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Modelling Moisture Dynamics of Agricultural Steppe Soils in the Greater Caucasus

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Abstract. *The aim of the work is to study the dynamics of moisture and the process of moisture infiltration in grey-brown ordinary plowed soil under conditions of natural moisture, after precipitation. The relevance of this research problem is also determined by the progressive degradation of the soil cover, its intensive exploitation, the deterioration of the water and nutrient regime of agricultural soils, erosion, desertification, and salinization. Accurate information on the water regime of steppe zone soils is crucial for maintaining their biological productivity. The modeling data correlates well with experimental data on changes in soil moisture, which will allow for future forecasts and hydromeliorative calculations. The main hydrological parameters of the soil (approximation parameters of the main hydrophysical characteristic) of the agricultural landscape soils were obtained using Rosetta Lite pedotransfer functions in the RETC program, using data on particle size distribution, density, porosity, minimum water capacity, wilting point, and yield point moisture content. It was found that the α parameter (the reciprocal of the capillary air entry pressure during soil drying) is significantly lower in the upper arable horizon than in the denser B and C horizons, which is typical for soils subject to tillage. Moisture chronoisopleths were constructed in the Surfer program, clearly reflecting changes in the moisture status of the soil horizons of the arable steppe during and after rainfall. It has been established that, as early as the third day after precipitation and with the initial moisture level in the upper arable horizon, the pressure in all soil layers equalizes. In the absence of a pressure gradient, the downward flow of moisture between horizons virtually ceases.*

Keywords: *capillary-sorption pressure, hydrological and hydrophysical characteristics, soil humidity, pedotransfer functions, modeling, vegetation*

Introduction

Moisture monitoring is a critical factor in crop yield management and adaptation to dry periods. Studying these processes in soils or assessing the impact of tillage operations helps prevent water stress in crops. The processes of water entry into the soil, its subsequent retention and distribution are an important component of the regime of any soil and are significantly determined by the physical properties of the soil – density, porosity, particle size distribution (Bunyatova et al., 2025; Gahramanova et al., 2026; Hasanova & Mammadova, 2023).

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In the dry steppe soils, where atmospheric moisture is practically the only source of water, the process of water absorption and its subsequent redistribution in the soil unsaturated with moisture is of particular interest – infiltration, which divides precipitation on the earth's surface into surface runoff and water entering the soil profile. In Azerbaijan, effective management of irrigation and soil agrophysical properties is critical to protecting crops from precipitation shortages. Automatic weather stations and specialized sensors are used to more accurately calculate water consumption and monitor moisture dynamics (Hasanova et al., 2026; Hasanova Baba-zade et al., 2026; Ismayilov et al., 2025; Ismayilova et al., 2025a).

The primary quantitative characteristic of soil water-holding capacity is the fundamental hydrophysical characteristic the relationship between the capillary-sorption pressure of moisture (Pk-s) and moisture content. Vertical moisture movement in unsaturated steppe soils is characterized by the hydraulic conductivity function the relationship between the coefficient of hydraulic conductivity (Kvl) and Pk-s. The HYDRUS 1D model allows for the calculation and modeling of moisture transfer processes in soils, taking into account their physicochemical and hydrophysical properties (Ismayilova et al., 2025b; Mammadova et al., 2025a; Makki et al., 2025). Using specialized hydrophysical experimental software, HYDRUS 1D accounts for the influence of soil structure on its hydraulic properties and enables the accurate calculation of moisture transfer processes in soils (Mirzezadeh et al., 2025; Mammadova et al., 2026a).

Materials and Methods

Field and laboratory studies were conducted using standard methods. Field moisture was determined using the thermostat-weight method (GOST 5180-84), soil bulk density was determined using the cutting ring method, and solid phase density was determined pycnometrically (Mammadova et al., 2025b). The soil granulometric composition was determined using the Kachinsky pipette method. Total porosity was determined as the ratio of the bulk density of the soil to the density of its solid phase (Mammadova et al., 2026b). The minimum water capacity (LWC) in the field was determined 24 hours after the completion of the flooding experiments for water permeability, the wilting point moisture content (WP) of plants was determined using the potting miniature method (seedlings) according to GOST 28268-89, the liquid limit (SL) was determined according to GOST 5180-84, using a balancing cone, and the maximum hygroscopicity (MH) of the soil was determined by saturating the soil with vaporous moisture according to GOST 28268-89 (Mirzezadeh & Mammadova, 2026; Nasirova et al., 2025).

The subjects of this study were gray-brown ordinary soils of agricultural landscapes on deluvial loamy-gravelly deposits. The basin floor is a vast, gently rolling plain, the topography of which is complicated by the channels of river tributaries. Currently, the soil cover of the basin floor consists mainly of almost completely plowed soils (Mazhar et al., 2025; Madnee et al., 2025). The average annual precipitation in the basin is 450–600 mm, with most of it falling between May and July, during which time the moisture coefficient is 0.7–0.8.

The key to achieving a good harvest in steppe agricultural landscapes is creating optimal moisture and heat conditions in the soil profile. This hydrothermal regime ensures adequate plant nutrition and influences their growth and development. In summer, when moisture is insufficient, cereal crops fail to establish tillers and lag in growth. In such cases, the primary agricultural practices should be aimed at creating moisture reserves in the soil through hydrological reclamation. However, this approach is impossible without knowledge of the basic hydrological properties of the cultivated soils (Ramazanova et al., 2026; Shukurov et al., 2025; Sadigov et al., 2025). The agricultural landscape in question occupies a leveled, topographically uniform area and is represented by a plot of arable land under oat crops. To approximate the main hydrophysical characteristics of agrocenoses, the Van

Genuchten equation, currently the most widely used in global soil science, was used. Soil particle size distribution parameters, adjusted to the FAO International Soil Classification System, were used, along with density data, HB (TH33 in Hydrus 1D), and VZ (TH1500). When calculating the approximation parameters of the main hydrophysical characteristic in the RETC program, additional parameters were specified for more accurate curve construction: the PT indicator – soil moisture in this state corresponds to a pressure of pF = 2.17, as well as the MG indicator, corresponding to pF = 4.5. Modeling of vertical moisture transfer in the basin soils was carried out in HYDRUS-1D for a 7-day period, consisting of no precipitation on the first day, followed by two days of rain with varying intensity, and then four days of virtually no precipitation (Sadigov et al., 2026; Verdiyeva et al., 2025).

Soil moisture samples were collected on the evening of July 10; in triplicate, several days before sampling (July 6 and the morning of July 10) it rained, and the upper arable horizon was noticeably wetter than the underlying soil layers. The moisture content of the A arable horizon was 26% (0.279 cm^3/cm^3), the B horizon – 18.5% (0.211 cm^3/cm^3), and the C horizon – 15% (0.176 cm^3/cm^3). Over the next two days (July 12 and 13), rain fell, with precipitation amounts of 18 and 7 mm. On July 14 and 15, only 0.5 mm of precipitation fell. There was no precipitation on the last two days of the study period, July 16 and 17. A second moisture sample was taken four days after the rain, on July 17 (before the evening rain). To model soil moisture movement during the study period, five periods differing in precipitation amounts were defined in the Time Variable Boundary Condition. Under conditions of high humidity and cool daytime temperatures, evapotranspiration will not significantly influence moisture dynamics in the upper horizon.

For the initial and final conditions, we adopted a potential transpiration value of 0.12 mm/day. To account for water uptake by plant roots, the Root Water Uptake option was selected in the Main process, and the appropriate root uptake parameters for a given crop were entered from the built-in database in The Root Water Uptake Parameters. The "Corn – vegetative period" was selected, during which optimal water uptake by oat roots (between P_{opt} and P2 pressures) occurs within a soil water pressure range of -25 to -500 cmH_2O, which corresponds to the initial natural conditions of water content (and pressure) in the studied steppes on the study dates. Chronoisopleths of soil moisture were plotted using Surfer. Using the Soil Profile – Graphical Editor, when plotting the distribution of root systems at depths of 0–15 (or 0–20) cm, the root density was set to a constant value, decreasing linearly throughout the profile depth (Nasirova et al., 2026; Verdiyeva et al., 2026).

Results and Discussion

The bulk density of the soil under study increases with depth, while the texture of the lower horizon is finer than that of the upper and middle horizons. The wilting point moisture content can also be determined by calculation, multiplying the maximum hygroscopicity of the soil under study by factors ranging from 1.3 to 1.6. For example, a factor of 1.35 is used for wheat. The wilting point moisture content values we obtained using the seedling method (according to GOST 28268-89) correlate with the maximum hygroscopicity index within ranges from 1.2 to 1.48. According to the study results, the maximum values of water-holding capacity and residual moisture are characteristic of the upper humus arable horizon, while the minimum values are characteristic of the parent material. A similar pattern was previously observed in leached soils. Using additional soil-hydrological data (expressed in % moisture) to calculate the approximation parameters of the main hydrophysical characteristic of the plowed depression soils significantly adjusted the shape of the resulting water-holding curve. When calculating the approximation parameters of the main hydrophysical characteristic, taking into account the wilting point, maximum hygroscopicity, and yield point, the saturation moisture content, residual moisture content, α, and n values changed significantly, especially in the upper soil horizon. The A arable horizon showed a very low α value the reciprocal of the air entry pressure into large capillaries as the soil dries immediately after saturation. The air entry pressure into large capillaries itself graphically corresponds to the location of the first inflection in the curve of the main hydrophysical characteristic: when the soil moisture pressure is close to 0 and begins to decrease as the soil dries, soil moisture content does not change immediately. Initially, only a change in the curvature of the capillary meniscus occurs, after which some of the large capillaries empty and air enters. It is believed that soil cultivation methods influence its physicochemical properties and key soil-hydrological characteristics: for example, the α value is significantly lower in soils that are constantly subject to plowing than in soils in natural landscapes. Scientists have found that the α value in soils cultivated without moldboard cultivation ($\alpha = 0.0227$) is higher than in traditionally tilled soils ($\alpha = 0.0187$).

Our previous studies also showed that in soils that are not subject to annual tillage (under hayfields), the α value is significantly higher than in soils under oats. To simulate the dynamics of moisture in Hydrus 1D, the initial soil moisture pressure was set for each horizon (without a smooth decrease) in the graphical editor under Initial conditions, corresponding to the initial moisture content: 450 cm H_2O in the upper arable horizon, 600 cm H_2O in the B horizon, and 900 cm H_2O in the lower horizon. The soil moisture pressure was determined based on the curves of the main hydrophysical characteristics obtained in the RETC program and the measured moisture content at the time of sampling. Since the precipitation rate of 1.8 cm/day is significantly lower than the filtration coefficient in the arable horizon (88 cm/day), complete saturation of the soil with moisture (to the level of $\theta s = 0.459$) cannot occur under natural steppe conditions. The moisture content in ordinary chestnut soils after precipitation of 18+7 mm was 0.316 cm^3/cm^3, or 30%, which is slightly below the level of the least water capacity (0.35 cm^3/cm^3, or 33%). The underlying layers (B and C horizons), under conditions of periodic moistening of the upper horizon, gradually become saturated with moisture; downward moisture outflow from the A to B and further to the C horizon occurs even during periods of no precipitation.

However, the high density of the B and C horizons prevents rapid moisture penetration into them. Water loss from the upper horizon, under conditions of high atmospheric humidity and insignificant evapotranspiration (but taking into account root moisture consumption), occurs gradually. At the end of the period under consideration, the pressure in all soil layers is practically equalized and the downward flow of moisture from the upper horizon to the lower ones practically ceases on the 7th day (Fig. 2a). On the first day of the experiment, July 11, when there was no precipitation, the moisture content in the upper soil horizon decreased due to root water consumption, transpiration, and downward moisture flow. The latter was reflected in an increase in moisture content in the B and C horizons and a gradual vertical equalization of soil moisture pressure (Fig. 2b). After rain on July 12 (18 mm), the moisture content in all soil horizons increased significantly. The second rain (7 mm) on July 13 did not lead to a significant increase in moisture content in the upper A horizon – the moisture moved deeper into the soil profile (Fig. 1a and 1b).

Over the next two days, the moisture content in the upper arable horizon decreased due to root water consumption and downward moisture flow, and the B and C horizons continued to become moist. However, by the 7th day of the experiment, the pressure in all soil layers equalizes; in the absence of a difference in pressure, the downward flow of moisture between horizons ceases, and the moisture content begins to gradually decrease not only in the A horizon, but also in the B and C horizons as a result of root consumption and the evapotranspiration process. Moisture penetration between the upper loosened and less dense arable horizons is hindered, in part due to the higher density of the B horizon. The high moisture capacity of the upper loose arable horizon does not ensure optimal water management throughout the entire soil layer. The difference in soil water pressure levels out fairly quickly, and further moisture saturation of the B and C horizons slows, although differences in moisture content remain noticeable. Moisture exchange between the B and C horizons occurs fairly uniformly. When comparing moisture data obtained experimentally and using HYDRUS 1D modeling, the results were found to be consistent, with small discrepancies (less than 5%). The model slightly underestimates moisture content in the A and B horizons, which may be due to an overestimate of moisture loss due to transpiration (in the A horizon). The discrepancy in the data may also be due to the hysteresis effect of the main hydrophysical characteristic, which was not taken into account in the modeling. It is known that, at the same moisture pressure, the moisture content of the main hydrophysical characteristic obtained during drying will be higher than during wetting. This may be why the actual moisture content of the soil, which gradually loses moisture during drying, turned out to be slightly higher than the calculated value.

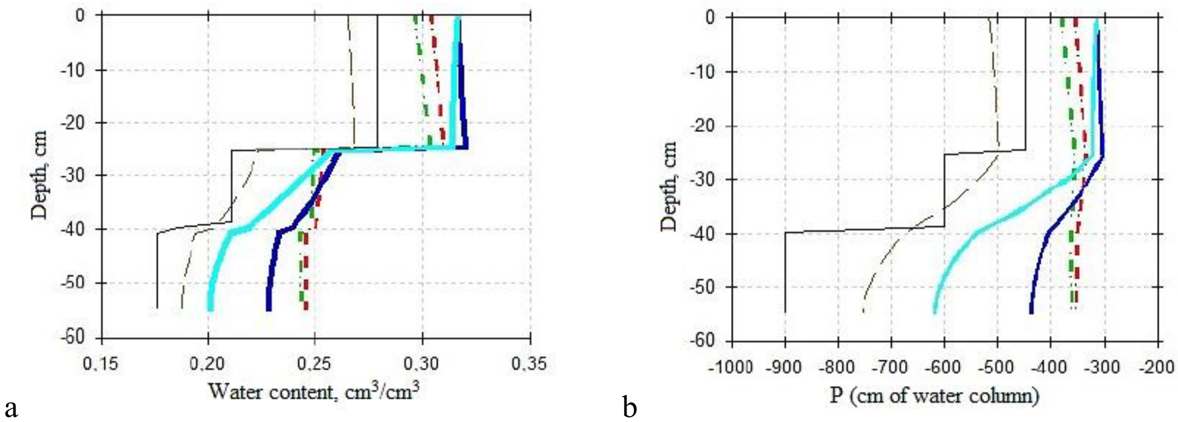

Figure 1

Dynamics of volumetric moisture: a) and moisture pressure; b) in a plowed field under oat crops in July 2024 under conditions of natural atmospheric moisture, after 25 mm of precipitation

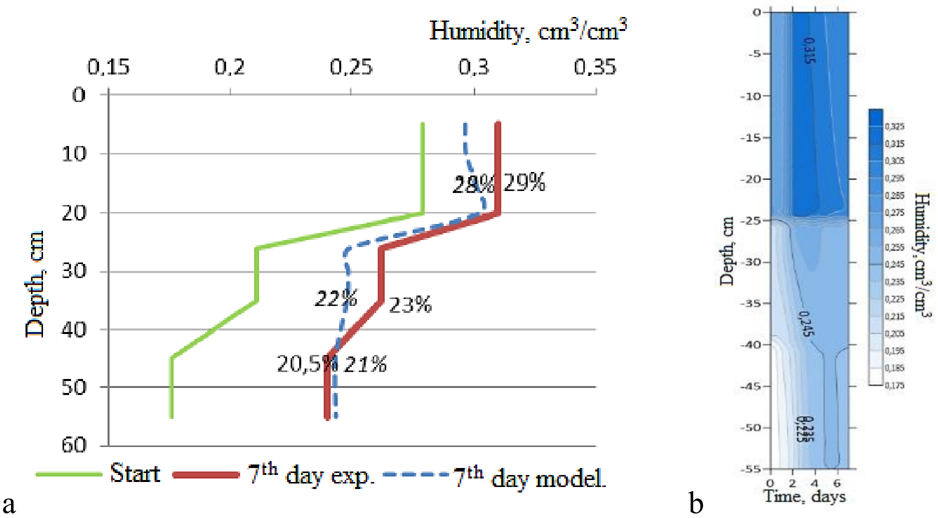

Figure 2

Actual and estimated moisture content of steppe soil horizons (a); Chronoisopleths of soil moisture in plowed steppe (based on the results of soil moisture movement modeling in Hydrus 1D) (b)

Note. By authors in July 10 and 17, 2024

Conclusion

Using the pedotransfer functions of the RETC program, hydrological parameters of the upper arable soils of steppe agrolandscapes were obtained and analyzed. It was found that the approximation parameter of the main hydrophysical characteristic of the A horizon – the α index (the reciprocal of the air inlet pressure) – is significantly lower in the upper horizon, which is constantly exposed to plowing, than in the B and C horizons. Using Hydrus 1D, soil moisture dynamics were modeled under natural moisture conditions over a 7-day summer period. It was found that the high moisture capacity of one upper arable horizon under oat crops does not ensure an optimal water regime for the entire soil layer. The resulting modeled moisture dynamics parameters for ordinary gray-brown soils were in good agreement with experimental soil moisture data, with the discrepancy being within 5%. It is possible that the reason for the discrepancy in the data is the hysteresis effect of the main hydrophysical characteristic, which was not taken into account in the modeling, and the actual moisture level in the gradually drying soil is slightly higher than the calculated one. Good water permeability of the upper arable horizon does not necessarily mean optimal water conditions for the entire soil layer.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Gahramanova, A. Y., Akhundova, S. M., & Alakbarli, G. Y. (2025). Main eco-properties of hazelnut (*Corylus avellana* L.) on the Sheki–Zagatala economic region. *International Journal of Advances in Applied Sciences, 14*(1), 77–85. https://doi.org/10.11591/ijaas.v14.i1.pp77-85

Gahramanova, A. Y., Mammadova, R. N., Hasanova, T. A., Alakbarli, G. Y., Mammadova, G. I., & Asgarova, G. F. (2026). Studies on gray-brown soils with rapeseed (*Brassica napus* L.) as a forage crop in the Sheki region of the Greater Caucasus. *SABRAO Journal of Breeding and Genetics, 58*(1), 432–441. https://doi.org/10.54910/sabrao2026.58.1.40

Hasanova, T., & Mammadova, G. (2023). The impact of changes in soil moisture indicators on biological activity in recent years on the southern slope of the Greater Caucasus. *Nature and Science International Scientific Journal, 5*(3), 7–12. https://doi.org/10.36719/2707-1146/30/7-12

Hasanova Baba-zade, R. A., Aliyeva, M. M., Nasirova, A. I., Suleymanova, A. V., Hasanova T. A., & Asgarova, G. F. (2026). Current state of microstructure in the Kur-Araz lowland of the Azerbaijan by remote sensing and photometry. *Bulgarian Journal of Agricultural Science, 32*(3), 213–224.

