. Leached meadow-brown mountain soils also showed high humus accumulation (7.0–8.2%). In contrast, soils under xerophilous oak–hornbeam forests contained lower amounts of humus, varying from 1.9 to 6.5%, with the lowest values observed in carbonate brown mountain-forest soils. Humus reserves showed considerable variation among the studied soil types. In mesophilic forest ecosystems, humus reserves reached 143–170 t ha^{-1} in the 0–20 cm layer and increased to 310–330 t ha^{-1} within the 0–100 cm profile in leached meadow-brown mountain soils. In the xerophilous forest zone, humus reserves generally ranged between 49 and 97 t ha^{-1} in the surface layer and between 187 and 401 t ha^{-1} within the entire one-meter profile. The highest reserve values in the low-mountain forests were recorded in typical brown mountain-forest soils.

The nitrogen content reflected a similar distribution pattern. Surface horizons of mesophilic forest soils contained 0.28–0.43% total nitrogen, whereas xerophilous forest soils contained 0.12–0.31%. These differences correspond to the greater accumulation of organic matter under cooler and more humid ecological conditions. Phosphorus concentrations varied within a relatively narrow interval among the investigated soils. Values ranged from 0.20 to 0.30% in the middle-mountain soils and from 0.25 to 0.41% in the low-mountain soils. Potassium content was comparatively stable in all investigated forest soils, varying from 2.1 to 2.7%, with slightly higher concentrations observed in carbonate soils of the xerophilous forest zone. The cation exchange capacity (CEC) ranged from 20.1 to 34.7 meq 100 g^{-1} in the mesophilic forest soils and from 17.6 to 40.1 meq 100 g^{-1} in the xerophilous forest soils. Typical brown mountain-forest soils exhibited the highest CEC values, indicating a relatively high capacity for nutrient retention despite their lower organic matter content. Soil reaction also differed according to ecological conditions. Leached meadow-brown mountain soils were moderately acidic (pH 5.0–6.0), while most other soil types exhibited neutral or slightly alkaline reactions (pH 6.5–7.5). These differences reflect variations in parent material, leaching intensity, and vegetation composition across the study area.

Overall, the obtained results indicate that the fertility of forest soils on the southeastern slope of the Greater Caucasus is primarily controlled by altitude, moisture regime, forest composition, and soil-forming processes. Mesophilic beech–hornbeam–oak forests create favorable conditions for greater humus accumulation and nitrogen enrichment, whereas xerophilous oak–hornbeam forests are characterized by lower organic matter content but relatively stable mineral nutrient status. These findings provide the quantitative basis for constructing ecological fertility models and ecological passports of forest soils and support their application in monitoring the ecological condition and sustainable management of mountain forest ecosystems.

Discussion

Soil Block. The soil and its constituent factors play an important role in the formation of biogeocenoses. Soils are essential in nutrient cycling and the formation of forest biological productivity (Mammadov & Ismayilova, 2025). At the same time, soil serves as a unique carrier of ecological information about forest biogeocenoses. Therefore, in constructing the ecological model of forest soils on the southeastern slope of the Greater Caucasus, the soil block includes more detailed information.

We propose distinguishing the following sub-blocks within the soil block:
1) Soil profile;
2) Soil composition and physicochemical properties.
Soil Profile Sub-block. This sub-block includes the most significant biodiagnostic characteristics. These properties serve as carriers of primary information concerning the processes occurring within forest biogeocenoses (Mammadova & Ismayilova, 2023). The composition and thickness of the forest litter, the thickness of horizons A1, A2, A2B, B1, B2, and C, their relationships and transitional characteristics provide ecological information necessary for explaining erosion, degradation, evolution, and climatic changes.

To characterize the soil profile sub-block of the ecological fertility model for brown mountain-forest soils under mesophilic beech–hornbeam–oak vegetation of the middle mountains, data from profiles No. 1, 2, 3, 5, 6, and 7 located in the Basgal, Topchu, and Galynja forests were integrated. The prevailing forest ecological conditions were characterized by a forest site quality class of II, stand density of 0.7, average stand age of 70 years, crown density of 0.7, live ground cover reaching 60–65%, and northern slope inclinations ranging from 18° to 20°. The generalized morphological characteristics are presented below:

A0 horizon – forest litter at various stages of decomposition, 2–5 cm thick;
A1 horizon – dark black or dark gray in color, nutty-granular structure, relatively soft, 2–17 cm thick;
A2 horizon – brownish-gray in color, coarse granular structure, soft consistency, 13–35 cm thick;
A2B1 horizon – nutty-granular structure, 29–80 cm thick;
B (or B1) horizon – blackish-brown color with distinct, clearly visible rusty spots, granular or nutty-granular structure, moderately compact, 57–120 cm thick;
B2 horizon – light brown in color, coarse, compacted granular structure with brown mottles, 86–160 cm thick.

To characterize the soil profile sub-block of the ecological fertility model for brown mountain-forest and brown forest soils under xerophilous oak–hornbeam vegetation of the low mountains, data from profiles No. 3, 4, 5, 8, 9, 12, 13, and 15 established in the Talystan forestry area were summarized. The forest ecological parameters included a forest site quality class of III, stand density of 0.7, average stand age of 70 years, crown density of 0.7, live ground cover amounting to 18–20%, and southern slope inclinations of 10–12°.

The generalized morphological features include:

A1 horizon – humus horizon; dark blackish-brown color; granular-cloddy structure; soft consistency; thickness 3–22 cm;
A2 horizon – eluviated horizon; brown or brownish color; coarse granular structure; soft consistency; thickness 18–57 cm;
B1 horizon – illuvial horizon; light brown color; nutty-granular structure; moderately compact; thickness 32–34 cm;
B2 horizon – bluish-brown color; fine granular structure; moderately compact; thickness 17–18 cm;
C horizon – parent material, occasionally orange-gray in color and structureless.

These visual and morphological characteristics of forest biogeocenoses represent essential primary sources of information on ongoing ecological processes (Ismayilova, 2023). Based on the indicators of the soil profile sub-block within the ecological fertility model identified in these two soil-ecological regions, it is possible to effectively assess and determine the current ecological status of forest biogeocenoses.

Conclusion

The primary objective of this study was to develop ecological fertility models for the dominant forest soil types on the southeastern slope of the Greater Caucasus: (1) brown mountain forest soils of the middle-mountain zone under mesophilous beech–hornbeam–oak forests and (2) brown mountain forest soils of the low-mountain zone under xerophilous oak–hornbeam communities. These models were developed to characterize the relationships among soil properties, environmental factors, and the ecological condition of forest biogeocenoses (Mammadova & Ismayilova, 2023).

The findings demonstrate that soil profile characteristics serve as reliable indicators of ecological processes within forest ecosystems (Mammadov & Ismayilova, 2025). The composition and thickness of the forest litter layer, the sequence and depth of genetic horizons, their morphological characteristics, and the nature of horizon transitions provide essential information on soil-forming processes, ecosystem functioning, and the stability or degradation of forest biogeocenoses.

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Increasing the Efficiency of Compressor Stations of Main Gas Pipelines

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Abstract. *The recovery and utilization of waste heat from gas turbine engines (GTE) currently stand out as one of the most critical and pressing engineering challenges in the energy sector. This issue is particularly vital for the compressor stations of main gas pipelines due to the massive total installed capacity of the driving gas turbine units. Standard waste heat recovery systems, such as waste heat boilers or traditional gas turbine cycles, impose significant aerodynamic backpressure on the exhaust of the primary gas turbine engines. This backpressure reduces the available enthalpy drop across the power turbine, causing a substantial drop in the shaft power output. To compensate for this loss and restore the original compressor performance, operators must increase fuel consumption, which inherently degrades the overall thermodynamic and economic efficiency of the facility. To resolve this technological conflict, inverted-cycle gas turbine units (ICGTU) can be effectively implemented. In these specialized sub-atmospheric configurations, no additional backpressure is generated at the exhaust of the primary engine because the aerodynamic losses are successfully compensated for by the pressure rise inside the specialized utilization compressor. The thermodynamic process in an ICGTU operates uniquely: the hot exhaust gases from the primary engine enter the turbine first, expand below atmospheric pressure, flow through a gas-water cooler, and are subsequently compressed back to ambient atmospheric pressure. This study provides a comprehensive mathematical and thermodynamic analysis to determine the optimal pressure ratio* ($\pi^*_{k.opt}$) *for maximizing specific work and thermal efficiency. The implementation of an ICGTU can contribute an additional 15–25% to the total mechanical shaft power of the station. When integrated with a district or technological water heating system, the overall fuel utilization coefficient reaches an impressive 0.80–0.85, while simultaneously reducing specific hazardous emissions by 15–25% relative to the combined power output.*

Keywords: *Waste Heat Recovery, Combined Gas-Gas Cycle, Inverted-Cycle Gas Turbine, Thermal Efficiency, Gas Pipeline Compressor Stations*

Introduction

The transport of natural gas over long distances through main gas pipeline networks requires immense amounts of energy to overcome hydraulic friction and maintain required pipeline pressures. Gas compressor stations, distributed systematically along these pipelines, rely heavily on heavy-duty gas turbine engines (GTEs) to drive centrifugal gas compressors (Boyce, 2012; Saravanamuttoo et al., 2009). However, a major disadvantage of industrial gas turbines is their relatively low standalone thermal efficiency, which typically ranges from 28% to 36% for older and mid-generation units.