Hasanova, T. A., Jafarov, A. M., Huseynova, S. M., Isagova, V. G., Mammadova, G. I., Madnee, M., & Asgarova, G. F. (2026). Modeling humus stocks and introducing a saturation coefficient to assess soil organic carbon capacity in forest soils of the Sheki–Zagatala Region, Azerbaijan. *International Journal of Agriculture and Biosciences, 15*(5), 1969–1977. https://doi.org/10.47278/journal.ijab/2026.116

Ismayilov, A., Hasanova, R., Isaqova, V., Mirzezadeh, R., & Hasanova, T. (2025). Soil salinization in Ujar region of Azerbaijan with index application and various methods comparison. *Proceedings of the Bulgarian Academy of Sciences, 78*(6), 946–954. https://doi.org/10.7546/CRABS.2025.06.18

Ismayilova, A., Shukurov, S., Hasanaliyeva, L., Osmanova, S., Asgarova, G., & Hasanova, T. (2025a). Modern soil cover of natural cenoses and agrocenoses landscapes of the Kur–Araz plain. *Advances in Biology & Earth Sciences*, *10*(2), 314–325.

https://doi.org/10.62476/abes.102314

Ismayilova, A. A., Mirzezadeh, R. I., Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Asgarova, G. F., & Madnee, M. (2025b). Biomass and enzymatic activity assessment of the coniferous-deciduous forests in Azerbaijan. *SABRAO Journal of Breeding and Genetics, 57*(6), 2584–2595. https://doi.org/10.54910/sabrao2025.57.6.31

Mammadova, R., Hasanova, T., & Aliyeva, M. (2025a). Ecological state of modern soil cover in agrocenoses of the Greater Caucasus Sheki region. *Ecological Systems Modelling. Collective monograph, 3*, 57–73. https://doi.org/10.21303/978-9908-9706-6-0.ch3

Makki, H. A., Saeed, A., Hussain, T., Rafay, T., Madnee, M., Abid, M., Hasanova, T. H., & Nurrochmat, N. A. (2025). Enhancing soil rehabilitation in saline and sandy soils of Punjab, Pakistan using wastewater reuse and native tree species. *Egyptian Journal of Soil Science, 65*(4), 2039–2054. https://doi.org/10.21608/EJSS.2025.426305.2378

Mirzezadeh, R. I., Ramazanova, F. M., Hasanova, T. A., Mammadova, G. I., & Asgarova, G. F. (2025). Assessment of variations caused by biological activities in the Greater Caucasus forest soils used for agriculture. *SABRAO Journal of Breeding and Genetics, 57*(4), 1634–1643. https://doi.org/10.54910/sabrao2025.57.4.29

Mammadova, G., Salimova, Sh., Aliyeva, G., Isagova, V., & Hasanova, T. (2026a). Modern approaches in the study of soil bioactivity in Katekh and Garakli village (Azerbaijan) irrigated alluvial meadow and mountain forest brown soils. *Bulgarian Journal of Agricultural Science, 32*(2), 278–285.

Mammadova, R. N., Salimova, S. J., Huseynova, S. M., Mammadova, G. I., Hasanova, T. A., Rafiyeva, H. L., & Jafarova, G. A. (2025b). Plant leaves as a biogeochemical indicator of the environmental state in different regions of Azerbaijan. *Comptes Rendus de l'Académie Bulgare des Sciences, 78*(11), 1601–1610. https://doi.org/10.7546/CRABS.2025.11.03

Mazhar, I., Safeer, M., Madnee, M., Sarfaraz, A., Hasanova, T. A., & Bashir, M. A. (2025). Phytochemical composition and antioxidant potential of *Moringa oleifera* from the Cholistan Desert: Implications for human nutrition. *Global Forests, 4*(1), 50–61. https://doi.org/10.54219/globalforests.04.01.2025.394

Madnee, M., Hussain, T., Hasanova, T. A., Nurrochmat, N. A., Bashir, M. A., Ali, M. M., Ghaffar, M. U., & Qanitha, M. (2025). Enhancing soil fertility in arid and semi-arid climates using leguminous trees: A species-specific agroforestry approach. *Journal of Agroforestry and Environment, 18*(2), 152–168. https://doi.org/10.55706/jae1834

Mammadova, G. I., Salimova, Sh. J., Jafarov, A. M., Huseynova, S. M., Isayeva, K. K., Isagova, V. G., & Hasanova, T. A. (2026b). Rocky soil compositions influence on the microorganisms and vegetation at the Sheki-Zagatala Economic Region, Azerbaijan. *SABRAO Journal of Breeding and Genetics, 58*(3), 101–112. https://doi.org/10.54910/sabrao2026.58.3

Mirzezadeh, R. I., & Mammadova, G. I. (2026). Soil Protection: A Strategic Priority of the Soil Museum. *Nature & Science, 8*(3), 5−11. https://doi.org/10.36719/2707-1146/66/5-11

Nasirova, A. I., Hasanova, T. A., Asgarova, G. F., & Abasova, N. A. (2025). Modeling of soil electrical conductivity for sustainable land use in salinized areas. *Agrarian Bulletin of the Urals, 25*(8), 1199–1208. https://doi.org/10.32417/1997-48682025-25-08-1199-1208

Nasirova, A. I., Isagova, V. G., Mirzezadeh, R. I., Gahramanova, A. Y., Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Asgarova, G. F., & Mammadova, R. N. (2026). Changing the biological activity of soil in sunflower crops. *Comptes Rendus De L Academie Bulgare Des Sciences, 79*(1), 145–156. https://doi.org/10.7546/CRABS.2026.01.18

Ramazanova, F., Huseynova, S., Isagova, V., & Jafarova, G. (2026). Diagnostics of irrigated soils in the dry steppe and semi–desert zones of Azerbaijan. *Nature & Science, 8*(3), 12−19. https://doi.org/10.36719/2707-1146/66/12-19

Sadigov, R. A., Mammadova, G. I., Isagova, V. G., Hasanova, T. A., & Madnee, M. (2026). Current state of production of alternative energy on the Absheron Peninsula. *International Journal of Applied Power Engineering, 15*(1), 37–45. https://doi.org/10.11591/ijape.v15.i1.pp37-45

Shukurov, S. Kh., Ismayilova, A. A., Sadigov, R. A., Karimova, M. J., Hasanova, T. A., & Asgarova, G. A. (2025). Determination of soil salinization by hyperspectral remote sensing in the Shirvan Plain. *International Journal of Advances in Applied Sciences, 14*(3), 662–670. https://doi.org/10.11591/ijaas.v14.i3.pp662-670

Sadigov, R. A., Nazarova, M. K., Garayeva, I. E., Mammadova, G. I., Hasanova, T. A., & Madnee, M. (2025). Modern research on the use of alternative energy resources in Azerbaijan. *International Journal of Advances in Applied Sciences, 14*(3), 907–915. https://doi.org/10.11591/ijaas.v14.i3.pp907-915

Verdiyeva, F. B., Hasanova, T. A., Ismayilova, M. E., Huseynov, E. Y., Jabiyeva, T. E., & Asgarova, G. A. (2025). Bioecological characteristics of modern soil cover in subtropic regions of Azerbaijan. *International Journal of Advances in Applied Sciences, 14*(4), 1200–1207. https://doi.org/10.11591/ijaas.v14.i4.pp1200-1207

Verdiyeva, F. B., Abdullayeva, R. K., Ismayilzadeh, N. N., Fatdayeva, A. K., Mammadova, G. I., Hasanova, L. U., Asgarova, G. F., & Hasanova, T. A. (2026). Biosynthesis of seeds and bioecological parameters of gray-meadow soils by remote sensing (Republic of Azerbaijan) under wheat crops. *International Journal of Agriculture and Biosciences, 15*(4), 126–137. https://doi.org/10.47278/journal.ijab/2026.075

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Organic-Medium Synthesis of $Cd_3Sb_2S_8$ and Its Thermogravimetric Analysis (TGA)

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Abstract. *In this study, the $Cd_3Sb_2S_8$ semiconductor compound was synthesized in a non-aqueous medium using antimony ore obtained from the Daridag deposit in the Julfa district of the Nakhchivan Autonomous Republic. The raw ore was initially enriched by flotation and subsequently converted into Sb_2S_3, Sb_2S_5, and Na_3SbS_4 precursor compounds through successive chemical transformations. The final $Cd_3Sb_2S_8$ phase was prepared by a solvothermal process in ethylene glycol at 150 °C, achieving an approximate product yield of 90%. A possible reaction pathway describing the formation of $Cd_3Sb_2S_8$ was proposed, and the sequential nucleation and crystal growth processes were discussed. The thermal behavior of the synthesized material was evaluated by thermogravimetric (TG) analysis, which demonstrated high thermal stability with a total mass loss of only 14.34% up to approximately 900 K. The obtained results indicate that the synthesized $Cd_3Sb_2S_8$ is a thermally stable semiconductor material with potential for further investigation in advanced functional applications.*

Keywords: *$Cd_3Sb_2S_8$, non-aqueous synthesis, solvothermal method, thermogravimetric analysis, semiconductor*

Introduction

The thioantimonate(III) compound $Cd_3Sb_2S_8$ was synthesized by an environmentally friendly ionothermal method (Gang et al., 2021). CdS thin films were prepared by the pyrolytic deposition method, and their structural, optical, and electrical properties were investigated (Abhijit & Elahipasha, 2011). The physicochemical properties of the samples were evaluated using spectrophotometry, X-ray diffraction (XRD), scanning electron microscopy (SEM), and other advanced analytical techniques (Chen et al., 2022). Sulfide-based semiconductor compounds of heavy metals exhibit high optical absorption coefficients, favorable electronic properties, and broad application potential in optoelectronics, solar energy conversion, and sensor technologies (Valiyeva et al., 2025; Fatemipayam et al., 2025).

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Materials and Methods

Antimony ore extracted from the Daridag deposit located in the Julfa district of the Nakhchivan Autonomous Republic was used as the starting material for the synthesis of $Cd_3Sb_2S_8$ (Ganiyev et al., 2026). The ore was first enriched by the flotation method (Aliyeva, 2021), after which high-purity Sb_2S_3 was obtained through successive chemical transformations (Aliyeva et al., 2026). In the next stage, Sb_2S_3 was oxidized to Sb_2S_5, and Na_3SbS_4 was subsequently synthesized from this product (Aliyeva, 2022; Aliyeva, 2024). The prepared Na_3SbS_4 served simultaneously as both the antimony and sulfur source during the synthesis process.

The $Cd_3Sb_2S_8$ sample was synthesized in a non-aqueous medium using ethylene glycol as the solvent via the solvothermal method (Hajiyeva et al., 2026). During the synthesis, Na_3SbS_4 and $Cd(NO_3)_2{\cdot}4H_2O$ were sequentially added to the reaction solution, while NH_4Cl was introduced to establish a homogeneous reaction system and to promote controlled crystal growth. The resulting mixture was sealed in a hermetically closed reactor and maintained at 150 °C for 8–10 h. During this period, $Cd_3Sb_2S_8$ crystals gradually formed through the interaction of Cd^{2+} ions with thioantimonate-derived complex species (Aliyeva et al., 2026).

After completion of the heat treatment, the reactor was allowed to cool naturally to room temperature. The resulting solid phase was separated from the solution by vacuum filtration. The precipitate was washed several times with distilled water followed by ethanol to remove soluble impurities. The purified product was dried at 110 °C, ground into a homogeneous powder, and prepared for subsequent physicochemical characterization. The calculated product yield was approximately 90%, indicating that the selected technological parameters and reaction conditions provided high synthesis efficiency.

The overall reaction can be expressed as follows:

$$2Na_3SbS_4+3Cd(NO_3) \xrightarrow{ethylene\,glycol} Cd_3Sb_2S_8\downarrow+6NaNO_3$$

It should be noted that this equation represents the overall stoichiometric expression of the process (Yang et al., 2024; Zhou et al., 2013), while the reaction actually proceeds through several intermediate steps.

Formation Mechanism of $Cd_3Sb_2S_8$

Stage I. Dissociation of Sodium Thioantimonate

In the non-aqueous ethylene glycol medium, sodium thioantimonate dissociates to form the thioantimonate (Han et al., 2022) complex:

$$\mathrm{Na_3SbS_4} \rightarrow \mathrm{3Na^+ + SbS_4^{3-}}$$

Stage II. Ionization of Cadmium Nitrate

Cadmium nitrate dissolves in ethylene glycol, generating cadmium ions.

$$\mathrm{Cd(NO_3)_2} \rightarrow \mathrm{Cd^{2+} + 2NO_3^-}$$

Stage III. Interaction of the Complexes

Upon heating, Cd^{2+} ions approach the SbS_4^{3-} complexes and initially form Cd–S coordination bonds.

$$3Cd^{2+} +2SbS_4^{3-}\rightarrow Cd_3Sb_2S8\downarrow$$

This intermediate complex represents the initial stage of crystallization.

Stage IV. Nucleation

Heating the reaction medium to 150 °C decreases the stability of the intermediate complexes, and their condensation initiates the crystallization of $Cd_3Sb_2S_8$

$$[\mathrm{3Cd - SbS_4}]^{3-} \rightarrow \mathrm{Cd3Sb_2S_8}\ \text{(nuclei)}$$

At this stage, very fine dark-brown particles are observed in the solution.

Stage V. Crystal Growth
During the subsequent stages of the reaction, the SbS_4^{3-} and Cd^{2+} ions present in the solution attach to the surfaces of the previously formed crystallization nuclei, resulting in the gradual growth of the crystals.

$$Cd_3Sb_2S_8 \text{ (nuclei)} + Cd^{2+} + SbS_4^{3-} \rightarrow Cd_3Sb_2S_8 \text{ (crystal growth)}$$

Stage VI. Crystal Growth
During the solvothermal treatment, the previously formed $Cd_3Sb_2S_8$ nuclei gradually develop through the incorporation of Cd^{2+} and SbS_4^{3-} species from the solution onto their surfaces. The elevated temperature enhances ion mobility, promoting the orderly development of the crystal structure. As the reaction proceeds, the crystallinity increases, resulting in homogeneous $Cd_3Sb_2S_8$ particles.
Stage VII. Removal of By-products
After the separation of the main product, Na^+ and NO_3^- ions remain in the solution, while excess sulfur is present in elemental or polysulfide forms. During the washing process, these by-products are removed from the system, thereby increasing the purity of the $Cd_3Sb_2S_8$ sample.

Brief Description of the Reaction Mechanism

When Na_3SbS_4 dissolves in ethylene glycol, thioantimonate complexes are formed in the solution (Garayev & Aliyeva, 2022). Their interaction with Cd^{2+} ions leads to the formation of intermediate coordination compounds. Heating the reaction mixture to 150 °C accelerates the transformation of these complexes into $Cd_3Sb_2S_8$ crystal nuclei. Subsequent attachment of ions to the surfaces of these nuclei promotes crystal growth, resulting in the formation of a well-crystallized $Cd_3Sb_2S_8$ phase. Ethylene glycol maintains the stability of the reaction medium, whereas NH_4Cl regulates the crystallization process, facilitating the formation of homogeneous particles (Mamedova, 2021b).

Results and Discussion

Thermogravimetric (TG) analysis was performed to evaluate the thermal stability of the $Cd_3Sb_2S_8$ compound and to investigate the mass changes occurring during heating (Azimova et al., 2026). This technique enables the determination of the material's thermal stability (Mamedova, 2020a), decomposition stages, and the release of volatile components (Mamedova & Nasirli, 2021; Mamedova, 2021a). The TG results provide valuable information on the high-temperature behavior of the synthesized sample and allow the evaluation of the temperature range in which the material can be effectively applied.

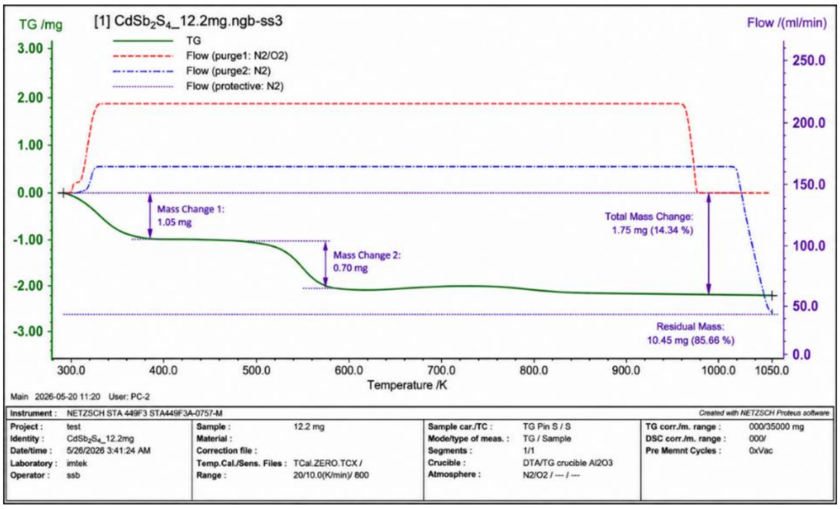

Figure 1
Thermogravimetric (TG) analysis of the $Cd_3Sb_2S_8$ compound

The TG analysis demonstrated that the mass change of the $Cd_3Sb_2S_8$ sample during heating occurred in a stepwise manner. A mass loss of 3.90 mg in the temperature range of 320–450 K was attributed to the removal of adsorbed water and volatile residual species. An additional mass loss of 1.65 mg was recorded within the 470–560 K range, indicating the onset of thermal transformations in the material. The TG curve remained nearly unchanged in the temperature interval of 700–920 K. In the temperature range of 920–1050 K, a further mass loss of 1.75 mg was observed, which was attributed to the partial decomposition of the crystal structure (Mamedova, 2020b) together with the release of sulfur-containing volatile species. These results confirm that the $Cd_3Sb_2S_8$ compound possesses high thermal stability over a wide temperature range (Mamedova, 2020b; Mamedova, 2016).

The results of this study demonstrated that the high-yield synthesis of $Cd_3Sb_2S_8$ in a non-aqueous medium is feasible using the Na_3SbS_4 precursor obtained from the antimony ore of the Daridag deposit. The sample synthesized by the solvothermal method exhibited high crystallinity and a homogeneous morphology, confirming the effectiveness of the selected synthesis conditions. Thermal analysis showed that the material retained its thermal stability over a broad temperature range, with gradual structural changes occurring only at elevated temperatures. The proposed formation mechanism consistently explains the nucleation and crystal growth stages in agreement with the experimental results.

Conclusion

In this study, the $Cd_3Sb_2S_8$ semiconductor compound was successfully synthesized from the antimony ore of the Daridag deposit using a non-aqueous solvothermal method, yielding a high product recovery. Structural and thermal analyses confirmed that the synthesized sample possesses high crystallinity and excellent thermal stability. The proposed reaction mechanism is consistent with the experimental findings and provides a reasonable explanation for the formation stages of the $Cd_3Sb_2S_8$ phase. The obtained results indicate that the synthesized $Cd_3Sb_2S_8$ material is a promising semiconductor for applications in photocatalysis, solar energy conversion, photodetectors, and other optoelectronic systems.

Conflict of Interest

The authors declare that they have no conflict of interest regarding this article.

References

Abhijit, A. Y., & Elahipasha, M. (2011). Photoelectrochemical investigations of cadmium sulphide (CdS) thin film electrodes prepared by spray pyrolysis. *Journal of Alloys and Compounds, 509*(17), 5394–5399. https://doi.org/10.1016/j.jallcom.2011.02.061

Aliyeva, S. H. (2021). Investigation of the conditions for obtaining sodium thiostibitate. *Scientific Works of the Nakhchivan Branch of ANAS: Nature and Technical Sciences Series, 4*, 51–55.

Aliyeva, S. H. (2022). Investigation of the conditions of obtaining antimony thiostibiat. *Scientific Works of the Nakhchivan Branch of ANAS: Nature and Technical Sciences Series, 2*, 59–67.

Aliyeva, S. H. (2024). Study of the conditions for obtaining silver(I) thiostibate from the Sb_2S_5–$AgNO_3$–H_2O system. *International Scientific Journal Science and the World, 7*(131), 20–26.

Aliyeva, S., Baghban, A., Ganiev, B., Mammadova, G. A., Jamalova, R. H., et al. (2026). Controlled aqueous synthesis of Ag_3SbS_4 in the Na_3SbS_4–$AgNO_3$–H_2O precursor system with thermodynamic and physicochemical characterization. *Solid State Sciences, 179*, 108373. https://doi.org/10.1016/j.solidstatesciences.2026.108373

Aliyeva, S., Heybatova, A., & Pashayeva, A. (2026). Synthesis and X-ray phase analysis of $Cd_3Sb_2S_8$ obtained from Schlippe's salt. *Scientific Work*, 62–65.

https://doi.org/10.36719/2663-4619/1/62-65

Azimova, N. M., Mamedova, G. A., Aliyeva, S. H., Jamalova, R. H., et al. (2026). Synthesis of zeolites of the chabazite group based on natural minerals of Nakhchivan: The influence of various factors on the process of their crystallization. *Journal of Chemistry and Technologies, 34*(2*).* https://doi.org/10.15421/jchemtech.v34i2.345095

Chen, Y., Cheng, Y., Zhao, J., Zhang, W., et al. (2022). Construction of Sb_2S_3/CdS/$CdIn_2S_4$ cascaded S-scheme heterojunction for improving photoelectrochemical performance. *Journal of Colloid and Interface Science, 627*, 1047–1060. https://doi.org/10.1016/j.jcis.2022.07.117

Fatemipayam, N., Keramati, N., & Mehdipou, M. G. (2025). Synthesis and characterization of cadmium sulfide and titania photocatalysts supported on mesoporous silica for optimized dye degradation under visible light. *Scientific Reports, 15*, 8160. https://doi.org/10.1038/s41598-025-92077-7

Gang, Y., Chao, W., et al. (2021). Multinary thioantimonates(III) with d^{10} transition metals: Ionothermal synthesis, crystal structures and physical properties. *Journal of Cluster Science, 33*, 1569–1577. https://doi.org/10.1007/s10876-021-02080-x

Garayev, A. M., & Aliyeva, S. (2022). Investigation of the conditions for the production of antimony thiostibiat. *Nature & Science, 4*(6), 55–59. https://doi.org/10.36719/2707-1146/21/55-59

Ganiyev, B., Kholikova, G., Sharipov, Sh., Mardonov, U., & Aliyeva, S. (2026). Comprehensive investigation of the physicochemical properties of the $Cd_3Sb_2S_8$ compound (chemical and X-ray phase analysis, precipitation kinetics). *Nature & Science, 8*(2*),* 56–60. https://doi.org/10.36719/2707-1146/65/56-60

Hajiyeva, G., Seyidova, I., Aliyeva, S. H., Isgandarova, U., & Seyidov, M. (2026). Integrated evaluation of exodynamic processes in the Nakhchivanchay Basin based on geological and geophysical indicators using GIS and remote sensing methods. *Scientific Work*, *20*(4), 303–316. https://doi.org/10.36719/2663-4619/128/303-316

Han, T., Luo, M., Liu, Y., Lu, C., et al. (2022). Sb_2S_3/Sb_2Se_3 heterojunction for high-performance photodetection and hydrogen production. *Journal of Colloid and Interface Science, 628*, 886–895. https://doi.org/10.1016/j.jcis.2022.08.072

Mamedova, G. A. (2016). The ion-exchange properties of natural zeolite mordenite. *Fine Chemical Technologies, 11*(1), 29–33. https://doi.org/10.32362/2410-6593-2016-11-1-29-33

Mamedova, G. A. (2020a). Synthesis and study of faujasite zeolite based on Nakhchivan native mineral. *Glass and Ceramics, 77*, 15–18. https://doi.org/10.1007/s10717-020-00228-1

Mamedova, G. A. (2020b). Synthesis of different structural types of zeolites in the halloysite dolomite-obsidian system. *Chemistry Journal of Moldova, 15*(1), 31–40. https://doi.org/10.19261/cjm.2020.664

Mamedova, G. A. (2021a). Influence of synthesis conditions on clinoptilolitic zeolite crystallization. *Glass and Ceramics, 78*, 168–171. https://doi.org/10.1007/s10717-021-00370-4

Mamedova, G. A. (2021b). Influence of temperature and alkalescency on the crystallization of ZSM and ZK zeolites. *Theoretical Foundations of Chemical Engineering, 55*, 479–489. https://doi.org/10.1134/S0040579521030131

Mamedova, G., & Nasirli, G. (2021). Investigation of various influencing factors of hydrothermal synthesis of analcime zeolite. *Chemistry Journal of Moldova, 16*(1), 60–67. https://doi.org/10.19261/cjm.2021.792

Valiyeva, N., Aliyeva, S. H., & Mammadova, A. (2025). *$CuSbS_2$-nın üzvi mühitdə alınma şəraitinin araşdırılması (Investigation of the conditions for the production of $CuSbS_2$ in an organic medium).* In *Scientific Sources XXII Collection of Theses* (pp. 191–193). https://doi.org/10.36719/2663-4619/XXII/TT/2025

Yang, M., Fan, Z., Du, J., Feng, C., Li, R., et al. (2024). Designing atomic interface in Sb_2S_3/CdS heterojunction for efficient solar water splitting. *Small, 20*(31), 2311644. https://doi.org/10.1002/smll.202311644

Zhou, L., Hu, X., & Wu, S. (2013). Effects of deposition temperature on the performance of CdS films with chemical bath deposition. *Surface and Coatings Technology, 228*, 171–174. https://doi.org/10.1016/j.surfcoat.2012.06.04

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Statistical Variability Indices and Concentration Coefficient of Soil Microelements in Azerbaijan

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Abstract. *The aim of this study is to investigate the current state of essential, potentially toxic, and poorly understood microelement content in soils under vegetation in dry-steppe ecosystems. The objectives of the study included: determining regional characteristics of microelement content in soils and plants, identifying their relationships in the plant-soil system (hidden micronutrient deficiency), determining the intensity of biological uptake by plants from the soil, which characterizes their ecological activity, and assessing the removal of elements by aboveground phytomass and their involvement in biogenic migration. Soil and vegetation samples were collected from dry-steppe ecosystems. Soil samples were collected from the root layer (0–20/40 cm), prepared for laboratory analysis, and the microelement contents were determined. Statistical and correlation analyses were performed to evaluate the relationships between microelement contents in soils and vegetation. The results of the correlation analysis revealed a direct, significant relationship between the microelement content in soils and their accumulation in vegetation for Cd, Cr, Mn, Fe, Zn, Ba, and Pb. A moderate to strong positive correlation was found between the content of Cd, Cr, Mn, Fe, Zn, Ba, and Pb in vegetation and soil (r = 0.51–0.82). No correlation was found for the remaining trace elements: B, Zr (r = -0.07–0.08), Li, Al, Ti, Ni, Cu, and Mo (r = 0.19–0.39). The findings of this study are important for the development of agriculture in Azerbaijan, as the removal of heavy metals from soils and irrigation water is supported by national law and remains a priority for environmentalists and soil scientists.*

Keywords: *microelement deficiency, plant-soil system, eco-biological parameters, vegetation, heavy metals*

Introduction

Plants remain one of the main sources of biologically active substances. Experts predict that global demand for studying plant soils used to produce natural fertilizers will only grow. Microelements are an important component of plant mineral nutrition. Many of them are vital because, as components of biologically active substances, they perform a variety of catalytic and regulatory functions in metabolic processes – absorption, transport, oxidation-reduction, biosynthesis of organic compounds, and the transfer of genetic information (Akhundova et al., 2025; Bunyatova et al., 2025).

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The modern classification of trace elements based on their importance to living organisms is presented as follows: a) vital – Fe, Mn, I, Cu, Zn, Co, Cr, Mo, Se; b) conditionally essential – Li, B, Ni, Cd, V, Si, F, Br, Ti; c) potentially toxic – Al, Cd, Pb, Hg, Ba, Ti, Bi. In addition, Fe and Si are classified as mesoelements. The number of biologically significant elements is expanding: elements significant for individual species now include As, Br, Sr, Cd, Sn, Ba, W. Each element has its own safe concentration range, within which normal soil function occurs under plants (Hasanova et al., 2026; Akhundova et al., 2025; Bunyatova et al., 2025).

Violations of this range lead to various pathological abnormalities in metabolic processes, leading to microelement deficiency in the case of a deficiency, and to toxic microelement deficiency in the case of an excess (Ramazanova et al., 2026). In recent decades, ecologists and agricultural chemists have focused primarily on studying heavy metal pollution of soils, natural waters, and plants caused by industrial emissions. Steppe ecosystems occupy significant areas of Azerbaijan, perform important biosphere functions, and are of high economic importance (Verdiyeva et al., 2025).

The content of microelements in soils under plants, as an important factor in the functioning of steppe ecosystems, has been poorly studied. Only data are available on the content of Mn, Zn, Cu, Co, and I in some steppe vegetation, and a study of lead in the "rock-soil-humic substances-plants" system in forest-steppe and steppe soils of the Republic of Azerbaijan (Hasanova & Mammadova, 2023). The region's deep inland location allows these ecosystems to exist in extremely arid conditions. The climate of Azerbaijan's dry steppe zones (primarily the Kura-Araz Lowland, Shirvan, Aran and Absheron) is a dry subtropical climate with hot summers and mild to cool winters. It is characterized by insufficient precipitation (130–300 mm per year), high evaporation, frequent winds, and average temperatures of 1–4 °C in January and 21–27 °C in July. The parent rocks are deluvial and deluvial-proluvial deposits, as well as sand and gravel deposits. The basis of the soil cover is typical Kastanozems soils with a thin humus horizon (Gahramanova et al., 2026; Hasanova Baba-zade et al., 2026; Ismayilov et al., 2025; Ismayilova et al., 2025a; Ismayilova et al., 2025b; Nasirova et al., 2026).

Materials and Methods

The method for determining microelements in soil under vegetation includes sampling from the root layer (0–20/40 cm), removing roots, drying, crushing and sifting (0.25–1 mm sieve). Variation and statistical parameters of element contents were studied in soils, plant ash, and their interaction coefficients in the vegetation-soil system. Average element contents in soils ranged from 3.0 mg/kg for Mo to 70–180 mg/kg for Al. These can be roughly divided into the following groups: slightly high contents (Fe and Al), which are classified as macroelements in soils (42–350–70–180 mg/kg); moderate contents (Zr, Mn, B, Ti) (318–5040 mg/kg); low contents (Li, Cu, Ni, Pb, Cr, Zn, Cd) (20–100 mg/kg); and very low contents (Mo, B, Co) (3.1–6.2 mg/kg). All data on microelement contents in chestnut soils are within the limits of normal variation according to the classification of G.N.Zaitsev (1990) (Shukurov et al., 2025; Shukurov et al., 2026; Mammadova et al., 2025a; Mammadzada et al., 2025; Mirzezadeh et al., 2025; Makki et al., 2025).

Results and Discussion

The content of Ba, Li, Mn, Pb, Ti, Al, B, Cd, and Fe in soils is within the lower limit of 9–21%, while Cr, Ni, Cu, Zn, Zr, and Mo are within the upper limit of 27–34%. The average content of Cd and Pb reaches their maximum permissible concentration (MPC) in soils (Table 1). The content of trace elements in the cuttings of steppe vegetation varied by 4 orders of magnitude: from 0.07 for B to 217 mg/kg for Fe (Aliyeva, 2025; Mammadzade, 2025).

According to the average content in vegetation, trace elements are conditionally divided into the following groups: high content – Fe, Al (217–266); average – Ba, Ti, Sr, Mn, Zn (22–67); low – B, Cu, Li, Cr, Mo, Cd, Zr (1.22–6.9) and very low – Ni, Pb (0.07–0.88) mg/kg. The series of these elements according to the degree of decrease in content in steppe vegetation is presented as follows: AI > Fe > Sr > Mn, Ba > Ti > Zn > Cu > B > Zr > Cr > Li > Mo > Cd > Pb > Ni. The results of the correlation analysis revealed a direct, significant relationship between the microelement content in soils and their accumulation in vegetation for Cd, Cr, Mn, Fe, Zn, Ba, and Pb. The pairwise correlation coefficients for these elements ranged from 0.56 for Zn to 0.81 for Pb. For the remaining microelements, no correlation was found in the vegetation-soil system. A comparative analysis of the content of all studied microelements in the phytomass of steppe communities, either within the norm or within the clarkes in the absence of a norm, showed that the phytocenoses of sample plots 3 in the Absheron Steppe and 15 in the Kura-Araz Steppe (12 elements out of 16), as well as sample plots 13 in the Aran Steppe (8 out of 13), and sample plot 16 in the Shirvan Steppe (10 out of 16) were best provided with them. The lowest microelement status of vegetation was observed in sample plots 11 of the Aran steppe (10 elements out of 15, normal – 1, elevated – 2). The most unfavorable microelement status of steppe phytocenoses was observed in sample plots 7 of the Lerik steppe (7 elements out of 15, content increased by 2.0–3.7 times, normal – 5) and sample plots 14 of the Aran steppe (5 out of 15, increased by 2.9–4.1 times, normal – 5).

Regarding the supply of steppe vegetation with individual microelements, a deficiency of B and Ni and a decrease in Zr compared to the clarke were found in all phytocenoses, Mn and Li were within the norm, the concentration of Fe in vegetation in all sample plots was above the norm from 2.2 to 6.5 times, Mo in 15 sample plots (by 2.3–10.8 times), Ba in 14 sample plots (1.7–4.1), Sr in 14 sample plots (1.7–3.8). Exceeding the maximum permissible level in vegetation was noted for Mo (> 3 mg/kg) in three sample plots, Fe (> 300 mg/kg) in two and Cr (> 5 mg/kg) in two sample plots. It should be noted that there are no standards in plants for such toxic microelements as B and Al. Based on the differences identified, it can be concluded that the steppe vegetation of Azerbaijan is provided with microelements in significantly different ranges – from a deficiency for some to exceeding the maximum level for others. Compared to clarke soils, chestnut soils in steppe ecosystems are characterized by normal contents of Li, B, Al, Ti, Cd, Cr, Co, Zn, and Zr; elevated contents of Pb (2.9 times), Mo (2.5 times), and Ba (1.9 times); and decreased contents of Mn (1.7 times), Ni (1.4 times), and Cu (1.2 times). This is determined by the predominance of granitoids, a group of acidic rocks, as bedrock. The average values and ranges of content for 16 microelements in steppe vegetation were determined. Elements were classified by content as high (Fe, Al – > 200 mg/kg), medium (Ba, Ti, Sr, Mn, Zn – 23–69), low (B, Cu, Li, Cr, Mo, Cd, Zr – 1.22–7.0), and very low (Be, Ni, Pb – 0.08–0.89 mg/kg).

Significant heterogeneity in microelement content in vegetation was revealed, due to both the biological characteristics of plants, the intensity of their absorption from the soil, and ecological and geochemical factors determining the bioavailability of elements (Mammadova et al., 2026a; Mammadova et al., 2025b; Mammadova et al., 2025; Mazhar et al., 2025).

The lowest coefficient of variation (15%) was observed for Li, and the highest for Cr (59%). According to the intensity of biological absorption from soil by vegetation, which characterizes the ecological activity of elements in the soil, Mo (10.5), Zn (5.2), B (3.6), and Cu (3.4) were classified as high; Li (1.6) and Mn (1.1) were classified as medium; Al, Ti, Cd, Cr, Fe, Co, Ni, Zr, Ba, and Pb (0.09–0.83) were classified as low. A moderate to strong positive correlation was found between the content of Cd, Cr, Mn, Fe, Zn, Ba, and Pb in vegetation and soil ($r = 0.51–0.82$). No correlation was found for the remaining trace elements: B, Zr ($r = -0.07–0.08$), Li, Al, Ti, Ni, Cu, and Mo ($r = 0.19–0.39$). A comparison of microelement levels in steppe vegetation with standard values (or clarkes) revealed that concentrations of Fe (3.7 times higher than normal), Mo (2.3 times higher than normal), Ba (2.8 times higher than normal), and Sr (1.3 times higher than normal; Mn (1.8 times higher than normal), and Zn (1.4 times lower than normal), Cu (1.4 times lower than normal, and B (3.4 times lower than normal).