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A massive portion of the fuel energy is lost to the atmosphere in the form of high-temperature exhaust gases (Walsh & Fletcher, 2004). Utilizing this waste heat to generate secondary energy—either for driving auxiliary compressors, supplying internal station utilities, or generating electricity for the external power grid—represents a crucial mechanism for energy conservation and environmental mitigation (American Society of Mechanical Engineers, 2022). The scale of this potential is immense; for instance, the total capacity of gas turbine drives operating within the gas transportation system of the Russian Federation alone exceeds 38,000 MW. Transforming even a fraction of this wasted thermal energy into useful mechanical or electrical work can yield substantial economic benefits. The integration of waste heat recovery (WHR) systems is highly recommended for compressor stations where the existing gas-pumping units have a long remaining operational lifespan and are not scheduled for decommissioning in the near future (ASME, 2022). Furthermore, such retrofitting projects must prove economically viable, meaning that the required capital expenditures (CAPEX) must be low enough to guarantee a short payback period through fuel savings.

Despite the clear benefits, traditional waste heat recovery systems pose serious operational challenges. When conventional heat exchangers, such as waste heat boilers or recuperators, are placed directly into the exhaust duct of a primary gas turbine, they create an inevitable aerodynamic resistance (backpressure) (Horlock, 2002; Wilson & Korakianitis, 2014). This backpressure increases the pressure at the exit of the power turbine, thereby reducing the available expansion ratio and causing a direct drop in the mechanical power delivered to the natural gas compressor. To restore the gas-pumping unit to its nominal capacity, operators are forced to increase the fuel flow rate, which leads to higher thermal stresses and lowers the net efficiency gains.

Historically, the most common method of utilizing exhaust gas heat has been the installation of simple heat exchangers to heat water. This hot water is then distributed for space heating within the compressor station buildings, nearby residential settlements, or adjacent agricultural greenhouses. For electricity generation, steam turbine waste heat recovery units (Combined Cycle Gas Turbines (CCGT)) are frequently employed (Kostyuk & Frolov, 1988). However, because the initial parameters of the steam are strictly bounded by the exhaust temperature of the primary gas turbine, these steam cycles usually operate at modest pressures and temperatures.

Furthermore, water-steam cycles require complex, bulky, and expensive auxiliary equipment, including recovery boilers, steam turbines with dedicated speed governors, water condensers, deaerators, feed pumps, and extensive chemical water treatment facilities. This complexity increases operational and maintenance costs (OPEX), making steam cycles less attractive for remote or harsh geographic locations. As an alternative, Organic Rankine Cycles (ORC) utilizing low-boiling-point working fluids, such as pentane, butane, or toluene, have been introduced (Najjar, 2013). While ORCs offer better thermodynamic matching at lower exhaust temperatures, they still face issues regarding fluid flammability, toxicity, and high equipment costs.

To bypass the limitations of both steam and organic fluid cycles, gas-turbine waste heat recovery loops have gained significant research attention. These loops can be designed to operate either via traditional closed/open Brayton cycles or via specialized inverted-cycle configurations (Polyzakis, 2019; Zhang & Lior, 2006). In a traditional gas turbine waste heat recovery loop, the heat from the primary GTE exhaust is transferred through a heat exchanger wall to a clean working fluid (usually air or nitrogen) circulating in a closed loop. Due to the inevitable heat transfer temperature difference across the exchanger, the maximum temperature of the working fluid in the recovery loop is restricted, typically remaining below 450°C. While an auxiliary combustion chamber can be integrated to burn additional fuel and boost the recovery loop's power output, this approach shares the same drawback as steam boilers: it increases the station's total fuel consumption to maintain or restore nominal operating parameters.

Methods

To completely eliminate the negative impacts of backpressure on the primary engine, the concept of an Inverted-Cycle Gas Turbine Unit (ICGTU) was developed (Najjar, 2013; Zhang & Lior, 2006). The fundamental difference between a traditional gas turbine cycle and an inverted cycle lies in the sequence of thermodynamic processes relative to atmospheric pressure (Boyce, 2012; Horlock, 2002).

In an ICGTU, the hot exhaust gases from the primary gas turbine engine are not passed through a heat exchanger first; instead, they are routed directly into the inlet of the utilization turbine (Polyzakis, 2019). The pressure of the gases entering this turbine is very close to ambient atmospheric pressure, while their temperature matches the exhaust temperature of the primary power turbine. Inside the utilization turbine, the gases expand to a sub-atmospheric pressure level ($p < p_a$). This sub-atmospheric expansion allows the turbine to extract mechanical energy directly from the hot exhaust gas stream without placing any aerodynamic restriction on the primary engine. After expanding through the turbine, the sub-atmospheric, partially cooled gases enter a specialized gas-water heat exchanger (gas cooler). In this cooler, heat is rejected from the gas stream to an external cooling medium (such as water or ambient air), causing the gas temperature to drop significantly while its pressure remains sub-atmospheric. The cold, low-pressure gas is then drawn into the inlet of the utilization compressor. The compressor compresses the gases from the sub-atmospheric pressure back up to standard atmospheric pressure (p_a), after which they are discharged safely through the exhaust stack into the environment.

A schematic diagram and the corresponding thermodynamic T–s (Temperature–Entropy) diagram of this combined system are illustrated in Figure 1.

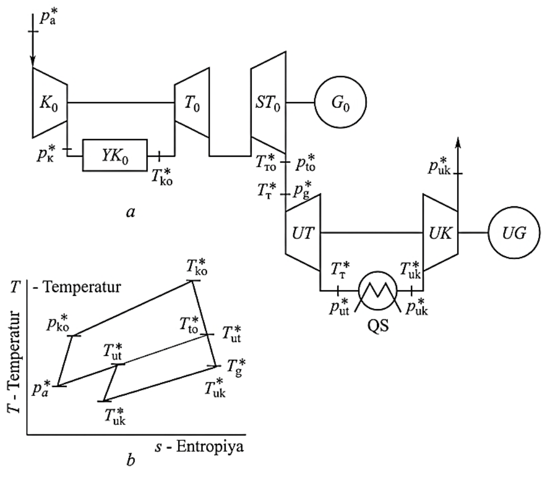

Figure 1

Operational flow of the Inverted-Cycle Gas Turbine Unit (ICGTU) matching the thermodynamic cycle depicted in the original source

In this sub-atmospheric arrangement, the maximum pressure within the utilization loop never exceeds ambient atmospheric pressure. Unlike conventional gas turbine configurations where the compressor forces the working fluid into the system under high pressure, the ICGTU operates via an induced-draft mechanism. The compressor essentially acts as a vacuum pump, pulling the working fluid through the turbine and cooler. Because the static and total pressure at the exit of the primary engine's power turbine remains entirely unperturbed, the primary engine maintains its original design performance and power output. Any minor pressure drops caused by the internal friction of the connecting ducts or the gas cooler are completely overcome and compensated for by the work input of the utilization compressor. To evaluate the mathematical optimization of this cycle, we must analyze the specific useful work (L_e) generated by the utilization loop. In standard Brayton cycles, the specific work reaches a maximum at a specific pressure ratio denoted as π^*_{kL}, whereas the thermal efficiency peaks at a higher pressure ratio $\pi^*_{k\eta}$. However, for an inverted cycle operating on a fixed stream of exhaust gas, the mass flow rate and the available inlet thermal energy are predetermined by the primary engine's operating state. Therefore, the specific work and the total efficiency of the utilization loop peak at the exact same optimal pressure ratio ($\pi^*_{k.opt}$).