Exceedances of the maximum permissible levels in vegetation were noted for Mo at three sample sites, and for Fe and Cr at two. These differences in content are the cause of unfavorable ratios in vegetation between Fe:Zn, Fe:Mn, Zn:Cu, and Cu:Mo. Due to the low biological productivity of steppe phytocenoses, the involvement of microelements in the biogenic migration of aboveground phytomass is 1–2 orders of magnitude less compared to the average capture of them by the annual growth of terrestrial vegetation (Madnee et al., 2025; Mammadova et al., 2026b; Mammadov et al., 2026).

Distribution of the concentration coefficient which calculated by dividing the total content of each microelement in treated soil by its content in untreated soil ($C_{amended}/C_{control}$) in the soil profile showed in Figure 1. The results of the analysis of total potentially hazardous trace elements concentrations in soil samples with additives and control samples are presented in Figure 2 to graphically display the change in concentration with depth.

The study of micronutrients in the soil under vegetation is critically important for fertility management, as their deficiency or excess directly inhibits enzymatic processes, disrupts photosynthesis, and reduces crop immunity. Accurate analysis helps prevent plant diseases and increase yields. A balanced level of trace elements protects the flora from adverse weather conditions (drought, frost), and also strengthens immunity to fungal and bacterial diseases (Nasirova, 2023a; Nasirova, 2023b; Nasirova et al., 2025; Nasirova & Verdiyeva, 2023).

Microelements are part of enzymes, vitamins, and hormones. They regulate the process of photosynthesis, nitrogen, and carbohydrate metabolism. Forbs form complex root systems that actively extract elements from deep soil horizons. Studying this process allows us to understand how minerals are redistributed and returned to the soil with sediments. In arid climates, due to the high alkalinity of the environment, many trace elements are converted into insoluble forms that are inaccessible to plants. On the contrary, some metals can accumulate to toxic concentrations, inhibiting biomass growth. Toxicological monitoring helps prevent contamination of agricultural products (Rzayeva, 2023; Rzayeva & Mamedzade, 2024; Sadigov et al., 2025; Sadigov et al., 2026; Samadov et al., 2026a; Samadov et al., 2026b; Verdiyeva et al., 2026; Togola et al., 2023).

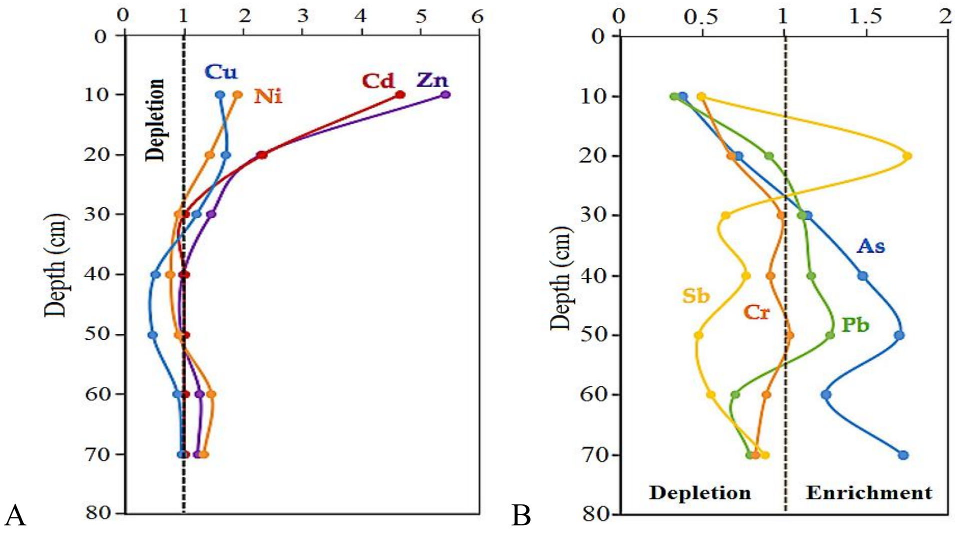

Figure 1
Distribution of the concentration coefficient

Note. Cd, Cu, Ni, and Zn (A); As, Cr, Sb, and Pb (B)

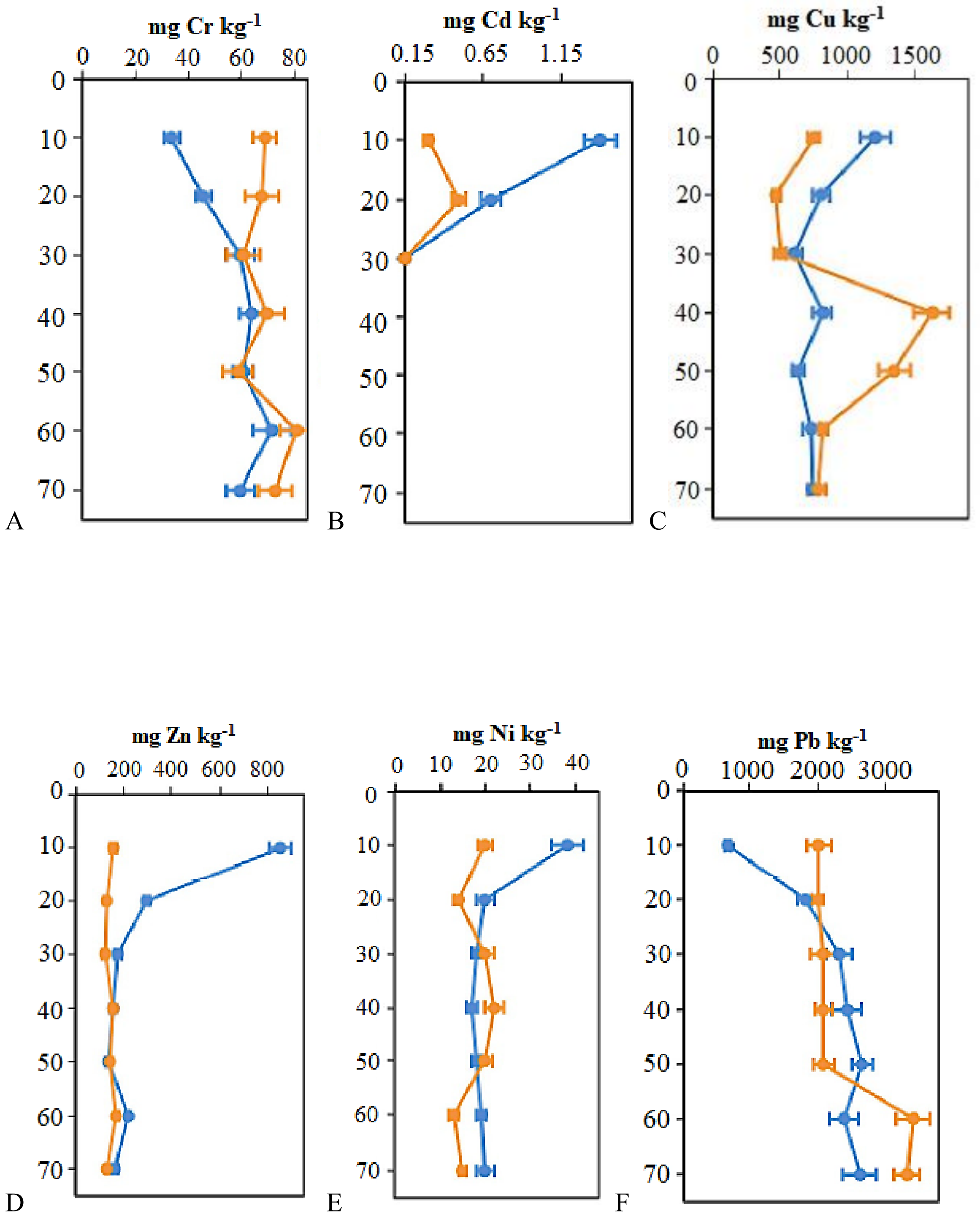

Figure 2

Distribution of microelements along soil sampling sites
(with amended soils – blue lines; and control soils – orange lines) of the soil profile

Table 1

Variational statistical indicators of the content (C) of some studied microelements in soils under vegetation, in vegetation ash and the correlation coefficient (r) in the soil-vegetation system of steppe phytocenoses

Microelements	C in soils, mg/kg		V* %	C in ash, mg/kg		V, %	r	Clarke in soils, mg/kg***	MPC in soils, mg/kg***
	M ± m	limits		M ± m	limits				
Li	22.3 ± 0.6	18–27	11	34.3 ± 1.14	28–43	15	0.19	25	–*****
B	16.4 ± 1.29	13–22	21	57.0 ± 9.5	27–97	44	-0.07	20	25
Al	74480 ± 320	53100–94980	17	6638 ± 1090	2500–15000	66	0.29	71000	–
Ti	5060 ± 148	3670–6080	13	557 ± 41	325-960	33	0.23	5000	–
Cr	62 ± 4.2	35–98	28	35.0 ± 2.6	17-53	31	0.72	70	100/90
Mn	786 ± 28	535–960 827 ± 45	15	827 ± 45	400–1125	22	0.60	1000	1500
Fe	45360 ± 261	30040–60110	22	3875 ± 164	1470–8000	46	0.70	40000	–
Co	10.9 ± 0.07	9–15	20	8.8 ± 0.29	6–10	10	0.05	8	50
Ni	29.1 ± 2.0	15–49	28	9.5 ± 0.88	4–16	38	0.21	50	100
Cu	25.0 ± 2.1	10–49	35	80.0 ± 8.4	33–175	42	0.39	30	100
Zn	81.0 ± 7.0	42–136	33	414 ± 46	200–800	45	0.57	90	300
Mo	3.0 ± 0.24	1.3–4.5	34	29.0 ± 1.8	13–42	28	0.38	1.2	5
Pb	35.0 ± 1.4	28–48	16	13.4 ± 1.1	9–25	33	0.82	12	100/32

Conclusion

The study helps identify heavy metal contamination and trace element concentrations in the soil. This allows for timely intervention to prevent toxins from entering groundwater or the food chain. It also helps assess fertility, optimize fertilizer application, increase yields, and ensure the quality of agricultural products. The analysis revealed deficiencies and excesses of certain trace elements that impact plant, animal, and human health, and helps monitor the level of heavy metal contamination in soils. Differences in content of microelements are the cause of unfavorable ratios in vegetation between Fe:Zn, Fe:Mn, Zn:Cu, and Cu:Mo. Exceedances of the maximum permissible levels in vegetation were noted for Mo at three sample sites, and for Fe and Cr at two. The lowest microelement status of vegetation was observed in sample plots 11 of the Aran steppe. The most unfavorable microelement status of steppe phytocenoses was observed in sample plots 7 of the Lerik steppe and sample plots 14 of the Aran steppe. Regarding the supply of steppe vegetation with individual microelements, a deficiency of B and Ni and a decrease in Zr compared to the clarke were found in all phytocenoses.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Akhundova, S., Mammadova, G., Bunyatova, L., Alakbarli, G., Ahmadova, A., Aliyev, F., Bagirova, C., & Shammadova, I. (2025). Study of the modern bio-ecological state of Absheron coastlines. *Advances in Biology and Earth Sciences, 10*(1), 168–176. https://doi.org/10.62476/abes.101168

Aliyeva, M. M. (2025). Activity of soil biota in the modern soil cover of Ujar, Kurdamir, and Salyan regions. *Bulgarian Journal of Agricultural Science, 31*(6), 1086–1091.

Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Gahramanova, A. Y., Akhundova, S. M., & Alakbarli, G. Y. (2025). Main eco-properties of hazelnut (*Corylus avellana* L.) on the Sheki-Zagatala economic region. *International Journal of Advances in Applied Sciences, 14*(1), 77–85. https://doi.org/10.11591/ijaas.v14.i1.pp77-85

Gahramanova, A. Y., Mammadova, R. N., Hasanova, T. A., Alakbarli, G. Y., Mammadova, G. I., & Asgarova, G. F. (2026). Studies on gray-brown soils with rapeseed (*Brassica napus* L.) as a forage crop in the Sheki region of the Greater Caucasus. *SABRAO Journal of Breeding and Genetics, 58*(1), 432–441. http://doi.org/10.54910/sabrao2026.58.1.40

Hasanova, T., & Mammadova, G. (2023). The impact of changes in soil moisture indicators on biological activity in recent years on the southern slope of the Greater Caucasus. *Nature & Science, 5*(3), 7–12. https://doi.org/10.36719/2707-1146/30/7-12

Hasanova Baba-zade, R. A., Aliyeva, M. M., Nasirova, A. I., Suleymanova, A. V., Hasanova, T. A., & Asgarova, G. F. (2026). Current state of microstructure in the Kur-Araz lowland of the Azerbaijan by remote sensing and photometry. *Bulgarian Journal of Agricultural Science, 32*(3), 213–224.

Hasanova, T. A., Jafarov, A. M., Huseynova, S. M., Isagova, V. G., Mammadova, G. I., Madnee, M., & Asgarova, G. F. (2026). Modeling humus stocks and introducing a saturation coefficient to assess soil organic carbon capacity in forest soils of the Sheki-Zagatala Region, Azerbaijan. *International Journal of Agriculture and Biosciences, 15*(5), 1969–1977. https://doi.org/10.47278/journal.ijab/2026.116

Ismayilov, A., Hasanova, R., Isagova, V., Mirzezadeh, R., & Hasanova, T. (2025). Soil salinization in Ujar region of Azerbaijan with index application and various methods comparison. *Proceedings of the Bulgarian Academy of Sciences, 78*(6), 946–954. https://doi.org/10.7546/CRABS.2025.06.18

Ismayilova, A., Shukurov, S., Hasanaliyeva, L., Osmanova, S., Asgarova, G., & Hasanova, T. (2025a). Modern soil cover of natural cenoses and agrocenoses landscapes of the Kur-Araz plain. *Advances in Biology & Earth Sciences*, *10*(2), 314–325. https://doi.org/10.62476/abes.102314

Ismayilova, A. A., Mirzezadeh, R. I., Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Asgarova, G. F., & Madnee, M. (2025b). Biomass and enzymatic activity assessment of the coniferous-deciduous forests in Azerbaijan. *SABRAO Journal of Breeding and Genetics, 57*(6), 2584–2595. https://doi.org/10.54910/sabrao2025.57.6.31

Mammadova, R., Hasanova, T., & Aliyeva, M. (2025). Ecological state of modern soil cover in agrocenoses of the Greater Caucasus Sheki region. *Ecological Systems Modelling. Collective monograph, 3*, 57–73. https://doi.org/10.21303/978-9908-9706-6-0.ch3

Mammadzada, V. T., Aliyeva, M. M., Rzayeva, A. L., Nasirova, A. I., & Mammadova, R. N. (2025). Soil bioactivity study through innovative approaches in Lankaran–Astara region, Azerbaijan. *SABRAO Journal of Breeding and Genetics, 57*(3), 1180–1191. http://doi.org/10.54910/sabrao2025.57.3.29

Mirzezadeh, R. I., Ramazanova, F. M., Hasanova, T. A., Mammadova, G. I., & Asgarova, G. F. (2025). Assessment of variations caused by biological activities in the Greater Caucasus forest soils used for agriculture. *SABRAO Journal of Breeding and Genetics, 57*(4), 1634–1643. https://doi.org/10.54910/sabrao2025.57.4.29

Makki, H. A., Saeed, A., Hussain, T., Rafay, T., Madnee, M., Abid, M., Hasanova, T. H., & Nurrochmat, N. A. (2025). Enhancing soil rehabilitation in saline and sandy soils of Punjab, Pakistan using wastewater reuse and native tree species. *Egyptian Journal of Soil Science, 65*(4), 2039–2054. http://doi.org/10.21608/EJSS.2025.426305.2378

Mammadzade, V. T. (2025). Microbiological activity of natural biotopes of mountain-forest yellow earth soils. *Agrarian Bulletin of the Urals, 25*(01), 10–19. https://doi.org/10.32417/1997-4868-2025-25-01-10-19

Mammadova, G., Salimova, Sh., Aliyeva, G., Isagova, V., & Hasanova, T. (2026a). Modern approaches in the study of soil bioactivity in Katekh and Garakli village (Azerbaijan) irrigated alluvial meadow and mountain forest brown soils. *Bulgarian Journal of Agricultural Science, 32*(2), 278–285.

Mammadova, R. N., Salimova, S. J., Huseynova, S. M., Mammadova, G. I., Hasanova, T. A., Rafiyeva, H. L., & Jafarova, G. A. (2025b). Plant leaves as a biogeochemical indicator of the environmental state in different regions of Azerbaijan. *Comptes Rendus de l'Académie Bulgare des Sciences, 78*(11), 1601–1610. https://doi.org/10.7546/CRABS.2025.11.03

Mazhar, I., Safeer, M., Madnee, M., Sarfaraz, A., Hasanova, T. A., & Bashir, M. A. (2025). Phytochemical composition and antioxidant potential of *Moringa oleifera* from the Cholistan Desert: Implications for human nutrition. *Global Forests, 4*(1), 50–61. https://doi.org/10.54219/globalforests.04.01.2025.394

Madnee, M., Hussain, T., Hasanova, T. A., Nurrochmat, N. A., Bashir, M. A., Ali, M. M., Ghaffar, M. U., & Qanitha, M. (2025). Enhancing soil fertility in arid and semi-arid climates using leguminous trees: A species-specific agroforestry approach. *Journal of Agroforestry and Environment, 18*(2), 152–168. https://doi.org/10.55706/jae1834

Mammadova, G. I., Salimova, Sh. J., Jafarov, A. M., Huseynova, S. M., Isayeva, K. K., Isagova, V. G., & Hasanova, T. A. (2026b). Rocky soil compositions influence on the microorganisms and vegetation at the Sheki-Zagatala Economic Region, Azerbaijan. *SABRAO Journal of Breeding and Genetics, 58*(3), 101–112. http://doi.org/10.54910/sabrao2026.58.3

Mammadov, G. S., Teymurov, M. A., Mammadov, Z. R., Yusifova, M. M., Osmanova, S. A., Gasimov, A. M., Akhundova, A. A., & Salimova, S. J. (2026). Climate change effects on soil fertility and moisture in the Nakhchivanchay River Basin, Azerbaijan. *International Journal of Agriculture and Biosciences, 15*(1), 77–86. https://doi.org/10.47278/journal.ijab/2025.152

Nasirova, A. (2023a). Modern and comprehensive soil studies in grape agrocenoses in Azerbaijan. *International Journal of Advances in Applied Sciences, 13*(2), 217–224, https://doi.org/10.11591/ijaas.v13.i2.pp217-224

Nasirova, A. (2023b). Cultivation of *Malva sylvestris* L. species in the Ganja-Kazakh economic region in recent years. *Advances in Biology & Earth Sciences, 8*(1), 114–117.

Nasirova, A. I., Hasanova, T. A., Asgarova, G. F., & Abasova, N. A. (2025). Modeling of soil electrical conductivity for sustainable land use in salinized areas. *Agrarian Bulletin of the Urals, 25*(8), 1199–1208. https://doi.org/10.32417/1997-48682025-25-08-1199-1208

Nasirova, A. I., & Verdiyeva, F. B. (2023). Determinations of feed quality and mallow organic residues. *Proceedings of the Bulgarian Academy of Sciences, 76*(5), 803–809. https://doi.org/10.7546/CRABS.2023.05.17

Nasirova, A. I., Isagova, V. G., Mirzezadeh, R. I., Gahramanova, A. Y., Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Asgarova, G. F., & Mammadova, R. N. (2026). Changing the biological activity of soil in sunflower crops. *Comptes Rendus De L Academie Bulgare Des Sciences, 79*(1), 145–156. https://doi.org/10.7546/CRABS.2026.01.18

Ramazanova, F., Huseynova, S., Isagova, V., & Jafarova, G. (2026). Diagnostics of irrigated soils in the dry steppe and semi-desert zones of Azerbaijan. *Nature & Science, 8*(3), 12–19. https://doi.org/10.36719/2707-1146/66/12-19

Rzayeva, A. (2023). Microbiological studies of mountain forest brown and mountain forest greyish-brown soils. *Bulletin of Science and Practice, 9*(4), 109–112. https://doi.org/10.33619/2414-2948/89/13

Rzayeva, A. L., & Mamedzade, V. T. (2024). Some physicochemical indicators of mountain-forest brown soil. *Agrarian Scientific Journal, 11*, 42–48. https://doi.org/10.28983/asj.y2024i11pp42-48

Samadov, P. A., Rzayeva, A. L., Aliyeva, M. M., Nasirova, A. I., Mammadova, R. N., Mammadzade, V. T., Aghayeva, T. S., & Shirinova, G. F. (2026a). Eco-biological features of mountain gray-brown development in the Karabakh steppe (Republic of Azerbaijan). *International Journal of Agriculture and Biosciences, 15*(4), 1691–1699. https://doi.org/10.47278/journal.ijab/2026.063

Samadov, P. A., Mammadov, Z. R., Aliyeva, M. M., Rzayeva, A. L., Nasirova, A. I., Mammadova, R. N., Mammadzade, V. T., Aliyeva, B. B., & Sadikhova, M. E. (2026b). Eco-biological indicators of mountain forest soils in the Lankaran Region, Azerbaijan. *SABRAO Journal of Breeding and Genetics, 58*(1), 442–452. https://doi.org/10.54910/sabrao2026.58.1.41

Sadigov, R. A., Nazarova, M. K., Garayeva, I. E., Mammadova, G. I., Hasanova, T. A., & Madnee, M. (2025). Modern research on the use of alternative energy resources in Azerbaijan. *International Journal of Advances in Applied Sciences, 14*(3), 907–915. https://doi.org/10.11591/ijaas.v14.i3.pp907-915

Sadigov, R. A., Mammadova, G. I., Isagova, V. G., Hasanova, T. A., & Madnee, M. (2026). Current state of production of alternative energy on the Absheron Peninsula. *International Journal of Applied Power Engineering, 15*(1), 37–45. https://doi.org/10.11591/ijape.v15.i1.pp37-45

Shukurov, S. Kh., Ismayilova, A. A., Sadigov, R. A., Karimova, M. J., Hasanova, T. A., & Asgarova, G. A. (2025). Determination of soil salinization by hyperspectral remote sensing in the Shirvan Plain. *International Journal of Advances in Applied Sciences, 14*(3), 662–670. https://doi.org/10.11591/ijaas.v14.i3.pp662-670

Shukurov, S. Kh., Karimova, L. R., Yusifova, S. N., Isagova, V. G., Novruzova, S. S., Jafarova, G. A., Isagova, G. J., Asarova, G. F., & Amanova, S. S. (2026). Monitoring the current state of soil-vegetation cover using traditional and remote sensing methods. *Agrobiological Records, 23*, 149–157. https://doi.org/10.47278/journal.abr/2026.013

Togola, A., Yusifova, M., Sadigova, N., Akhundova, A., Karimova, L., & Nuriyeva, K. (2023). Anthropogenic impacts on Ajinohur arid forests of Azerbaijan. *Acta Biologica Sibirica. 9*, 1125–1140. https://doi.org/10.5281/zenodo.10297250

Verdiyeva, F. B., Hasanova, T. A., Ismayilova, M. E., Huseynov, E. Y., Jabiyeva, T. E., & Asgarova, G. A. (2025). Bioecological characteristics of modern soil cover in subtropic regions of Azerbaijan. *International Journal of Advances in Applied Sciences, 14*(4), 1200–1207. https://doi.org/10.11591/ijaas.v14.i4.pp1200-1207

Verdiyeva, F. B., Abdullayeva, R. K., Ismayilzadeh, N. N., Fatdayeva, A. K., Mammadova, G. I., Hasanova, L. U., Asgarova, G. F., & Hasanova, T. A. (2026). Biosynthesis of seeds and bioecological parameters of gray-meadow soils by remote sensing (Republic of Azerbaijan) under wheat crops. *International Journal of Agriculture and Biosciences, 15*(4), 126–137. https://doi.org/10.47278/journal.ijab/2026.075

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Evaluating the Hydrological and Erosional Benefits of Afforestation Interventions in Ayubia National Park, Pakistan: Implications for Groundwater Recharge and Sediment Yield Reduction

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Abstract. *The effects of deforestation on hydrological services and stability of soil are a major concern in the mountain areas. This study quantitatively evaluates the benefits of afforestation interventions on groundwater recharge and sediment yield in the sensitive ecosystem of Ayubia National Park, Pakistan. A comparative watershed study was used, evaluating four watersheds (two afforested "treated" and two degraded "untreated"). Field measurements were made of infiltration capacity (double ring infiltrometer), stream discharge (velocity-area method), and sediment yield (fixed area plots). Findings showed treated areas yielded significantly higher infiltration capacity (up to 40 mm/h) as compared to untreated ($p < 0.001$). The average stream discharge after rainfall in vegetated watersheds increased moderately by 25% as compared to a 92% increase in an untreated watershed indicating great flood-mitigating ability of vegetated watersheds. In addition, sediment yield was about 50% lower in treated areas. Vegetation cover (trees, shrubs, grass) was determined to be the most significant determinant of improved soil porosity and infiltration by multivariate regression analysis. The conclusion drawn by the findings is quite clear and as per the requirements, afforestation is found as one of the key nature-based solutions for managing water resources sustainably and improving groundwater recharge, mitigating floods and reducing erosion in the vulnerable watersheds of the Himalayan region.*

Keywords: *deforestation, watershed management, nature-based solutions, land use change, infiltrometer and discharge flow*

Introduction

Forest resources are crucially important and essential contributors to a wide range of ecological functions that are vital for life, such as controlling hydrology, conserving soil, preventing erosion and preserving biodiversity. Forests that exist on earth are approximately 3870 million hectares, 95% of them are natural forests and 5% plantations (Sousson et al., 1995).

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27% of the planet's entire forests are in Europe, 5% in Latin America and the Caribbean 19% in Asia and Pacific, 17% in Africa and the remaining 12% in North America (FAO, 2001). The forest areas account for 5.2% in Pakistan which represent 4.606 million hectares, with a high proportion (17%) of forest lands in KP province (Ali et al., 2020).

During the last decade of the 20th century, the world lost nearly 14.6 million ha of forest per year and forests were converted to agriculture or urban land use. Even though 5.2 million ha of forests were naturally regenerated through forest expansion and that were added during that period, still the net loss is 9.6 million ha of forests per year (FAO, 2001). Despite their importance, global deforestation continues at an alarming rate, leading to the degradation of critical services. Forest cover in Pakistan is one of the lowest in the region with a high deforestation rate and is linked with increased risks of flooding, sedimentation and water scarcity (Khan & Khan, 2009).

The Himalayan region is a critical zone of global biodiversity and is particularly vulnerable. Ayubia National Park, situated in the Western Himalayas of Pakistan, is a protected national land whose ecologic values are very high. It is subjected to extreme pressure from surrounding human settlements and historical deforestation, which have altered its hydrological properties and accelerated soil erosion. It is therefore important to quantify the benefits of interventions such as afforestation for assisting in the formulation of effective watershed management strategies in such sensitive areas (Qasim et al., 2017; Nurrochmat et al., 2024). Watershed restoration projects have shown tangible improvements in the ability to control the hydrology and resilience of the ecosystems in mountain areas (Berke et al., 2003).

The effects of land use and rainfall on sediment loss and annual runoff were studied in eight land use cases in the north Mediterranean and in the Atlantic coastline in Portugal, Spain, France, Italy and Greece (Moore & Wondzell, 2005). Groundwater recharge to an aquifer is simply the water which enters the aquifer in any direction. Recharge to a groundwater flow system is normally assumed to be the height of the water column that enters in the groundwater zone divided by the time. Despite being a fundamental aspect in hydrological cycle, recharge cannot be measured directly due to the difficulty of measurement at the spatial level, where most of the processes occur (Mirzezadeh & Mammadova, 2026; Jafarova, 2026). Therefore, recharge rate has been calculated from indirect sources using climatic, spatial scale and temporal scale. Groundwater is a valuable, hidden, yet replenishable resource that exists beneath the surface of the ground. Headwater hillslopes generate runoff and contribute to groundwater flow (Manna et al., 2016).

Groundwater is an important resource that is often out of sight and out of mind. In Ireland, about 25% of total water is supplied by groundwater, although in most rural settings, groundwater supply forms a much larger share and in some regions of the country, is nearly the only supply (Allen & Chapman, 2001).

The whole process entails an increase in sediment yield through runoff. The increased runoff is correlated with increased rainfall and subsequently with increased kinetic energy utilized in the initial erosion of hill slopes and also in the transportation of the eroded silt in streams. Conspicuous differences exist, though, in the percentage of annual runoff increase in rates of sediment yield. With resulting changes in average cover between forest and rangelands, there is more sensitivity of the sediment loss to changes in runoff (Thomas Dunne & Leopold, 2016).

Various landscape types are subject to a variety of land uses common to the Mediterranean area such as agricultural land where cereals are grown rain-fed, vines, olives, eucalyptus plantation or natural vegetation. Land use was found to have very significant impacts on runoff and soil erosion. Hilly slopes with vines had average sediment loss of 142.8 tonnes per km² per year (Kosmas & Danalatos, 1997).

The changes in watershed hydrology are the major factors related to land use and land cover change. Vegetation cover directly affects infiltration, generation of surface runoff, and detachment and transport of sediment. The previous research in the other watersheds (Ayubia & adjoining Himalayan watersheds) also showed decrease in infiltration capacity and spring discharge after deforestation and overgrazing (Kamran, 2003; Kamran, 2005; Kamran, 2007). Though forests provide overall benefits, there is limited quantitative data to prove their effectiveness at the site-level in the Western Himalayas. This is especially important for validating management actions and optimizing future investments in nature based solutions.

This study aims to fill this knowledge gap by conducting a comparative analysis of treated (afforested) and untreated (degraded) watersheds in Ayubia National Park. The specific objectives are:

1. To quantify the impact of afforestation on soil infiltration capacity and its implications for groundwater recharge.
2. To assess the effect of plantations on sediment yield in local streams.
3. To develop a multivariate model relating vegetation cover to soil hydrological properties.

Materials and Methods

The study sites included peripheral sites of Ayubia National Park which are Namli Maira (1,800–2,980 m elevation; 250 ha) and Lundi Mandri (1,860–2,650 m elevation; 43.26 ha), Mohra (1,980–2,680 m elevation; 35.99 ha), and Arifabad (1,800–2,480 m elevation; 20.22 ha) under a temperate monsoon climate. A comparative design included treated and untreated areas (planting species such as *Pinus wallichiana*).

Figure 1
Collective map of study area showing all sites

Experimental Design and Field Measurements

Infiltration Capacity: Soil infiltration capacity was measured using a double-ring infiltrometer (fig. 2). The inner ring had a diameter of 21.5 cm. A constant head of 4 cm was maintained. Readings were taken at 1, 2, 3, 4, 5, 10, 20, 35, 55, and 85 minutes until a steady-state rate was achieved. Three replicates were taken per site. The infiltration capacity (Ic, mm/hr) was calculated as:–

$$Ic = D / T$$

Where, D is the depth of water added (mm) and T is the time interval (hours). The use of infiltration-based approaches for evaluating watershed restoration effectiveness has been widely reported in hydrological studies (Itsukushima et al., 2016).

Figure 2
Double ring infiltrometer

Stream Discharge and Sediment Load: Stream discharge (Q, m^3/s) was measured at predetermined GPS-marked points using the velocity-area method as following:

$$Q = V \times A$$

Where, V is flow velocity (m/s) and A is the cross-sectional area (m^2). Measurements were taken both before and after rainfall events. Water samples were collected simultaneously to determine sediment concentration (mg/L).

Sediment Yield from Plots: Sediment yield was quantified using fixed-area research plots of 8.93 m^2. Runoff was channeled into collection drums (Fig. 3). The settled sediment volume in the drum (radius = 25 cm) was measured and converted to a volume (cm^3). This volume was then extrapolated to a per-hectare basis (m^3/ha) to standardize the yield.

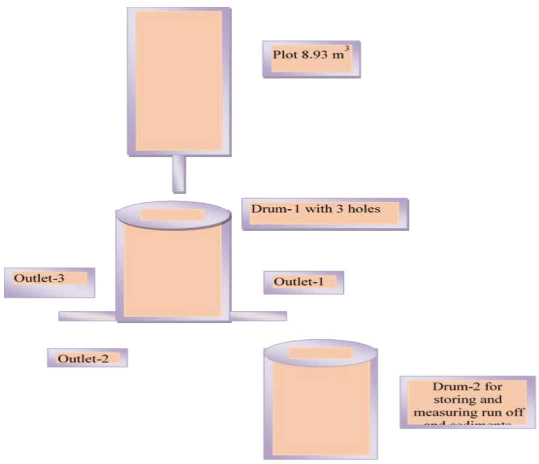

Figure 3
Rectangular fixed research plot

Ancillary Data
Vegetation surveys were conducted to record species composition, density and canopy cover percentage at each site (Fig. 4). Soil samples were collected for texture analysis using the USDA classification system.

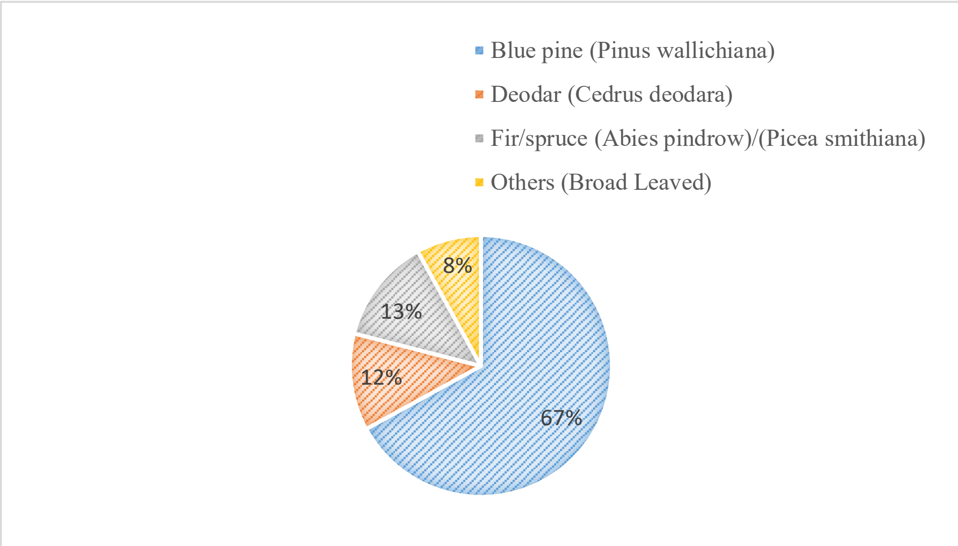

Figure 4
Floral diversity in the study area

Statistical Analysis: Statistical procedures followed standard biometric approaches described by Steel et al. (1997). Data analysis employed ANOVA and t-tests ($\alpha = 0.05$); multivariate regression (Infiltration Rate = $\beta 0 + \beta 1$Vegetation Density + $\beta 2$Slope + ε) using R software; ArcGIS for spatial analysis (Madnee et al., 2025a).

Results

Discharge Rate of Water in Streams
To determine the rate of discharge, two streams, one each from protected and unprotected watersheds were examined. The discharge rates for both the streams were calculated before and after rainfall in different seasons of the year. The resultant values of discharge rates of both streams examined in different months are given in table 1. It should be noted that Stream I and Stream II represents streams at protected and unprotected sites respectively. The average difference in discharge rate (before and after rainfall) for Stream I was almost double that of Stream II. The watersheds of the stream I located at the protected forestland have dense vegetation; on contrast stream II being feed by watershed of open forestland have sparse vegetation. Dense vegetation at the watershed area means high evapotranspiration rates after rainfall and less change in the water discharge, similarly sparse vegetation means minimal evaporation rates and high discharge rates, especially after rainfall.

The data analysis clearly reveals that the variation in the discharge rates of stream I before and after rain is quite less than stream II. The maximum increase in the discharge rate after rainfall at stream I was found to be 38%, and 25% on average. On the other hand, at stream II the maximum recorded change in discharge rate was 160% in the month of September, with average increase of 92% in discharge rate after rainfall. This means that the effect of rainfall on stream flow is much higher for Stream II compared to Stream I. Therefore, we can conclude that vegetation regulates the flow of water from the watersheds of these streams and thus protect the downstream areas from floods during heavy rainfall mentioned in figure 5.

Sediment Yield

Comparative analysis of the sediment yield in the two streams show that there is a close relation between density of vegetation in the watersheds of a stream and the amount of sediment (eroded soil particles) in that stream. The resultant values of sediment concentration before and after rainfall at both streams in various months are given in table 2.