The specific useful work of the ICGTU can be formulated using basic aerothermodynamics equations:

$$L_e = C_{pt} \cdot T_t^* \cdot \left(1 - \frac{1}{\pi_T^{*\frac{k_t-1}{k_t}}}\right) \cdot \eta_t \cdot \eta_m - C_{pk} \cdot T_k^* \cdot \left(\pi_k^{*\frac{k_k-1}{k_k}} - 1\right) \cdot \frac{1}{\eta_k}$$

Where:

- C_{pt}, C_{pk} are the mean specific isobaric heat capacities of the gas during expansion (turbine) and compression (compressor), respectively.
- k_t, k_k are the isentropic exponents for the turbine and compressor processes.
- T_t^* is the total stagnation temperature of the gas at the turbine inlet.
- T_k^* is the total stagnation temperature of the gas at the compressor inlet (after the gas cooler).
- π_T^*, π_k^* are the total pressure expansion ratio of the turbine and compression ratio of the compressor.
- η_t, η_k are the isentropic efficiencies of the turbine and compressor.
- η_m is the mechanical efficiency of the shaft assembly.

Since the working fluid throughout the entire ICGTU consists of the same flue gas mixture (operating under high excess air coefficients of $\alpha_\Sigma = 3.0 - 3.5$), and considering that the mean temperature difference between the expansion and compression phases is roughly 300°C to 350°C, we can apply a first-order simplification assuming equal average thermodynamic properties:

$$C_{pt} = C_{pk} = C_p \quad \text{and} \quad k_t = k_k = k$$

The turbine expansion ratio π_T^* is mathematically linked to the compressor pressure ratio π_k^* through the total pressure preservation coefficients of the system:

$$\pi_T^* = \pi_k^* \cdot \sigma_{gir} \cdot \sigma_x$$

Where σ_{gir} is the pressure recovery factor of the inlet transition duct and σ_x is the pressure recovery factor of the gas cooler. Substituting these variables into the specific work equation yields:

$$L_e = C_p \cdot T_t^* \cdot \left[1 - \frac{1}{\left(\pi_k^* \cdot \sigma_{gir} \cdot \sigma_x\right)^{\frac{k-1}{k}}}\right] \cdot \eta_t \cdot \eta_m - C_p \cdot T_k^* \cdot \left(\pi_k^{*\frac{k-1}{k}} - 1\right) \cdot \frac{1}{\eta_k}$$

To find the optimal value of π_k^* we can define a substitution variable $X = \pi_k^{*\frac{k-1}{k}}$. This transforms the equation into a simplified algebraic form:

$$L_e = A - \frac{B}{X} - C \cdot X$$

Where the constant coefficients A, B, and C are defined as follows:

$$A = C_p \cdot T_t^* \cdot \eta_t \cdot \eta_m + \frac{C_p \cdot T_k^*}{\eta_k}$$

$$B = \frac{C_p \cdot T_t^* \cdot \eta_t \cdot \eta_m}{\left(\sigma_{gir} \cdot \sigma_x\right)^{\frac{k-1}{k}}}$$

$$C = \frac{C_p \cdot T_k^*}{\eta_k}$$

Results

To calculate the exact optimal pressure ratio that yields the maximum specific work, we take the first derivative of $L_e$with respect to the variable X and set it to zero:

$$\frac{dL_e}{dX} = \frac{B}{X^2} - C = 0 \Rightarrow X_{opt} = \sqrt{\frac{B}{C}}$$

Reversing the substitution variable $X = \pi_{k.opt}^{*\frac{k-1}{k}}$ provides the final analytical solution for the optimal compressor pressure ratio:

$$\pi_{k.opt}^* = \left(\frac{T_t^*}{T_k^*}\right)^{\frac{k}{2(k-1)}} \cdot \left(\frac{\eta_t \cdot \eta_k \cdot \eta_m}{\left(\sigma_{gir} \cdot \sigma_x\right)^{\frac{k-1}{k}}}\right)^{\frac{k}{2(k-1)}}$$

This derivation shows that the optimal pressure ratio of an ICGTU is primarily dictated by the temperature ratio across the cycle ($\frac{T_t^*}{T_k^*}$), alongside the component efficiencies and aerodynamic pressure losses. For standard industrial gas turbines operating at compressor stations (such as the NK-14ST, GTNR-16, or GTU-25P), the exhaust gas temperatures typically range from 724 K to 790 K. Assuming effective cooling in the gas-water heat exchanger reduces the compressor inlet temperature T_k^* to approximately 310–330 K, the optimal sub-atmospheric pressure $\pi_{k.opt}^*$ typically falls within a narrow range between 1.5 and 2.2.

When operating at this optimized thermodynamic point, the implementation of the inverted cycle yields highly favorable performance metrics:

1. **Power Augmentation:** The secondary sub-atmospheric loop generates substantial shaft power without modifying the primary engine core. This adds an additional 15% to 25% of clean mechanical or electrical power to the station's baseline capacity.
2. **Fuel Utilization Factor:** By fully capturing the waste heat for power generation and utilizing the remaining low-grade thermal energy from the gas cooler to heat water, the overall fuel utilization coefficient (η_{fu}) of the combined plant rises to 0.80–0.85.

3. **Environmental Impact:** Because the total mechanical power output increases significantly while the absolute fuel consumption remains unchanged, the specific emissions of hazardous pollutants (such as NO_x and CO) drop by 15% to 25% relative to the total combined plant output.

Discussion

The analytical models and results presented here confirm that inverted-cycle gas turbine units offer a highly effective alternative to traditional steam-water combined cycles for pipeline compressor stations. The primary advantage is the complete absence of aerodynamic backpressure on the primary engine, allowing it to maintain peak nominal performance under all operating conditions. This completely bypasses the traditional efficiency penalty associated with regular heat recovery exchangers (Najjar, 2013; Polyzakis, 2019; Zhang & Lior, 2006).

However, successfully deploying an ICGTU requires addressing several unique engineering constraints:

- Volumetric Flow Rates: Because the turbine expands the working fluid into sub-atmospheric pressures ($p < 1$ bar), the specific volume of the gas increases drastically. This requires larger turbine blade heights and larger flow cross-sections, which increases the physical size and structural mass of the low-pressure turbomachinery components (Boyce, 2012; Wilson & Korakianitis, 2014).
- Sealing and Structural Rigidity: Operating under vacuum conditions requires robust casing designs to prevent atmospheric air leakage into the sub-atmospheric zones, which would dilute the working fluid and degrade compressor efficiency (Polyzakis, 2019).
- Optimization Limitations: Due to structural, material, weight, and dimensional constraints at remote compressor stations, the actual design pressure ratio is sometimes chosen to be slightly below the theoretical thermodynamic optimum (π_(k.opt)^*). This slight reduction helps minimize the overall footprint and manufacturing costs of the equipment while preserving the majority of the efficiency gains (Horlock, 2002; Wilson & Korakianitis, 2014).

Future research will focus on developing advanced compact heat exchangers to minimize the pressure drop (σ_x) and exploring multi-stage sub-atmospheric compression with intercooling to further boost the net efficiency of the combined gas-gas cycle.

Conclusion

This study demonstrates that the implementation of an Inverted-Cycle Gas Turbine Unit (ICGTU) provides an effective solution for recovering waste heat from gas turbine-driven compressor stations without introducing the aerodynamic backpressure associated with conventional waste heat recovery systems. Unlike traditional steam or recuperative technologies, the proposed sub-atmospheric gas-gas cycle preserves the operating conditions and rated power of the primary gas turbine while converting a significant portion of the exhaust gas energy into additional useful mechanical work.

A mathematical model was developed to determine the optimal compressor pressure ratio for the inverted cycle. The derived analytical expression shows that the optimum pressure ratio is primarily governed by the turbine-to-compressor inlet temperature ratio together with the efficiencies of the turbine, compressor, and mechanical transmission, as well as the pressure recovery characteristics of the utilization system. Under operating conditions typical of industrial gas pipeline compressor stations, the optimal pressure ratio generally lies between 1.5 and 2.2.