Stream I having good vegetation on its watersheds have low concentrations of sediment before rainfall with small amount of increase in sediment concentration after rainfall. On the other hand, stream II having poor vegetation on its catchment area have high concentration of sediment before rainfall but the increase in sediment concentration on stream II after rainfall as given in the table 2. The average increase in the sediment concentration after rainfall in stream II was 100% more than that of stream I as shown in figure 6. The maximum sediment concentration in both the streams was recorded in the month of July after heavy rainfall, but still the increase in the sediment load in stream I was only 61ppm compared to 120 ppm increase in the sediment load of stream II. This is inversely related to total suspended sediment. The greater the amount of vegetation in the watershed, the lower the sediment load will be and vice versa. So, the conclusion is that vegetation of the upstream watershed is a filter and it intended to get fresh water from upstream to the downstream watershed.

The fixed area method was used to determine the sediment yield from various sites. The results are expressed in table 3. Results reveal that treated area has less sediment yield than untreated area. The most vulnerable is degraded soil because it has the maximum sediment yield or soil losses. The difference can be attributed to covered soil in treated area (planted area) than denuded soil in untreated area (unplanted area). More the plantation lesser will be the soil erosion and vice versa.

Infiltration Capacity

The p-value of 0.001 is lower than 0.05, proving that the difference between the infiltration capacities of both watersheds are significantly different. The mean infiltration rate at each time interval was highest at Spot 1, i.e., 40 $mm^3$and gradually started to decrease linearly and reached its minimum point at the last interval in both watersheds at all spots. While, the horizontal mean values describe that the infiltration rate was highest at the Spot 1 i.e. a bit lower in Spot 2 and further lower at Spot 3 in the treated area, which may be due to the difference in vegetation density and vegetation type but further lower at Spot 4 and minimum at Spot 5 in the untreated watershed, which are definitely due to the absence of management practices (Table 4).

Table 1

Discharge rates of streams

	Protected stream discharge rate (m^3/S)			Unprotected stream discharge rate (m^3/S)		
	B. Rain	A. Rain	Difference	B. Rain	A. Rain	Difference
April, 16	0.073	0.094	0.021	0.044	0.093	0.049
July, 16	1.573	1.963	0.39	1.03	1.94	0.91
September, 16	0.059	0.082	0.023	0.033	0.086	0.053
November, 16	0.046	0.061	0.015	0.039	0.085	0.046
Average	0.43775	0.55	0.11225	0.2865	0.551	0.2645

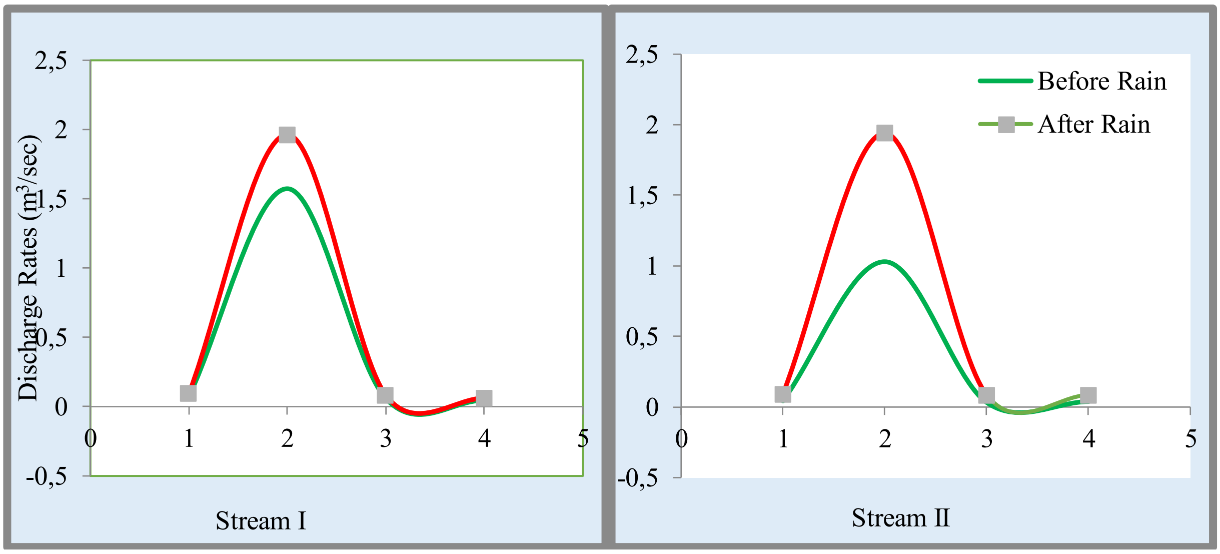

Figure 5

Discharge rate of water flow in the streams of both study sites (m^3/sec)

Table 2

Sediment concentration at protected and unprotected streams

	Sediment load in stream I(ppm)			Sediment load in stream II(ppm)		
	B. Rain	A. Rain	Increase	B. Rain	A. Rain	Increase
April, 16	114	144	30	117	177	60
July, 16	136	197	61	177	297	120
September, 16	110	131	21	138	210	72
November, 16	100	132	32	138	175	37
Average	115	151	36	142.5	214.75	72.25

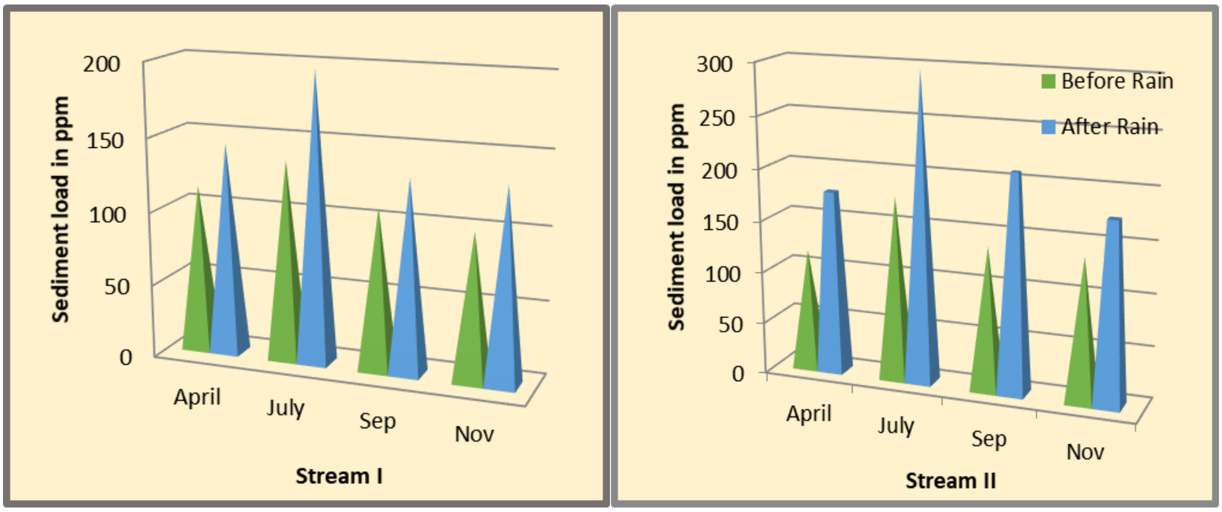

Figure 6
Sediment concentration before and after rainfall in both the streams

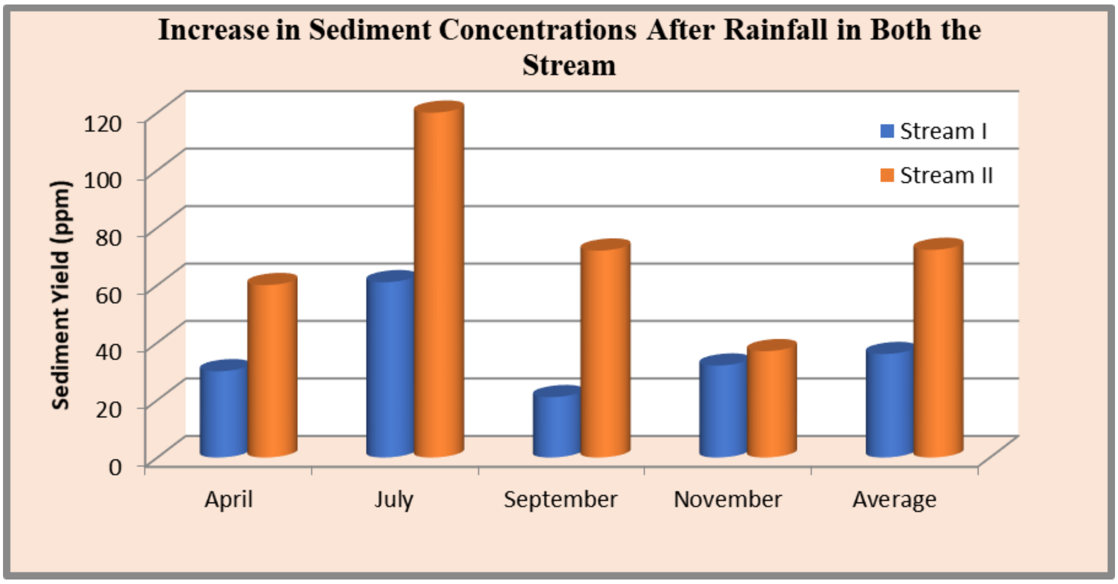

Figure 7
Increase in sediment concentrations after rainfall in both streams

Table 3
Sediment yield at various sites

Site locations of the research plot	Sediment yield in plot size of 8.93 m^2 (cm^3)	Sediment yield m^3/ha
Treated	46560	52.13
Untreated	47347	53.02
Improved agricultural land	51522	57.69
Conventional land	55459	62.10
Degrades soils	62332	69.80

Table 4
Infiltration capacity of all study sites around Ayubia National Park

Time taken (min)	Amount of Water Infiltrated (mm^3)					Mean
	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	
1	150	133.3	127.66	111.3	83	121.08
2	48	45	37.2	33.6	22.2	37.20
3	44.2	37.6	31	27.3	19.5	31.92
4	34.1	30.2	28.8	22	16	26.22
5	31.8	30.1	26.7	21.9	14	24.90
10	28.7	24.7	25	14	8.9	20.26
20	26.7	23.6	24.6	12.3	7.3	18.90
35	15.8	11.4	11.3	7.7	6.3	10.50
55	11.6	7.6	6.2	5.7	3.5	6.92
85	9.4	6.4	5	3.8	2.5	5.42
Mean	40.030	34.990	32.346	25.975	18.320	

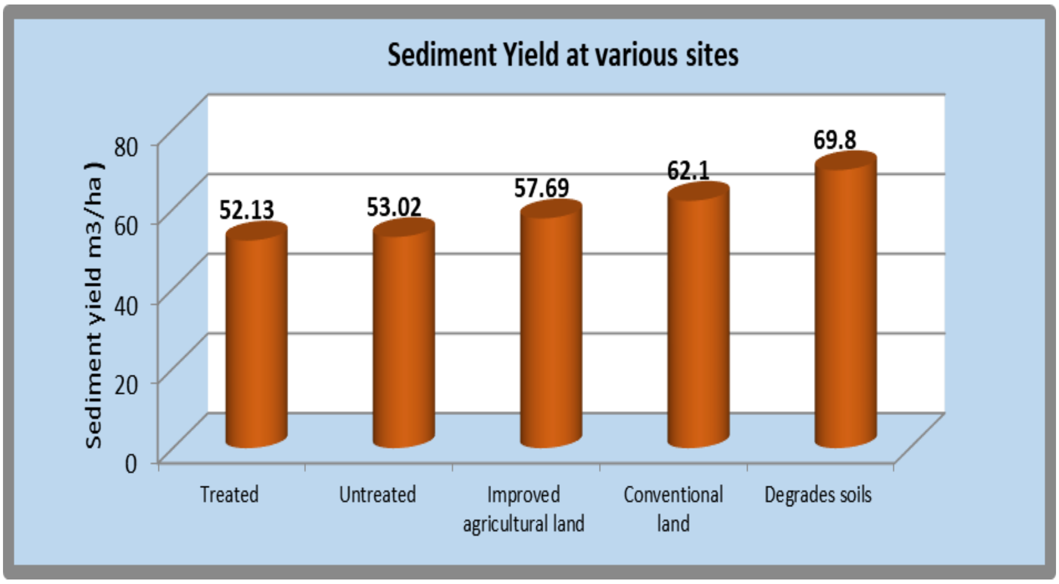

Figure 8
Sediment yield at various sites around Ayubia National Park

Discussion

The findings of this study supports the effectiveness of nature-based solutions in sustainable water resources management with empirical evidence. Afforestation interventions on the sensitive Himalayan ecosystem of Ayubia National Park positively influenced the hydrological functions. There is marked difference in infiltrative capacity for afforested and non-afforested watersheds, as seen in our comparative study. We observed a significant difference in the infiltration capacity of degraded versus afforested watersheds, and to regulate and control streamflow as well as sedimentation. An important result of this work is the significantly higher infiltration capacity for treated areas than for degraded areas, up to 40 mm/h. This enhancement can be directly attributed to the re-establishment of vegetation, because it enhances soil structure through several mechanisms (Makki et al., 2025; Madnee et al., 2025b). Tree roots create macropores and channels in the soil that facilitate rapid water movement through the soil profile (Ilstedt et al., 2007). At the same time, organic matter added with litter fall increases soil water-holding capacity, porosity, and aggregation (Bargués-Tobella et al., 2014; Bari et al., 2026), minimizing surface crusting and runoff initiation. This is consistent with the global average of above average infiltration rates found in forests compared to disturbed or non-forested sites (Zhou et al., 2022).

The effects on aquifer recharge in this hilly area are serious. Afforestation allows more rainwater to infiltrate underground by reducing runoff and is therefore likely to lead to increased aquifer renewal. This is not only an environmental benefit, but also a critical water security measure for communities that are highly reliant on springs and shallow groundwater. The results of the study indicate that watershed restoration could be an anticipatory step towards abating the growing water scarcity occurring in the Western Himalayas and driven by climate change and population pressure (Rasul, 2014; Safeer et al., 2025).

Vegetated watersheds' feedback to rainfall events is much more moderate, thus highlighting the flood mitigation service of afforestation. An untreated watershed had a very large change when it rained (the average change was 92%), while a treated watershed had a smaller change (25%). This differential response is an immediate result of the enhancement of infiltration capacity, a ‘sponge' that reduces and delays the amount of surface runoff to stream channels. This buffering capacity is an essential ecosystem service. It can modify the intensity of flood peaks, decreasing the potential for flash floods in steep, mountainous areas prone to intense rainfall. These findings reflect similar results from other montane sites that have shown a strong reduction of the peak flow and an increase in the lag time between the rainfall and the runoff due to the forest cover (Bruijnzeel, 2004). Given that downstream areas, including the city of Abbottabad, are susceptible to flooding; the investment in afforestation upstream makes it a direct and cost-effective natural infrastructure for disaster risk reduction.

Another key benefit is the approximately 50% reduction in sediment yield, demonstrating effective control of soil erosion and improvement of water quality (fig. 8). Vegetation cover reduces the direct effect on the soil surface of rainfall, and root systems act to promote soil cohesion and to reduce the erosive forces acting on the soil (Gyssels et al., 2005). A dense canopy and understorey structure, also found in afforested areas, is also associated with reduced velocity of overland flow, resulting in reduced sediment transport capacity. Reductions in soil erosion and sediment export with improved vegetation cover have also been reported in Ethiopian watersheds using GIS-based soil loss assessment (Gelagay & Minale, 2016).

Afforestation helps in maintaining the precious thin top soil in the mountainous terrain, thereby retaining their fertility and eco-function. Second, it drastically reduces the sediment load to downstream reservoirs and rivers. Reservoirs that receive a high amount of sediment silt up, lose storage capacity and life, and stress aquatic ecosystems as well through turbidity (Syvitski et al., 2005). The lower sediment concentration in streams from treated watersheds, as documented in our study (Fig. 6), indicates a clear pathway to safeguarding downstream water infrastructure and biodiversity, aligning with the findings of Madnee et al. (2025) on the role of vegetation in stabilizing soil systems even in arid climates.

The multivariate regression model verified that vegetation cover is the most important factor affecting soil hydrological responses, consistent with studies showing strong relationships between vegetation cover, soil protection, and ecosystem productivity (Zafar et al., 2026). This study significantly reinforces WWF-Pakistan's afforestation efforts and serves as a solid scientific basis for advocating policy changes. Our findings indicate that forest rehabilitation in the degraded watersheds of the Himalayas is not just conservation but investment towards the management of water resources. The findings are validated by the recommendations of broader climate smart ecological interventions recommended for dryland and mountain ecosystem of Pakistan (Qureshi et al., 2024).

This study finds that afforestation and integrated watershed management are crucial elements for strategic scaling-up endeavours for adaptation to climate change as a policy issue and as a water management tool for policy makers (Ali et al., 2026) These interventions deliver three benefits: increased water security through groundwater recharge, safe communities through flood risk reduction and longer water infrastructure life through reduced sedimentation. Future research needs to quantify the economic value of these hydrological services to enhance the rationale for investments in nature based solutions.

Conclusion

The significance of plantations in improving hydrological services and soil resource protection in the Rawal and Abbottabad watersheds in Ayubia National Park, Pakistan is emphasized in this study. Field data from treated (planted) and untreated areas reveal that afforestation significantly mitigates flood risks and frequencies through improved water retention and reduced sediment yields. Results showed that infiltration capacities were much higher (up to 40 mm/h) and sediment loads were much lower for the treated areas compared to the untreated areas and the finding resulted from the use of the statistical analysis (p<0.001). Stream discharge following rainfall significantly increased in unprotected areas (92%), suggesting vegetation stabilizes the flow of water that generates flooding downstream, while being moderated in vegetated watersheds (25%). WWF-Pakistan's conservation initiatives not only protect nature but also socio-economically support the livelihoods of communities. This study therefore strongly suggests that the application of watershed integrated management practices should be promoted in order to facilitate sustainable use of land and water resources within environmentally vulnerable areas such as Ayubia National Park.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ali, A., Ashraf, M. I., Gulzar, S., Akmal, M., & Ahmad, B. (2020). Estimation of soil carbon pools in the forests of Khyber Pakhtunkhwa Province, Pakistan. *Journal of Forestry Research*, *31*(6), 2313–2321. https://doi.org/10.1007/s11676-019-01059-9

Ali, M. M., Sarmin, I. J., Akter, N., Bashir, M. A., Bari, M. S., Shil, S. K., ... & Mohamud, A. O. (2026). Scaling agroforestry for climate change mitigation and sustainable agricultural intensification in South Asia. *Discover Environment*, *4*(1), 351.

Allen, A., & Chapman, D. (2001). Impacts of afforestation on groundwater resources and quality. *Hydrogeology Journal,* 9, 390–400. https://doi.org/10.1007/s100400100148

Bargués-Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., & Ilstedt, U. (2014). The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. *Water Resources Research, 50*(4), 3342–3354.

Bari, M. S., Rahman, M. S., Bashir, M. A., Sultana, R., Madnee, M., & Ali, M. M. (2026). Agroforestry enhances economic returns, land efficiency and soil health in the char lands of Bangladesh. *Agroforestry Systems*, *100*(85). https://doi.org/10.1007/s10457-026-01457-z

Berke, P., MacDonald, J., White, N., Holmes, M., Line, D., Oury, K., & Ryznar, R. (2003). Greening development to protect watersheds: Does new urbanism make a difference? *Journal of the American Planning Association, 69*(4), 397–413.

Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agriculture, Ecosystems and Environment, 104*(1), 185–228. https://doi.org/10.1016/j.agee.2004.01.015

FAO. (2001). *Global Forest Resources Assessment 2000: Main Report. Food and Agriculture Organization of the United Nations.* https://www.fao.org/forest-resources-assessment/fra-2000/en

Gelagay, H. S., & Minale, A. S. (2016). Soil loss estimation using GIS and remote sensing techniques: A case of Koga watershed, Northwestern Ethiopia. *International Soil and Water Conservation Research, 4*(2), 126–136. https://doi.org/10.1016/j.iswcr.2016.01.002

Gyssels, G., Poesen, J., Bochet, E., & Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: A review. *Progress in Physical Geography*, *29*(2), 189–217. https://doi.org/10.21608/ejss.2025.426305.2378

Ilstedt, U., Malmer, A., Verbeeten, E., & Murdiyarso, D. (2007). The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis. *Forest Ecology and Management*, *251*(1–2), 45–51. https://doi.org/10.1016/j.foreco.2007.06.014

Itsukushima, R., Ideta, K., Iwanaga, Y., Sato, T., & Shimatani, Y. (2016, February). Evaluation of infiltration capacity and water retention potential of amended soil using bamboo charcoal and humus for urban flood prevention. In *Proceedings of the 11th International Symposium on Ecohydraulics, Melbourne, Australia* (pp. 7–12).

Jafarova, S. (2026). Soil pollution and agricultural productivity losses. *Nature & Science, 8*(2), 83–89. https://doi.org/10.36719/2707-1146/65/83-89

Kamran, M. (2003). *Impacts of overgrazing and deforestation on infiltration capacity of soil and drying up of springs at Ayubia National Park*. WWF-Pakistan Report.

Kamran, M. (2005). *Impact of forest density on water properties and sediment yield at Miandam, Swat.* WWF-Pakistan Report.

Kamran, M. (2007). *Impact of forest density on stream water properties at Nathiyagali sub-watersheds.* WWF-Pakistan Report.

Khan, S. R., & Khan, S. R. (2009). Assessing poverty–deforestation links: Evidence from Swat, Pakistan. *Ecological Economics*, *68*(10), 2607–2618.

Kosmas, C., & Danalatos, N. G. (1997). The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena, 29*(1), 45–59.

Madnee, M., Hussain, T., Abid, M., Khalid, M., Makki, H. A., Nurrochmat, N. A., & Bashir, M. A. (2025a). Evidencing the socioeconomic impact of agroforestry in an arid climate: a case study of district Bahawalpur, Punjab, Pakistan. *Agroforestry Systems*, *99*(5), 1–18.

Madnee, M., Hussain, T., Allahverdi, T. H., Nurrochmat, N. A., Bashir, M. A., Ali, M. M., Ghaffar, M. U., & Qanitha, M. (2025b). Enhancing soil fertility in arid and semi-arid climates using leguminous trees: A species-specific agroforestry approach. *Journal of Agroforestry and Environment*, 18(2), 152–168. https://doi.org/10.55706/jae1834

Madnee, M., Hussain, T., Sabir, M. A., Abid, M., Khalid, M., Makki, H. A., ... & Nurrochmat, N. A. (2025). Differential responses of leguminous tree species to drought stress: implications for agroforestry and restoration in arid and semi-arid climates. *Agroforestry Systems, 99*(4), 1–21. https://doi.org/10.1007/s10457-025-01178-9

Makki, H. A., Saeed, A., Hussain, T., Rafay, M., Madnee, M., Abid, M., ... & Nurrochmat, N. A. (2025). Enhancing soil rehabilitation in saline and sandy soils of Punjab, Pakistan using wastewater reuse and native tree species. *Egyptian Journal of Soil Science*, *65*(4).

Manna, F., Cherry, J. A., McWhorter, D. B., & Parker, B. L. (2016). Groundwater recharge assessment in an upland sandstone aquifer of southern California. *Journal of Hydrology,* 541, 787–799. https://doi.org/10.1016/j.jhydrol.2016.07.039

Mirzezadeh, R., & Mammadova, G. (2026). Soil protection: A strategic priority of the Soil Museum. *Nature & Science, 8*(3), 5–11. https://doi.org/10.36719/2707-1146/66/5-11

Moore, R. D., & Wondzell, S. M. (2005). Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. *Journal of the American Water Resources Association, 41*(4), 763–784. https://doi.org/10.1111/j.1752-1688.2005.tb03770.x

Nurrochmat, N. A., Hassan, N. U., Madnee, M., Husaain, H. S., Qanitha, M., Bronisz, K., ... & Sutrisno, S. (2024). Addressing environmental vulnerability: land cover dynamics assessment and afforestation strategies in Pakistan for disaster resilience. In *BIO Web of Conferences* (Vol. 123, p. 01021). EDP Sciences. https://doi.org/10.1051/bioconf/202412301021

Qasim, M., Bajwa, G. A., & Iqbal, M. J. (2017). Biodiversity Abundance and distribution in Ayubia National Park, Rawalpindi–Pakistan. *Science Technology Development*, *36*(1), 36–43.

Qureshi, R., Baig, M. B., & Belgacem, A. O. (2024). Climate change and innovative ecological interventions through climate-smart agriculture in the Cholistan desert of Pakistan. In *Climate-Smart and Resilient Food Systems and Security* (pp. 215–257). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-65968-3_9

Rasul, G. (2014). Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environmental Science and Policy*, 39, 35–48.

Safeer, M., Zubair, M., Hussain, T., Khan, M. A., & Madnee, M. (2025). Climatic variability linkages with agroforestry adoption in Pakistan: A socio-ecological review. *Agroforestry Systems,* 99, 263. https://doi.org/10.1007/s10457-025-01359-6

Sousson, J., Shrestha, B., & Uprety, L. P. (1995). *The social dynamics of deforestation: A case study from Nepal*. Parthenon Publishing Group.

Steel, R. G. D., Torrie, J. H., & Dickey, D. A. (1997). *Principles and Procedures of Statistics: A Biometrical Approach.* 3rd Edition. McGraw Hill Book Co. Inc.

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J., & Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science, 308*(5720), 376–380.

Thomas Dunne, T., & Leopold, L. B. (2016). *Water in Environmental Planning*. W. H. Freeman and Company.

Zafar, H. H., Aydin, S. M., Ali, R. S., Oqtay, N. M., Fakhraddin, A. H., & Madnee, M. (2026). Seasonal dynamic study of soil cover and plant productivity in pastures in the Khachmaz, Neftchala and Lankaran-Astara Regions. *Agrobiological Records, 24*, 165–174. https://doi.org/10.47278/journal.abr/2026.034

Zhou, G., Wei, X., Luo, Y., Zhang, M., Li, Y., Qiao, Y., Liu, H., & Wang, C. (2022). Forest recovery and its impacts on water yield and soil infiltration: A global meta-analysis. *Journal of Hydrology*, *610*, 127880. https://doi.org/10.1016/j.jhydrol.2022.127880

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The Effect of *Trichoderma* spp. on the Growth and Development of *Alhagi maurorum* and Evaluation of Its Potential for Biological Control

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Abstract. *Alhagi maurorum is characterized as a rapidly spreading weed outside its natural distribution range, with a high capacity to adapt to various soil and climatic conditions, and is particularly considered an undesirable plant in pasture and forage areas. In addition, the richness of this plant in biologically active compounds and its interactions with phytopathogenic microorganisms make it a relevant subject for investigation in the field of biological control. In modern agriculture, the investigation of alternatives to chemical control agents and the study of plant–microorganism interactions are of great importance for the development of biological control strategies. The aim of this study was to evaluate the interaction between Alhagi maurorum and Trichoderma spp. and to determine the effects of Trichoderma strains on plant development and biological resistance to phytopathogens. During the study, soil and plant samples were collected from different areas, fungal isolation was performed on Czapek medium, solidified malt extract medium, the obtained Trichoderma isolates were evaluated based on their morphological characteristics, and culture solutions were prepared. The results obtained demonstrated that the application of Trichoderma spp. could positively affect the growth parameters of Alhagi maurorum and indicated that the plant–microorganism interaction has considerable biological potential. Furthermore, the Trichoderma isolates were found to have potential as biological control agents capable of suppressing the development of phytopathogenic fungi. The findings of this study demonstrate that the interaction between Alhagi maurorum and Trichoderma spp. has significant scientific and practical potential for maintaining plant health, developing biological control agents, and promoting environmentally sustainable agricultural technologies.*

Keywords: *Alhagi maurorum, Trichoderma spp., microorganisms, biological control, biologically active compounds*

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Introduction

Plants that occur in the wild as well as those cultivated under agricultural conditions are widely used in medicine, the confectionery industry, perfumery, phytotherapy, and various other fields. As the practical and industrial importance of these plants increases, their areas of application also continue to expand almost every year. More than 35,000 plant species worldwide are used for medicinal purposes. According to data from previous and contemporary researchers, phenols, polyphenols, and flavonoids are considered natural antioxidant compounds of plants and are present at varying concentrations, particularly in medicinal plants (Tarawneh et al., 2010; Parthasarathy et al., 2009; Borchardt et al., 2009; Kiselova et al., 2006). In this regard, natural products possess interesting and beneficial biological properties and also perform various functions (Biswas et al., 2010). In general, in recent years, researchers have increasingly focused on natural products with the aim of developing more effective medicinal agents against cancer as well as viral and microbial infections (Revathi & Parimelazhghan, 2010). Among plants possessing the aforementioned properties, *Alhagi maurorum* is of particular interest. The number of studies conducted on this species in the aforementioned areas is limited, both internationally and in Azerbaijan. Nevertheless, *A. maurorum* is considered one of the plants with a wide distribution range and sufficiently abundant natural resources worldwide (Safarova, 2018), as well as throughout the territory of Azerbaijan. The limited number of scientific studies available indicates that environmental conditions may also play an important role in determining the biological effects of the components present in the plant. *Alhagi maurorum* is mainly distributed in areas with hot and arid climates and is characterized by its tolerance to saline soils. This plant usually grows and flowers actively during the spring and summer months. It can adapt well to unfavorable environmental conditions such as drought and salinity. Due to its thorny nature, it may hinder grazing by animals in pastures (Mandaville, 2011; Sharma, 2013). The ability of this species to adapt to saline and arid soils increases its economic and ecological importance (Jones & Brown, 2015). In particular, its occurrence in agricultural areas, meadows, and pastures may contribute to ecosystem services such as soil stabilization and the prevention of erosion (Brown & Green, 2016).

The plant is also considered an important resource from both agricultural and industrial perspectives (Almenova, 2021). It can be used as animal feed and may also be evaluated as a biomass source for bioethanol production. Alongside all these characteristics, it should also be emphasized that several factors affect the growth and productivity of *Alhagi maurorum*. One of these factors is diseases caused by phytopathogenic microorganisms. Examples of phytopathogenic microorganisms that cause diseases in *Alhagi maurorum* include *A. alternata, A. cucumerina, A. awamori, A. fumigatus, A. niger, A. repens, C. herbarum, E. alhagi, F. moniliforme, F. oxysporum, M. mucedo, P. cyclopium, P. chrysogenum,* and *P. restrictum*, among others.

Currently, fungal diseases constitute one of the important areas of integrated disease management in agriculture. Integrated disease management encompasses multiple strategies and a comprehensive approach based on knowledge of pathogens, plants, agronomic practices, and the interactions among them. Fungal diseases are strongly influenced by environmental conditions, pathogen virulence, and plant–pathogen interactions. In addition to affecting disease development, factors such as pesticide application, soil cultivation, the amount of primary inoculum, climatic conditions, and other environmental factors may also influence the biological control potential of microorganisms belonging to the genus *Trichoderma* against disease-causing pathogens in *Alhagi maurorum*. Several studies have demonstrated that the application of *Trichoderma* species has promising biological potential not only for reducing the effects of disease-causing pathogens but also for improving plant growth and development parameters (Shirinova et al., 2025).

Materials and Methods

Samples were collected from different regions of Azerbaijan for the study. Soil samples were collected from the rhizosphere zones where *A. maurorum* plants were growing in order to obtain *Trichoderma* spp. strains. The collected soil samples were placed in sterile bags, labeled, and transferred to the laboratory for microbiological analyses. The samples were stored at 5 °C until analysis. During the study, the effects of *Trichoderma* strains on the vegetative growth parameters of *A. maurorum*, particularly plant height, were evaluated. Czapek medium (CS) and agarized malt extract (AME) were used as nutrient media for the isolation of *Trichoderma* spp. strains from the soil samples.

Before cultivation on the nutrient media, the investigated samples were initially prepared as suspensions under sterile conditions. Serial dilutions were prepared from the resulting suspension, and the obtained solutions were inoculated onto the surfaces of the respective nutrient media using sterile pipettes. In addition, some samples were directly placed onto the nutrient media without prior dilution. The inoculated samples were incubated at 28 °C under thermostat conditions for 3–6 days. During this period, the morphological characteristics of the developing fungal colonies, including colony color, growth characteristics, and sporulation features, were observed. The morphological characteristics of the resulting fungal colonies were evaluated by microscopic examination, and the purity of the cultures was monitored. To obtain pure cultures, portions taken from selected colonies were inoculated onto the surface of fresh medium under sterile conditions and incubated again. The culture suspension of the obtained *Trichoderma* spp. strains was applied to the root zone of *A. maurorum* plants. Care was taken to ensure that the same application method was used for each *A. maurorum* plant.

Results and Discussion

In this study, changes in some biological characteristics of *A. maurorum*, a species that is important as a medicinal raw material and is also one of the plants that can be colonized by toxigenic, allergenic, and opportunistic pathogenic fungi, were investigated in relation to environmental conditions. The study revealed that camelthorn (*A. maurorum*) samples growing in different geographical regions differed from one another in terms of their morphometric characteristics, particularly plant height, as well as moisture content. It is assumed that the ecological characteristics of the environment in which the plant develops play an important role in the formation of these differences. The identified differences in morphometric and moisture parameters can be considered an expression of the adaptive characteristics of *A. maurorum* to different environmental conditions. At the same time, it is possible that temperature, soil moisture, nutrient availability, and other abiotic factors of the environment in which the plant develops affect its vegetative growth. These changes in environmental conditions are presumed to influence the moisture balance of the plant's tissues and organs, as well as its physiological status. On the other hand, the differences observed in the morphological characteristics of the plant may also be associated with the growth dynamics of microorganisms inhabiting its surface and tissues, including microscopic fungi. In this regard, the assessment of the morphometric and moisture parameters of *A. maurorum* samples together with their mycobiological characteristics is of considerable importance for determining plant–microorganism interactions.

Figure 1
Alhagi maurorum

As a result of the mycological studies conducted, various fungal species were identified in the mycobiota of the camelthorn plant (*Alhagi maurorum*) collected as a sample. A significant proportion of the detected taxa were isolated into pure cultures and identified based on their morphological and cultural characteristics, while the remaining taxa were identified on the basis of disease symptoms observed on the plant and the morphological characteristics of spore structures formed during the vegetation period. In assessing the taxonomic status of the identified fungal species, their systematic position according to modern classification systems and their accepted nomenclature were taken into consideration. Particular attention was also given to the presence of phytopathogenic fungal species that may cause various diseases in the plant. Considering the potential effects of these pathogens on the growth and phytosanitary condition of *A. maurorum*, the prospects of using antagonistic fungi belonging to the genus *Trichoderma* for their biological control were also considered one of the important directions of the study (Muradov et al., 2019).

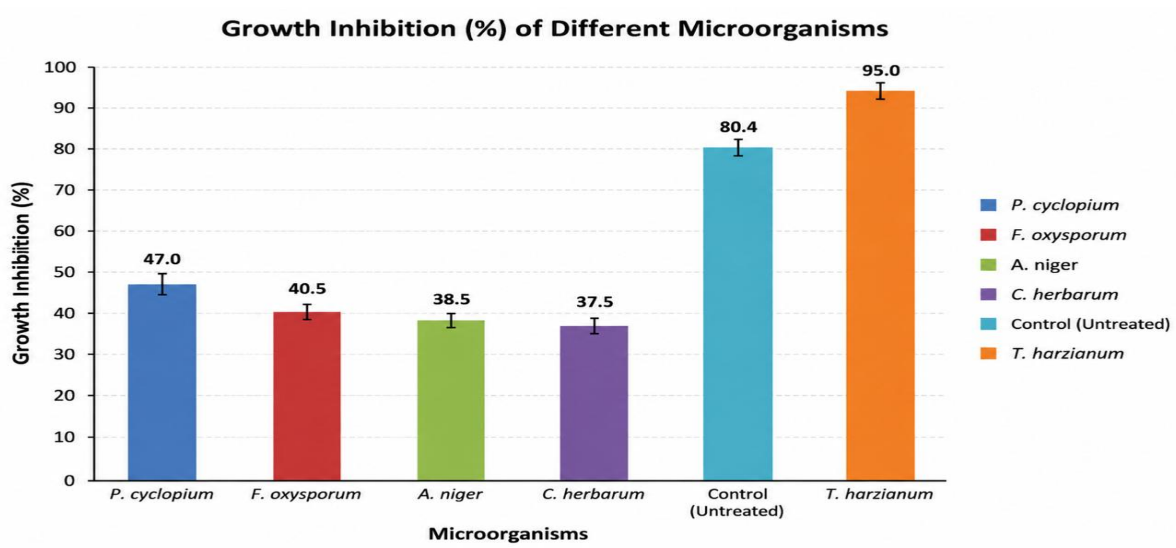

Figure 2
Effect of Trichoderma harzianum on the inhibition of the growth of various phytopathogenic microorganisms

The application of *Trichoderma* preparations as biocontrol agents is largely influenced by their stress tolerance (e.g., high temperature, desiccation, ultraviolet radiation, etc.) and storage stability (for more than one year under normal temperature conditions) (Alfiky & Weisskopf, 2021). Although *Trichoderma* plays an important role in promoting the growth and increasing the productivity of many plants, several challenges associated with the application of this genus in biological control still need to be addressed (Caruso et al., 2020; Boamah et al., 2021). For this purpose, it is necessary to develop effective *Trichoderma* preparations suitable for use through various application methods, enhance their biological control efficacy, and improve the preparation and processing technologies of *Trichoderma* formulations in order to extend the shelf life of biological control agents.