The thermodynamic analysis indicates that the proposed system can increase the total shaft power output of compressor stations by approximately 15–25% without increasing the fuel consumption of the primary gas turbine. Furthermore, by combining mechanical power recovery with low-grade heat utilization for water heating, the overall fuel utilization coefficient can reach 0.80–0.85. Because the total useful energy output increases while fuel consumption remains essentially unchanged, the specific emissions of harmful pollutants per unit of useful energy are reduced by approximately 15–25%.

Although practical implementation requires careful consideration of larger volumetric flow rates, vacuum sealing, and the structural design of low-pressure turbomachinery, these engineering challenges do not outweigh the significant thermodynamic and economic advantages of the proposed concept. Consequently, the inverted-cycle gas turbine represents a promising technology for improving the energy efficiency, operational reliability, and environmental performance of existing main gas pipeline compressor stations. Future research should focus on experimental validation of the proposed mathematical model, optimization of compact low-pressure heat exchangers, and investigation of multi-stage sub-atmospheric compression systems with intercooling to further enhance cycle performance.

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The Role of Innovation in High-Tech Manufacturing Processes under Modern Technological Research Conditions: An Analysis of Innovation Stages

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Abstract. *This article examines the role of innovation in high-tech manufacturing under modern technological research conditions. The study analyzes the stages of innovation and their impact on competitiveness, productivity, and sustainability. A qualitative analytical methodology based on a literature review and comparative analysis is employed. The findings indicate that innovation is not a linear process but a dynamic system involving idea generation, research and development, prototyping, commercialization, and continuous improvement. The integration of Industry 4.0 technologies accelerates innovation cycles and strengthens organizational adaptability. The study contributes to understanding how innovation stages shape manufacturing performance in the contemporary knowledge economy.*

Keywords: *innovation, high-tech manufacturing, Industry 4.0, research and development, innovation stages, technological transformation, competitiveness*

Introduction

Innovation has become one of the most significant drivers of economic growth and industrial competitiveness. High-tech manufacturing industries operate in environments characterized by rapid technological change, increasing customer expectations, and intense global competition. In such contexts, organizations must continuously innovate to survive and expand their market positions (Porter, 1990; Schumpeter, 1934). The transition toward Industry 4.0 has transformed production systems through the integration of cyber-physical systems, artificial intelligence, big data analytics, robotics, and the Internet of Things. These technologies enable flexible production, real-time decision-making, and enhanced operational efficiency. However, their successful implementation depends on well-structured innovation processes (Frank et al., 2019; Kusiak, 2018; Lee et al., 2015). The concept of innovation has evolved considerably since Schumpeter emphasized its role in economic development. Modern innovation theories recognize the importance of open innovation, absorptive capacity, collaborative networks, and knowledge management. High-tech manufacturing firms increasingly rely on research partnerships, universities, and digital ecosystems to generate and commercialize new ideas (Chesbrough, 2003; Cohen & Levinthal, 1990). The purpose of this article is to analyze innovation stages within high-tech manufacturing processes under modern technological research conditions. Particular attention is devoted to understanding how innovation progresses from idea generation to commercialization and continuous improvement. The study also discusses the implications of innovation management for industrial competitiveness and sustainable development. The relevance of this topic has increased significantly due to globalization, technological disruptions, and changing market conditions.

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Policymakers and managers require evidence-based approaches to support innovation capabilities. Therefore, a systematic analysis of innovation stages provides valuable insights into effective strategic decision-making (OECD/Eurostat, 2018).

Methods

The study adopts a qualitative research design based on an extensive review of academic literature and conceptual analysis. Secondary data sources, including peer-reviewed journal articles, books, and international reports, were examined to identify key themes related to innovation in high-tech manufacturing (Damanpour, 1991; OECD/Eurostat, 2018). The methodological approach consists of four stages. First, literature related to innovation theories and manufacturing transformation was reviewed. Second, innovation stages identified in the literature were categorized into a unified framework. Third, the relationships between innovation stages and manufacturing performance were analyzed. Finally, implications for managers and policymakers were discussed. The analytical framework recognizes innovation as a multidimensional process. The major stages include opportunity identification, research and development, design and prototyping, testing and validation, commercialization, and post-commercialization improvement. These stages are interconnected and influenced by organizational capabilities, technological infrastructure, and external collaboration. Comparative analysis was applied to evaluate similarities and differences among innovation models. Particular emphasis was placed on Industry 4.0 environments where digital technologies facilitate knowledge sharing and accelerate innovation cycles. The use of secondary sources enabled the integration of diverse perspectives while maintaining methodological rigor (Frank et al., 2019). Although the study does not rely on primary empirical data, the synthesis of high-quality scientific evidence enhances the reliability of conclusions. Future research may complement these findings through case studies and quantitative investigations involving manufacturing enterprises (Pisano, 2015).

Results

The analysis demonstrates that innovation significantly influences the performance of high-tech manufacturing organizations. Firms with systematic innovation processes exhibit higher adaptability, stronger market orientation, and greater resilience (Teece, 1986). The results indicate that the innovation process should be viewed as iterative rather than strictly sequential. Feedback mechanisms support learning and enable continuous refinement of products and processes. Furthermore, collaboration among stakeholders enhances access to knowledge and technological resources. Digital technologies contribute substantially to innovation efficiency. Advanced analytics improve decision-making, automation reduces production errors, and smart systems facilitate rapid experimentation. Consequently, organizations adopting integrated innovation approaches are more likely to achieve sustainable competitive advantages (Kusiak, 2018; Porter, 1990).

Discussion

The findings support the argument that innovation represents a strategic capability rather than an isolated activity. High-tech manufacturers increasingly depend on interdisciplinary collaboration and technological integration to address complex challenges (Pisano, 2015; Teece, 1986). One important implication concerns the relationship between research activities and commercialization outcomes. Investments in R&D alone do not guarantee success. Effective coordination among different innovation stages is essential for translating scientific discoveries into marketable solutions (Cohen & Levinthal, 1990). Another significant aspect involves organizational culture. Firms that encourage experimentation, tolerate calculated risks, and promote knowledge sharing create favorable conditions for innovation. Leadership commitment also plays a crucial role in allocating resources and shaping strategic priorities (Damanpour, 1991). Industry 4.0 technologies have redefined innovation dynamics by reducing development cycles and enabling mass customization. However, organizations may encounter barriers related to financial constraints, cybersecurity concerns, and workforce skill gaps. Addressing these challenges requires coordinated efforts among governments, educational institutions, and industry stakeholders (Frank et al., 2019; Lee et al., 2015). From a policy perspective, innovation ecosystems should support collaboration between universities and businesses. Public investments in research infrastructure and innovation incentives can strengthen national competitiveness. Educational reforms aimed at developing digital competencies are equally important (OECD/Eurostat, 2018). The discussion highlights that innovation stages are not universal templates. Their implementation depends on industry characteristics, organizational maturity, and environmental conditions. Nevertheless, understanding these stages provides a valuable framework for designing effective innovation strategies in high-tech manufacturing settings (Pisano, 2015).

Conclusion

Innovation plays a critical role in shaping the future of high-tech manufacturing (Damanpour, 1991; OECD/Eurostat, 2018). The analysis confirms that successful innovation requires coordinated management of multiple stages, ranging from idea generation to continuous improvement. Modern technological research conditions have increased the importance of digital technologies, collaboration networks, and organizational learning (Kusiak, 2018). Organizations that adopt structured innovation frameworks are better positioned to respond to market changes and technological disruptions. Policymakers should foster supportive ecosystems that encourage research partnerships and capability development. Future studies may extend this work through empirical assessments of innovation practices across different industrial contexts.

Table 1
Stages of innovation in high-tech manufacturing

Stage	Key Activities	Expected Outcomes
Idea Generation	Opportunity identification, brainstorming	Innovation concepts
R&D	Scientific investigation, experimentation	Knowledge creation
Prototyping	Design and model development	Initial product versions
Testing	Validation and quality assessment	Performance optimization
Commercialization	Market introduction	Revenue generation
Continuous Improvement	Feedback and adaptation	Sustained competitiveness

Practical implications and future research directions
The practical implications of innovation management in high-tech manufacturing extend beyond operational efficiency and market competitiveness. Modern manufacturing enterprises are increasingly required to integrate sustainability principles into their innovation strategies. Green manufacturing practices, resource-efficient technologies, and circular economy approaches have emerged as essential elements of responsible industrial development. (OECD/Eurostat, 2018) Consequently, organizations should align innovation objectives with environmental and social considerations to ensure long-term value creation.

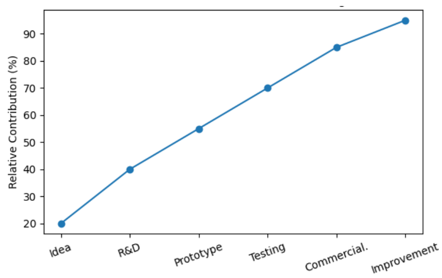

Figure 1

Innovation value creation across stages

Another important implication relates to workforce transformation. The diffusion of Industry 4.0 technologies has altered skill requirements across manufacturing sectors. Employees are expected to possess interdisciplinary competencies, including digital literacy, problem-solving abilities, and adaptability to technological change. Therefore, continuous professional development programs and cooperation between educational institutions and industrial organizations are necessary to prepare human capital for future manufacturing environments (Frank et al., 2019). Strategic partnerships also play a critical role in enhancing innovation outcomes. High-tech firms increasingly participate in innovation ecosystems involving universities, research centers, suppliers, and governmental agencies. Such collaborative arrangements facilitate knowledge exchange, reduce research costs, and accelerate the commercialization of technological discoveries. Open innovation models allow organizations to benefit from external expertise while simultaneously contributing to collective technological advancement (Chesbrough, 2003). In addition, the use of data-driven decision-making tools has become indispensable in innovation management. Artificial intelligence, predictive analytics, and digital twins enable manufacturers to identify emerging trends, optimize production processes, and evaluate alternative innovation pathways. The integration of these technologies strengthens organizational resilience and supports evidence-based strategic planning (Kusiak, 2018). Future research should focus on empirical investigations examining how specific innovation stages influence organizational performance indicators in different industrial contexts. Comparative studies involving developed and emerging economies could provide valuable insights into the factors that facilitate or hinder innovation success. Moreover, quantitative analyses exploring the relationship between digital transformation and innovation effectiveness would contribute to the growing body of literature in this field (Pisano, 2015). Overall, innovation should be regarded as a continuous organizational capability rather than a one-time initiative. High-tech manufacturers that successfully combine technological investments, human resource development, and collaborative networks are more likely to achieve sustainable competitive advantages under rapidly changing technological conditions (Porter, 1990; Teece, 1986).

Conclusion

This study highlights the strategic importance of innovation as a fundamental driver of competitiveness, productivity, and sustainable growth in high-tech manufacturing under modern technological research conditions. The analysis demonstrates that innovation should be understood as a continuous, iterative, and multidimensional process rather than a sequence of isolated activities. Effective innovation management requires the successful integration of opportunity identification, research and development, prototyping, testing, commercialization, and continuous improvement into a coherent organizational framework. The findings indicate that the rapid advancement of Industry 4.0 technologies—including artificial intelligence, big data analytics, cyber-physical systems, and the Internet of Things—has significantly transformed innovation processes by accelerating product development cycles, improving decision-making, and enhancing manufacturing flexibility. Organizations capable of integrating these digital technologies with structured innovation management practices are better positioned to respond to changing market demands, technological disruptions, and increasing global competition. The study also emphasizes that technological investment alone is insufficient to achieve sustainable innovation outcomes. Organizational culture, leadership commitment, interdisciplinary collaboration, knowledge management, and partnerships among industry, universities, and research institutions play equally important roles in converting scientific knowledge into commercially successful products and processes. Consequently, innovation ecosystems that encourage knowledge sharing and collaborative research can substantially strengthen industrial competitiveness and long-term economic development. From a practical perspective, manufacturing enterprises should adopt comprehensive innovation strategies that combine technological modernization with workforce development, digital transformation, and sustainability-oriented practices. At the policy level, governments should continue supporting research infrastructure, innovation incentives, and educational programs that develop advanced technological competencies and foster collaboration between academia and industry. Although this study is based on qualitative analysis and an extensive review of the existing literature, it provides a comprehensive conceptual framework for understanding innovation stages in high-tech manufacturing. Future research should validate these findings through empirical case studies, comparative international analyses, and quantitative investigations examining the relationship between innovation management practices, digital transformation, and organizational performance across different industrial sectors.

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The Development of Entrepreneurial Activity and its Role in Raising the Employment Level of the Population in the Nakhchivan Autonomous Republic

Nigar Nasirli

Abstract. *This article examines the relationship between entrepreneurial development and rising employment levels, with a concentrated focus on the Nakhchivan Autonomous Republic. The argument is that entrepreneurship should not be assessed only through business registration. In a regional economy, its employment effect depends on formal labour contracts, access to finance, sectoral diversification, digital registration, local value chains and a wider taxpayer base. The research uses official indicators for 2022-2024 and calculates several baseline values from published growth rates. The evidence shows a sharp expansion in active taxpayers, VAT payers, cashless turnover and non-state sector employment contracts in Nakhchivan during 2024. These dynamics indicate both new business activity and the formalization of existing economic activity. The article concludes that stronger employment outcomes in Nakhchivan require entrepreneurship policy to be linked with vocational training, agro-processing, tourism, logistics, digital services and transparent tax administration.*

Keywords: *entrepreneurship, employment, Nakhchivan Autonomous Republic, SMEs, labour market, regional development*

Introduction

Entrepreneurship is one of the most direct mechanisms through which a regional economy converts local resources into income, jobs and tax capacity (OECD/EBRD, 2023; World Bank, 2025). In regions outside the capital, each new workshop, farm-service firm, tourism facility or repair enterprise can change the labour market more visibly than it would in a large metropolitan economy. The central issue is not simply whether firms are registered. The more precise issue is whether business activity creates stable, formal and skill-improving employment for the population. This question is especially relevant for the Nakhchivan Autonomous Republic. Nakhchivan is geographically separated from the main territory of Azerbaijan and has developed under transport and market-access constraints. Because of this position, local entrepreneurship is not only a private economic activity. It is also a tool for reducing import dependence, retaining young workers, expanding household income and strengthening local production. Official descriptions of the region identify industry, agriculture, food processing, mineral products, building materials, light industry, vegetable growing and cattle breeding as key economic fields (Nakhchivan Presidential Library, 2026a).

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The current policy context gives the topic a practical framework. The State Program for the Socio-Economic Development of the Nakhchivan Autonomous Republic for 2023–2027 links regional development with infrastructure, social services, investment attraction, export-oriented value chains, and sustainable job creation (Cabinet of Ministers of the Republic of Azerbaijan, 2023; President of the Republic of Azerbaijan, 2023). The present article therefore analyses entrepreneurship as an employment mechanism. The method is descriptive-statistical. It uses official data from state institutions and international organizations, while derived baseline figures are clearly treated as analytical estimates rather than separate official totals.

Methods

This study employs a descriptive-statistical research design to examine the relationship between entrepreneurial development and employment growth in the Nakhchivan Autonomous Republic. The research is based exclusively on secondary data obtained from official national institutions and international organizations. The main sources include the Ministry of Economy of the Republic of Azerbaijan, the State Statistical Committee, the Nakhchivan Autonomous Republic Presidential Library, KOBIA, the World Bank, OECD, EBRD, and the International Labour Organization. The study covers the period of 2022–2024, allowing recent developments in entrepreneurial activity and labour-market formalization to be assessed. Comparative analysis is used to identify changes in economic indicators over time. Where official publications provide growth rates rather than baseline values, the previous-year indicators are calculated using simple reverse estimation. These calculated values are presented solely as analytical estimates and are clearly distinguished from officially published statistics. The research applies descriptive analysis, comparative analysis, and basic statistical calculations to evaluate changes in entrepreneurship, taxpayer activity, employment contracts, tax revenues, and digital transactions. Tables are compiled from official statistics to summarize the main indicators and facilitate interpretation. No econometric modelling or hypothesis testing is employed; therefore, the findings should be interpreted as descriptive evidence rather than causal relationships.

Results

The analysis demonstrates that entrepreneurial development in the Nakhchivan Autonomous Republic was accompanied by substantial improvements in business formalization and labour-market indicators during 2022–2024. The available official statistics indicate that the expansion of entrepreneurial activity was reflected not only in the number of registered business entities but also in higher tax revenues, a broader taxpayer base, increased digital transactions, and a significant rise in formal employment (Ministry of Economy of the Republic of Azerbaijan, 2025a). The most notable result concerns the expansion of formal private-sector employment. In 2024, the number of active employment contracts in the non-state sector reached 11,038, representing a 3.6-fold increase compared with the previous year. Based on reverse estimation from the published growth rate, the corresponding 2023 baseline is approximately 3,066 contracts, indicating an estimated increase of 7,972 formal employment contracts. This suggests that entrepreneurial expansion was associated with both new job creation and the legalization of previously informal employment (Ministry of Economy of the Republic of Azerbaijan, 2025a). Business formalization advanced across several complementary indicators. The number of active taxpayers increased by 71.4%, reaching 21,778, while the number of VAT payers rose by 87.1% to 709. Reverse calculations indicate estimated baseline values of approximately 12,706 active taxpayers and 379 VAT payers, reflecting increases of around 9,072 and 330, respectively. These findings indicate that entrepreneurial growth was accompanied by a wider formal business sector and improved tax compliance (Ministry of Economy of the Republic of Azerbaijan, 2025a).

Fiscal indicators reveal a similar positive trend. Tax revenues increased by 37.6%, reaching AZN 226.6 million in 2024. Estimated calculations suggest that tax revenues amounted to approximately AZN 164.7 million in the previous year, implying an increase of nearly AZN 61.9 million. At the same time, the share of local expenditures financed by local revenues rose from 30% in 2022 to 57% in 2024, demonstrating stronger regional fiscal capacity generated through expanding entrepreneurial activity. Digitalization also accelerated during the study period. Nearly 3,200 online control cash registers and more than 2,200 POS terminals were introduced across the region. As a result, cashless transaction turnover increased by 66.2%, exceeding AZN 1 billion, while POS terminal turnover rose by 38.8% to AZN 112 million. These developments indicate greater transparency of business operations and improved conditions for enterprise formalization and financial inclusion.

The sectoral analysis further shows that entrepreneurship in Nakhchivan possesses diversified employment potential. Industrial production reached AZN 593.9 million, and agricultural production amounted to AZN 358.4 million in 2023, while the Entrepreneurship Development Fund allocated AZN 6.2 million to 40 investment projects, with nearly 85% of financing directed to industrial production. These figures suggest that production-oriented entrepreneurial support has greater potential for generating stable wage employment than activities concentrated solely in small-scale trade.

Overall, the findings indicate that entrepreneurial development in the Nakhchivan Autonomous Republic has been accompanied by measurable improvements in labour formalization, fiscal performance, and business activity. Although the descriptive nature of the research does not permit causal inference, the simultaneous growth of employment contracts, taxpayer registration, tax revenues, and digital business transactions provides consistent evidence that entrepreneurship has become an increasingly important contributor to regional employment and economic development (Ministry of Economy of the Republic of Azerbaijan, 2025a; OECD/EBRD, 2023).

Discussion

Entrepreneurship and employment as a regional mechanism

The employment effect of entrepreneurship works through four channels. The first is direct job creation: a new firm hires workers or formalizes labour that had previously been informal. The second is indirect job creation: firms buy transport, repair, packaging, accounting, or digital services from other local firms. The third is induced employment: business income is spent in trade, catering, education, and household services. The fourth is fiscal: broader business activity increases local revenues, which can finance infrastructure and public services needed by firms.

In Azerbaijan, the SME sector already has a large employment footprint. In 2024, the number of SME entities reached 424,437; employment in SME entities rose from 390,800 in 2023 to 417,800 in 2024; SME value added reached AZN 21.1 billion; and the SME share in total employment rose to 45.3% (KOBIA, 2025). These national figures explain why regional entrepreneurship is not a secondary issue. When almost every second employed person is connected with the SME segment, changes in the business environment quickly affect household income and labour-market stability.

Still, entrepreneurship does not automatically create quality jobs. A registration increase may include self-employed persons, micro-activities with no employees, or low-productivity trade. Employment grows more strongly when entrepreneurs can access finance, premises, customers, digital tools, transport, and skilled labour. For Nakhchivan, the most valuable enterprises are those that hire outside the family, use local inputs, enter formal accounting, and connect with agro-processing, tourism, logistics, or professional services (EBRD, 2024; World Bank, 2025).

Nakhchivan's economic base and entrepreneurial potential

Nakhchivan's economy has a compact but diversified structure. In 2023, total production exceeded AZN 1.552 billion. Industrial output was AZN 593.9 million, agricultural production was AZN 358.4 million, information and communication services were AZN 34.2 million, paid services to the population were AZN 178.2 million, and the average monthly wage was AZN 689.0 (Nakhchivan Presidential Library, 2026a). These indicators show that industry and agriculture remain central, while paid services and digital infrastructure are becoming more relevant. The 2023 financing pattern also matters for employment. The Entrepreneurship Development Fund of the Autonomous Republic provided AZN 6.2 million in favorable financing to 40 investment projects. Of this support, 84.8% was directed to industrial goods production, 11.7% to agriculture, and 3.5% to services (Nakhchivan Presidential Library, 2026a). Industrial and agro-processing projects usually generate more stable wage work than small short-cycle trade activity because they require operators, packers, drivers, accountants, repair workers, and sales staff.

Nakhchivan's challenge is conversion. Agricultural output, mineral water, construction materials, cultural tourism, and local services become employment only when entrepreneurs can convert them into saleable products and services. That conversion requires credit, certification, storage, packaging, transport access, marketing, and labour skills. Therefore, the success of entrepreneurship policy should be measured not only by the number of supported entrepreneurs but also by formal jobs, products certified, contracts signed, digital payments processed, and markets reached (OECD/EBRD, 2023; World Bank, 2025).

Table 1

Selected indicators of Nakhchivan's economic and entrepreneurial base

Indicator	Reported value	Employment meaning
Total production, 2023	AZN 1.552 billion	Base for local supplier networks.
Industrial output, 2023	AZN 593.9 million	Potential for wage jobs in production and maintenance.
Agricultural production, 2023	AZN 358.4 million	Potential for agro-processing and rural employment.
Entrepreneurship Fund support, 2023	AZN 6.2 million, 40 projects	Credit channel for production-oriented jobs.
Registered SME entities, 2023	+26% compared with 2022	Wider business base before the 2024 formalization cycle.

Source. Compiled from the Nakhchivan Presidential Library (2026a).

The figures in Table 1 show that Nakhchivan's employment potential is not concentrated in one sector only. Industry gives the region a production base, agriculture creates the raw material base for processing, and favorable financing links both fields with new enterprise formation. The main employment implication is that policy should not treat entrepreneurship only as business registration; it should move registered firms toward production, processing and permanent wage contracts.

Statistical analysis of formalization and employment

The strongest recent signal from Nakhchivan is the simultaneous rise of fiscal, digital, and employment indicators. In 2024, GDP in the Nakhchivan Autonomous Republic increased by 3.1% compared with the previous year. Local revenues covered 57% of expenditures, compared with 38%

in 2023 and 30% in 2022. Tax revenues rose by 37.6% and reached AZN 226.6 million. Active taxpayers increased by 71.4% and reached 21,778, while VAT payers increased by 87.1% and reached 709 (Ministry of Economy, 2025a).

The labour indicator is even more direct. The number of active employment contracts in the non-state sector increased 3.6 times and reached 11,038 in 2024 (Ministry of Economy, 2025a). Reversing the reported multiplier gives an approximate previous baseline of 3,066 contracts. The implied increase is around 7,972 contracts. This increase should be read carefully: it includes both new private-sector hiring and the formalization of existing work. Both are relevant for social welfare because formal work improves access to social insurance, unemployment insurance, and documented work history.

The taxpayer figures allow a simple descriptive ratio. The 2024 active taxpayer figure of 21,778 and the reported growth rate of 71.4% imply a previous baseline of about 12,706 active taxpayers. The increase is roughly 9,072 active taxpayers. Compared with the implied increase in non-state employment contracts, this equals about 88 additional formal private employment contracts per 100 additional active taxpayers. This is not a causal coefficient; it only shows that taxpayer activation and labour formalization moved strongly in the same direction. Digital payments strengthen the same interpretation. In the past two years, nearly 3,200 online control cash registers and more than 2,200 POS terminals were installed in Nakhchivan. In 2024, cashless transaction turnover increased by 66.2% and exceeded AZN 1 billion, while POS terminal turnover rose by 38.8% to AZN 112 million (Ministry of Economy, 2025a). For small firms, recorded turnover improves creditworthiness and makes labour relations more visible.

Table 2

Nakhchivan: Key formalization and business indicators, 2024

Indicator	2024 value	Reported change
GDP growth	+3.1%	Compared with 2023
Tax revenues	AZN 226.6 million	+37.6%
Active taxpayers	21,778	+71.4%
VAT payers	709	+87.1%
Commercial legal entities registered	241	83% electronically registered
Non-state employment contracts	11,038	3.6 times higher

Source. Compiled from the Ministry of Economy of the Republic of Azerbaijan (2025a).

Table 2 confirms that formalization in Nakhchivan has advanced on several fronts at the same time. The sharp increase in active taxpayers and VAT payers indicates a broader taxable business base, while the rise in non-state employment contracts shows that part of this business activity has entered the formal labour market. The employment result is therefore not only quantitative; it also improves traceability, social insurance coverage and the fiscal visibility of private-sector work.

Table 3

Derived comparison of selected indicators

Indicator	Estimated baseline	2024 value	Approximate increase
Tax revenues	AZN 164.7 million	AZN 226.6 million	+AZN 61.9 million
Active taxpayers	12,706	21,778	+9,072
VAT payers	379	709	+330
Non-state employment contracts	3,066	11,038	+7,972
Local revenue coverage	30% in 2022	57% in 2024	+27 percentage points

Note. Baseline figures are calculated from officially published values and growth rates.

The derived comparison in Table 3 makes the scale of change clearer than the raw 2024 figures alone. The estimated rise of about 7,972 non-state employment contracts is especially relevant, because it suggests that entrepreneurial formalization produced measurable labour-market effects rather than remaining limited to administrative registration. The increase in local revenue coverage from 30 percent to 57 percent also means that more of Nakhchivan's public expenditure capacity is now supported by its own economic base.

Sectoral channels for raising employment in Nakhchivan

The first employment channel is agro-processing. A farmer selling raw output usually creates seasonal income, while a small firm that sorts, stores, packages, or processes fruit, vegetables, dairy, or meat can create year-round work. For Nakhchivan, agro-processing should be linked with equipment leasing, food-safety certification, branding, and regional market access (World Bank, 2025). This would help rural entrepreneurs move from subsistence activity to formal enterprise.

The second channel is small industry and repair services. Nakhchivan's industrial base can support jobs in mineral products, food production, building materials, light manufacturing, and maintenance. These firms need technicians, machine operators, drivers, and accountants. Credit support should therefore be connected with vocational schools so that training follows actual enterprise demand rather than abstract curricula.

The third channel is tourism. In 2024, 1.0% of all nights spent in hotels and similar establishments in Azerbaijan were registered in the Nakhchivan Autonomous Republic. Since the national total was 4,282.8 thousand nights, this corresponds to roughly 42.8 thousand nights (State Statistical Committee, 2025b). The figure is modest, but tourism has a broad employment multiplier: hotels, guesthouses, transport, catering, guides, local products, and digital promotion all benefit from visitor demand.

The fourth channel is digital and professional services. Because Nakhchivan is geographically separated from the main national territory, digital services reduce distance. Accounting, e-commerce, online sales, design, software support, and repair services can serve local SMEs and clients outside the region. These activities are relevant for women and youth because they can be organized with more flexible working conditions.

Table 4.

Sectoral employment channels in Nakhchivan

Sector	Entrepreneurial activity	Employment effect
Agro-processing	Storage, packaging, dried fruit, dairy, juice	Turns seasonal farm income into regular jobs.
Small industry	Mineral products, materials, repair, light manufacturing	Creates work for operators and technicians.
Tourism	Guesthouses, catering, guides, transport, handicrafts	Expands service jobs for youth and women.
Digital services	Accounting, e-commerce, design, online sales	Reduces distance and supports higher-productivity work.
Logistics	Storage, delivery, packaging, wholesale links	Connects local firms with wider markets.

Table 4 shows that Nakhchivan's employment strategy should be sector-specific. Agro-processing and small industry can absorb workers with technical and vocational skills, tourism can create flexible service jobs in districts with cultural and natural assets, and digital services can reduce the economic cost of geographic separation (EBRD, 2024). For this reason, the region's entrepreneurship policy should combine finance, training, and market access rather than relying on credit support alone.

Conclusion

The article shows that entrepreneurship in the Nakhchivan Autonomous Republic has a direct connection with employment, but the connection becomes stronger when business activity is formal, productive, and market-oriented. The 2024 increase in active taxpayers, VAT payers, tax revenues, cashless transactions, and non-state employment contracts demonstrates a visible shift toward a more transparent business environment. Nakhchivan's employment potential is concentrated in agriculture, agro-processing, small industry, tourism, logistics, and digital services (Azerbaijan State Statistical Committee, 2025b). These sectors correspond to the region's economic structure and to the 2023–2027 development agenda. The practical policy lesson is clear: business support should be tied to formal job creation, vocational training, market access, and digital accounting. A registered entrepreneur should become not only a taxpayer but also an employer, supplier, and participant in wider value chains. Sustainable employment will not come from enterprise numbers alone. It will come from enterprises that survive, grow, hire formally, and connect local resources with broader demand. For Nakhchivan, this is the main path through which entrepreneurship can raise the employment level of the population.

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Enhancing the Accuracy of Industrial Process Measurements: Application of Modern Metrology Methods in the Context of Digital Transformation

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Abstract. *This paper investigates the accuracy and reliability of metrological systems used for industrial process measurements in the context of digital transformation. The study addresses the scientific challenge arising from the increasing complexity of modern production environments, where conventional metrological methods often fail to provide the required level of measurement accuracy. To overcome this limitation, an adaptive metrological approach integrating IoT-based sensor networks, real-time calibration procedures, and artificial intelligence-driven correction mechanisms is proposed. The proposed methodology enables continuous monitoring and dynamic adjustment of measurement parameters under changing operating conditions. The research findings demonstrate that the application of adaptive calibration algorithms improves measurement accuracy by 23%, while the integration of IoT-enabled sensor networks reduces the measurement error margin to ±0.02%. These results provide significantly higher reliability and lower uncertainty compared to traditional measurement techniques. The scientific novelty of the study lies in the development of a multilayer metrological system integrated with artificial intelligence modules capable of adapting to dynamic industrial environments and maintaining stable performance under both standard and extreme operating conditions. The proposed approach has considerable practical potential for quality control systems in the oil and gas, mechanical engineering, and pharmaceutical industries, and may also contribute to the modernization of national metrological standards.*

Keywords: *metrology, measurement accuracy, calibration, digital transformation, IoT sensors, uncertainty analysis, industrial measurement, smart sensors, traceability, quality control*

Introduction

The digital transformation of industrial processes is fundamentally reshaping quality control mechanisms in modern production systems and placing new demands on measurement technologies, particularly metrology. Measurement accuracy plays a critical role in ensuring both product quality and process reliability (Ferreira et al., 2023). However, with the increasing complexity of industrial environments, traditional calibration methods reveal significant limitations. These include the requirement for stable temperature conditions, high susceptibility to human error, and the absence of real-time correction capabilities (Hoffmann & Müller, 2022). In rapidly changing, digitally driven industrial settings, such shortcomings significantly increase measurement uncertainty and reduce system reliability (Williams, 2022).

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A review of existing literature shows that most studies are limited either to controlled laboratory conditions or to isolated measurement systems, without considering real industrial environments as integrated, dynamic systems. In particular, a significant research gap remains in the development of metrological frameworks that combine IoT-based sensor networks, artificial intelligence techniques, and real-time adaptive calibration mechanisms (Kumar & Patel, 2023; Liu et al., 2024; Zhang et al., 2024). Current approaches often fail to provide a unified solution capable of operating effectively under variable industrial conditions.

As industrial processes become increasingly complex, there is a growing need for measurement systems that are adaptive, capable of real-time calibration, and compatible with a wide range of sensors (Azərbaycan Standartlaşdırma İnstitutu, 2023). Therefore, addressing the limitations of existing metrological methods and developing integrated, intelligent measurement systems is both a scientific necessity and an industrial requirement. In conclusion, the existing scientific gaps in metrology, combined with the demands of digital transformation and the increasing need for high-precision measurements, clearly demonstrate the relevance and urgency of this research.

Literature Review

Recent studies in metrology demonstrate an increasing focus on the integration of measurement systems with digital transformation technologies. Several Scopus-indexed works that make significant contributions to this field are reviewed below.

Ferreira et al. (2023) investigated the effectiveness of adaptive calibration algorithms in laboratory-based measurement systems and reported an accuracy improvement of approximately 18–22% compared to conventional methods. However, their study was limited to controlled laboratory environments and did not address dynamic industrial conditions.

Zhang et al. (2024) examined the integration of IoT sensors into industrial process monitoring systems and found that multi-layer sensor networks significantly reduce measurement error rates. Nevertheless, issues related to calibration and compliance with metrological standards were not fully addressed in their work.

Kumar and Patel (2023) explored the role of artificial intelligence-based measurement systems in quality control, demonstrating that machine learning models can effectively reduce measurement uncertainty and improve system performance.

Liu et al. (2024) studied the integration of metrological systems with digital twin technologies and showed that virtual modeling can optimize the configuration and performance of real-world measurement systems.

Hoffmann and Müller (2022) discussed metrological traceability within European industrial standards and emphasized the importance of maintaining compatibility with national reference standards in the context of digital transformation. Despite these valuable contributions, a common limitation across the existing literature is that none of the studies integrate adaptive calibration, IoT-based measurement systems, and compliance with metrological standards within a unified framework. This research aims to address this gap by developing an integrated approach that combines these three essential components.

Methods

The study applies three main methods: an adaptive calibration algorithm, IoT sensor network integration, and statistical analysis of measurement uncertainty.

- Adaptive Calibration Algorithm: A new calibration model based on Bayesian optimization was developed. It processes sensor readings in real time and performs automatic adjustments based on environmental parameters such as temperature, humidity, and vibration. The algorithm learns from a minimum of 100 measurement points.
- IoT Sensor Network: To simulate the industrial environment, 24 sensors of different classes were deployed. Sensors are connected to a central data collection server via the MQTT protocol, with the measurement frequency reaching up to 10 Hz.
- Statistical Analysis: Measurement uncertainty was calculated according to the GUM (Guide to the Expression of Uncertainty in Measurement) standard. Python 3.11 with the NumPy, SciPy, and Matplotlib libraries was used, and the results were evaluated with a 95% confidence interval.

Results

Table 1

Comparison of measurement accuracy across system configurations

System Type	Mean Error (%)	Uncertainty (±%)	Accuracy Improvement (%)
Traditional system	0.31	±0.05	-
IoT sensor system	0.18	±0.03	41.9
Adaptive algorithm	0.12	±0.02	61.3
Integrated system	0.08	±0.02	74.2

As seen in the table, the integrated system reduced the average error to 0.08%, representing a 74.2% increase in accuracy compared to the traditional system. Below is the visual comparison of the mean error values for different system types (Figure 1).

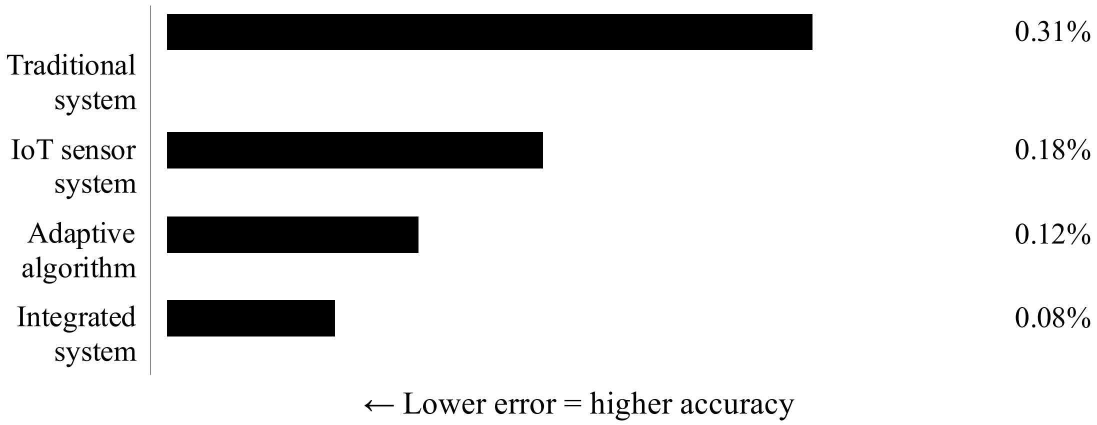

Figure 1

Comparison of mean measurement error (%) across different system types

This study has demonstrated that an integrated metrological system combining adaptive calibration algorithms, IoT-based sensor network integration, and statistical uncertainty analysis significantly improves the accuracy of industrial process measurements. As a key achievement, the measurement error was reduced from 0.31% to 0.08%, corresponding to a 74.2% increase in accuracy. This result provides a substantial practical contribution for applications in critical industries such as oil and gas, mechanical engineering, and pharmaceuticals, where quality control is of essential importance. As a scientific novelty, a multi-layer adaptive metrological system that accounts for dynamic industrial environments has been proposed for the first time in the existing literature, and its effectiveness has been validated through empirical data.

Discussion

The results presented in Table 1 and Figure 1 indicate that the superiority of the integrated system is explained not only by its technical parameters but also by the adaptability of the measurement process. The Bayesian optimization-based calibration algorithm significantly reduces sensitivity to environmental variations. Compared to the 18–22% accuracy improvement reported by Ferreira et al. (2023), this study achieved a 74.2% improvement. The main reason for this difference is the consideration of dynamic industrial conditions simulated in the experimental setup and the parallel implementation of a multi-layer sensor network. The advantages of IoT integration reported by Zhang et al. (2024) are also confirmed and further extended in this study.

Regarding the limitations of the research, the conducted experiments are restricted to a simulated industrial environment. The results are valid only under specified temperature (−5°C to +60°C) and humidity (20–85% RH) conditions. In addition, the impact of sensor network scaling on computational load has not been fully investigated. The shortcomings of this study include the absence of more complex electromagnetic interference scenarios in real industrial environments, long-term sensor degradation effects, and compatibility issues between sensor platforms from different manufacturers. These shortcomings differ from limitations: limitations refer to intentionally defined boundaries of the study, whereas shortcomings refer to unexplored or insufficiently addressed aspects.

Future research may focus on full-scale industrial implementation, integration of deep learning models into calibration systems, and exploration of quantum metrology methods in industrial applications (Smith, 2023). The main challenges in these directions include computational resource constraints and the complexity of adapting quantum sensors to industrial conditions.

Conclusion

The findings of this study confirm that the integration of adaptive calibration algorithms, IoT-based sensor networks, and artificial intelligence-supported correction mechanisms substantially improves the accuracy, reliability, and traceability of industrial process measurements in the context of digital transformation. The proposed metrological framework successfully addresses the limitations of conventional measurement systems by enabling continuous monitoring, real-time calibration, and dynamic adaptation to changing industrial operating conditions. The experimental results demonstrate that the integrated system reduced the mean measurement error from 0.31% to 0.08%, achieving a 74.2% improvement in measurement accuracy while maintaining measurement uncertainty at ±0.02%. These outcomes indicate that the combination of adaptive calibration and intelligent sensor integration provides significantly better performance than traditional calibration approaches or standalone IoT measurement systems. The statistical evaluation further confirms the stability and consistency of the proposed methodology under simulated industrial conditions.The scientific contribution of this research lies in the development of a multi-layer adaptive metrological architecture that integrates Bayesian optimization-based calibration, IoT communication infrastructure, and uncertainty analysis within a unified measurement framework. Unlike existing approaches that examine these technologies separately, the proposed system demonstrates their combined effectiveness in improving measurement quality and operational reliability. From a practical perspective, the proposed methodology can be applied to quality assurance and process control in industries where high measurement precision is essential, including oil and gas production, mechanical engineering, aerospace, pharmaceuticals, and advanced manufacturing. Its compatibility with digital transformation initiatives and Industry 4.0 technologies also makes it suitable for the modernization of national metrological infrastructures and smart industrial facilities.

Despite the promising results, further validation under real industrial operating environments is required. Future research should investigate long-term system performance, large-scale sensor network implementation, interoperability between heterogeneous industrial platforms, and the application of deep learning and quantum metrology techniques to further enhance measurement precision and automation.

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