Table 1

Trichoderma species under different environmental conditions

Economic region	Experimental treatment	Stem height (cm)	Number of leaves (per plant)	Number of flowers (per plant)	Effect on plant growth
Kura–Araz Lowland	Control	38,5	42	8	Control
	Trichoderma CS	48,6	55	12	Stimulating
Greater Caucasus	Control	36,9	40	7	Control
	Trichoderma CS	46,2	52	11	Stimulating
Absheron	Control	40,2	44	9	Control
	Trichoderma CS	51,4	60	14	Effective
Talysh zone	Control	34,6	38	6	Control
	Trichoderma CS	43,5	49	10	Effective

In *A. maurorum* plants treated with *Trichoderma* culture suspension, higher values were observed for stem height, leaf production, and flower formation compared with the control treatment. The most pronounced positive changes were recorded in the Absheron samples, followed by those from the Kura–Araz Lowland and Greater Caucasus. In the Talysh zone, the application of *Trichoderma* culture suspension also had a positive effect on the vegetative and generative development of the plant.

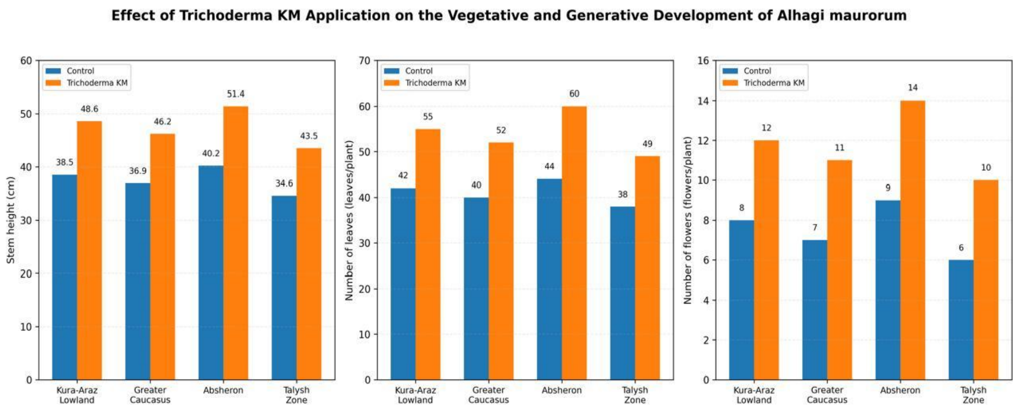

Figure 3

Effect of Trichoderma culture suspension application on the growth parameters of Alhagi maurorum plants in different ecological zones

The application of *Trichoderma* culture suspension significantly stimulated both the vegetative and generative development of *Alhagi maurorum* plants in all economic regions. Stem height increased in all regions. The highest value was recorded in Absheron, where stem height increased from 40.2 cm to 51.4 cm, corresponding to an increase of approximately 27.9%. The number of leaves also increased in all treatments, with the greatest increase again observed in Absheron (36.4%). The effect of *Trichoderma* culture suspension on the number of flowers was even more pronounced. In Absheron, the number of flowers increased from 9 to 14, while in the Talysh zone it increased from 6 to 10. The highest relative increase in flower number was observed in the Talysh zone (66.7%), followed by the Greater Caucasus (57.1%).

Table 2
Biological control indicators of Trichoderma application in Alhagi maurorum

Economic region	Optical density (656 nm)	AE	Expected biological control effect after *Trichoderma* application (%)	Effect on plant growth
Kura–Araz Lowland	0,715	1,250	75–85	high
Greater Caucasus	0,696	1,200	70–80	high
Absheron	0,734	1,268	78–88	high
Talysh zone	0,567	1,196	60–70	Moderate to high

The correlation of the biological control indicators of *Alhagi maurorum* across different economic regions with the application of microorganisms belonging to the genus *Trichoderma* indicates that, in areas with higher optical density values, the potential for *Trichoderma* preparations to colonize the rhizosphere of the plant and restrict the development of pathogenic microorganisms may be comparatively greater.

Conclusion

The obtained results indicate that the combined use of *A. maurorum* extracts and *Trichoderma* spp. represents a promising approach in terms of plant–microorganism interactions. In particular, the relatively high values observed in samples obtained from Absheron and the Kura–Araz Lowland indicate that these samples may have greater potential for integrated biological control with *Trichoderma* and for promoting plant growth. The results of the experimental studies conducted indicate that the interaction between *Trichoderma* spp. and *Alhagi maurorum* may be of potential importance for adaptation to arid and unfavorable environmental conditions. Colonization of the rhizosphere by *Trichoderma* isolates may stimulate the development of the plant root system, improve the uptake of water and mineral nutrients, and thereby support the growth capacity of *A. maurorum* under stress conditions. At the same time, the antagonistic activity of these fungi against phytopathogenic microorganisms may contribute to maintaining plant health and establishing a microbiological balance in the rhizosphere. At the same time, the results obtained showed that the application of *Trichoderma* culture suspension significantly stimulated the vegetative and generative growth parameters of *Alhagi maurorum* plants in all study zones. The highest growth parameters were recorded in the Absheron zone. In this area, significant increases in stem height, number of leaves, and number of flowers were observed following the application of *Trichoderma* culture suspension.

Declaration of Competing Interests

The authors declare that they have no conflict of interest.

References

Alfiky, A., & Weisskopf, L. (2021). Deciphering *Trichoderma*–plant–pathogen interactions for better development of biocontrol applications. *Journal of Fungi, 7*, 61. https://doi.org/10.3390/jof7010061

Almenova, G. (2021). Fodder species from family *Fabaceae* Lindl. crop wild relatives of cultivated plants of the Republic of Karakalpakstan. *International Journal of Academic Multidisciplinary Research, 5*(4), 328–330.

Biswas, A., Bari, M. A., Roy, M., & Bhadra, S. K. (2010). Inherited folk pharmaceutical knowledge of tribal people in the Chittagong Hill Tracts, Bangladesh. *Indian Journal of Traditional Knowledge, 9*(1), 77–89.

Boamah, S., Zhang, S., Xu, B., Li, T., & Calderon-Urrea, A. (2021). *Trichoderma longibrachiatum* (TGI) enhances wheat seedlings tolerance to salt stress and resistance to *Fusarium pseudograminearum*. *Frontiers in Plant Science, 12*, 741231. https://doi.org/10.3389/fpls.2021.741231

Borchardt, J. R., Wyse, D. L., Sheaffer, C. C., Kauppi, K. L., Fulcher, R. G., Ehlke, N. J., et al. (2009). Antioxidant and antimicrobial activity of seed from plants of the Mississippi River basin. *Journal of Medicinal Plants Research, 3*, 707–718.

Brown, L., & Green, K. (2016). *Calligonum triste*: A review of its traditional uses, phytochemistry and pharmacology. *Journal of Ethnopharmacology, 192*, 89–111.

Caruso, G., El-Nakhel, C., Rouphael, Y., Comite, E., Lombardi, N., Cuciniello, A., et al. (2020). *Diplotaxis tenuifolia* (L.) DC. yield and quality as influenced by cropping season, protein hydrolysates, and *Trichoderma* applications. *Plants, 9*, 697. https://doi.org/10.3390/plants9060697

Jones, C., & Brown, G. (2015). Comparative morphological and physiological responses to saline substrate in two saltland shrubs: *Haloxylon persicum* and *Salsola vermiculata*. *Flora—Morphology, Distribution, Functional Ecology of Plants, 214*, 39–48.

Kiselova, Y., Ivanova, D., Chervenkov, T., Gerova, D., Galunska, B., & Yankova, T. (2006). Correlation between the *in vitro* antioxidant activity and polyphenol content of aqueous extracts from Bulgarian herbs. *Phytotherapy Research, 20*, 961–965. https://doi.org/10.1002/ptr.1985

Muradov, P. Z., Shirinova, G. F., Asgerli, L. X., Allahverdiyev, E. I., & Gasımov, C. F. (2019). Species composition of fungi causing diseases in agricultural plants in agrarian sector of Azerbaijan. *Journal of Applied and Natural Science, 11*(4), 785–790. https://doi.org/10.31018/jans.v11i4.2168

Mandaville, J. P. (2011). *Bedouin ethnobotany: Plant concepts and uses in a desert pastoral world*. The University of Arizona Press.

Parthasarathy, S., Azizi, J. B., Ramanathan, S., Ismail, S., Sasidharan, S., Said, M. I. M., et al. (2009). Evaluation of antioxidant and antibacterial activities of aqueous, methanolic and alkaloid extracts from *Mitragyna speciosa* (Rubiaceae family) leaves. *Molecules, 14*, 3964–3974. https://doi.org/10.3390/molecules14103964

Revathi, P., & Parimelazhghan, T. (2010). Traditional knowledge on medicinal plants used by Irula tribe of Hasanur Hills, Erode District, Tamil Nadu, India. *Ethnobotanical Leaflets, 14*, 136–160.

Safarova, A. Sh. (2018). New species of fungi recorded in the Azerbaijan nature. *International Journal of Current Microbiology and Applied Sciences, 7*(11), 2235–2239. https://doi.org/10.20546/ijcmas.2018.711.250

Sharma, O. P. (2013). Biological activities of *Alhagi* species. *Journal of Medicinal Plants Research, 7*(10), 567–574.

Shirinova, G., Suleymanova, V., & Abdullayeva, S. (2025). The effect of fungi belonging to the *Trichoderma* genus on the biological productivity of food crops. *Nature & Science, 7*(11), 12–18. https://doi.org/10.36719/2707-1146/62/12-18

Tarawneh, K. A., Irshaid, F., Jaran, A. S., Ezealarab, M., & Khleifat, K. M. (2010). Evaluation of antibacterial and antioxidant activities of methanolic extracts of some medicinal plants in northern part of Jordan. *Journal of Biological Sciences, 10*, 325–332. https://doi.org/10.3923/jbs.2010.325.332

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Effect of Mineral Fertilizers on the Quantitative and Qualitative Indicators of Winter Triticale

Maharram Ismayilov

Abstract. *This study evaluates the effects of various mineral fertilizer (NPK) rates on the quantitative and qualitative indicators of winter triticale (cv. "Qismət") under the semi-desert, dry steppe climatic conditions of the Ganja region, Azerbaijan, alongside a comparative performance analysis with "Qırmızı buğda 1" wheat and a rye breeding line over a three-year period (2023–2025). The experimental plots were organized in a randomized block design. The results demonstrate that NPK application significantly enhanced the structural yield components and nutritional quality of triticale. Optimal results were achieved with the N90P90K40 treatment, which maximized mean grain yield at 64.20 c/ha (a 14.53 c/ha increase over the unfertilized control) and crude protein yield at 10.26 c/ha. Structural analysis revealed that this productivity surge was primarily driven by a 17.6% increase in grains per spike and a 16.4% improvement in grain weight. Comparative evaluation showed that triticale exhibits superior responsiveness to intensive fertilization, outperforming both wheat (maximum yield increase of 9.00 c/ha) and rye (maximum yield increase of 5.92 c/ha). Due to its tall-growing morphotype and moderate input response, the "Qismət" cultivar is categorized as a semi-intensive variety well-suited for improving localized concentrated fodder production.*

Keywords: *winter triticale, NPK fertilization, grain yield, crude protein, crop responsiveness*

Introduction

Triticale belongs to the grass family — *Poaceae* Barnhart, or *Gramineae* Juss., and the genus *Triticosecale* Witt. It is an artificially created crop, an amphidiploid. Thanks to breeding efforts, triticale varieties are currently being tested in 75 countries worldwide (Airikh, 2013; Mammadov & Ismayilov, 2012). Triticale successfully combines the valuable traits of its parent forms: From Rye: Multi-rowed spikes, a more balanced amino acid protein composition, and vigorous development (Longin et al., 2012; Gurbanov, 2011).

At the current stage of agricultural development, new objectives are being set based on an adaptive-landscape (ecological) framework. Global experience demonstrates that further progress in farming is contingent upon moving away from intensive, high-cost agrotechnologies and transitioning toward resource- and energy-saving biologized systems (Nazranov et al., 2011).

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Research demonstrates that optimizing the fertilizer system for the Samur triticale variety significantly enhances energy efficiency. Specifically, an optimized approach resulted in a yield increase of 2 t/ha, which boosted the net energy income by 71.3 GJ/ha and improved the energy efficiency coefficient by 20.4% (Nazranov et al., 2011). The yield formation process in cereal crops is highly dynamic and depends on numerous environmental factors. According to literature sources, nitrogen is the most significant among the nutritional elements. As is well known, nitrogen is an essential element for plant growth and development (Ismayilov, 2016a). While there is a substantial body of information regarding the application of mineral fertilizers, particularly nitrogen, for winter wheat and barley in the republic, experimental data on their utilization in triticale cultivation is extremely scarce or virtually non-existent (Ismayilov, 2016b).

Triticale exhibits intermediate characteristics between wheat and rye in terms of cultivation technology. Sowing time, seeding rate, plowing depth, fertilization system, and disease control measures must be optimized in accordance with local soil and climatic conditions (Seyidaliyev, 2016). There are a total of 4.2 million hectares of triticale cultivation area globally. Of this area, 80% is utilized for winter triticale cultivation, while 20% is used for spring cultivation (Kır & Yavuz, 2024). Small grain cereals such as wheat, barley, oats, rye, and triticale are primarily grown for their grains and utilized as human food; however, they are also harvested for fodder and used as roughage (Çaçan & Kökten, 2019).

Materials and Methods

The field experiments were conducted to study the effects of mineral fertilization on the "Qismət" winter triticale variety. For comparative analysis, the "Qırmızı buğda 1" wheat variety and a rye breeding line were also included in the trials. The experiments were organized in a randomized block design with multiple fertilizer treatments. The mineral fertilizers were applied in various combinations of Nitrogen (N), Phosphorus (P), and Potassium (K). The primary application rates included: Control: No fertilizer application; NPK Variants: Variations ranging up to $N_{90}P_{90}K_{60}$; Specific focus was placed on evaluating the increments of 30 kg/ha for N and P, and 20–50 kg/ha for K. Harvested grain from each plot was weighed and converted to centners per hectare (c/ha) at standard moisture content. Structural analysis was performed to determine the number of grains per spike and 1000-grain weight (g). The protein content in the grain was determined using the Kjeldahl method (or equivalent laboratory analysis). Crude protein yield (c/ha) was calculated by multiplying the grain yield by the protein percentage. The collected data were subjected to statistical processing to determine the reliability of the results. The statistical significance of yield differences between the treatments and the control variant was evaluated, and the economic efficiency of the fertilizer applications was calculated.

Results and Discussion

We have investigated the effects of various doses of NPK (Nitrogen-Phosphorus-Potassium) on several characteristics of the "Qismət" triticale variety; the results of these studies are presented below.

Number of plants preserved until harvest. For the variants where NPK was applied, this indicator averaged between 185 and 199 units/m² (compared to 176 units/m² in the control/unfertilized variant). The average differences observed between the control and experimental variants were statistically significant; this is evident when comparing the data with the $LSD_{0.95}$ (Least Significant Difference at 95% confidence level) indicators (Tables 1 and 2). However, when comparing some experimental variants with each other, the observed differences were not significant across all pairs. For instance, the differences in this trait among variants 5, 6, and 7 were non-significant, indicating that this variety did not exhibit sensitivity to increasing doses of potassium fertilizer.

Number of productive stems per 1 m² and productive tillering. In the "Qismət" variety, the highest number of productive stems per unit area (1 m²) was recorded in the variant treated with $P_{90}K_{60}$ + three applications of spring nitrogen top-dressing at a rate of 30 kg of active ingredient (a.i.) each. According to the three-year average, this indicator reached 270 units, representing an average increase of 21.6% compared to the control (unfertilized – 222 units). It should be noted that the differences between this variant and others with various fertilizer dosage ratios were statistically significant, with the exception of the variant where the highest NPK doses were applied. Specifically, the additional application of K_{30} (30 kg of potassium) did not stimulate shoot formation; on the contrary, a tendency toward a decrease in their number was observed. Based on the three-year average, productive tillering in the fertilized variants ranged from 1.25 to 1.36. The differences observed between the control and experimental variants were found to be statistically non-significant.

Plant height. The application of mineral fertilizers increased the plant height of the "Qismət" variety by 7–13 cm; however, due to the firm and resistant stems, no lodging (prostration on the soil) was observed in the plants.

Yield Components and Grain Yield Per Unit Area

The most significant increase in the grain set (grain filling) of the spike in the "Qismət" variety was observed in variants 4, 5, and 6. Compared to the unfertilized control variant, the average spike grain count increased by 10.1%, 15.6%, and 17.6%, respectively. Increasing the potassium fertilizer dose up to 50 kg/ha (a.i.) led to the reduction of some flowers and resulted in an average increase of only 3 grains per spike, which is considered statistically non-significant (Table 1). The most optimal variant was variant 5, where three applications of spring nitrogen top-dressing resulted in a 17.6% increase in spike grain count. As indicated by the data, the highest grain weight per spike was recorded in this specific variant, reaching 2.76 g. This represents an increase of 16.5% and 26.2%, respectively, compared to the control variant. In the "Qismət" variety, the 1000-grain weight in the fertilized variants showed a tendency to decrease compared to the control variant. However, the differences of 0.4–2.1 grams were found to be statistically non-significant, as they were lower than the $LSD_{0.95}$ value (3.8 g). The analysis of the yield structure of the triticale variety allowed for the identification of the leading role of individual components in the formation of productivity levels when different doses and ratios of mineral fertilizers were applied (Gurbanov et al., 2025).

Table 1

Effect of mineral fertilizers on yield structure components and variability of biological indicators in the "Qismət" triticale variety

No.	Variants	Indicators of studied traits				
		2023	2024	2025	Mean	Deviation from control
	I	II	III	IV	V	VI
Number of plants surviving until harvest (units/m²)						
1	Control (Unfertilized)	173	170	185	176	+
2	$N_{60}P_{60}K_{40}$	178	183	193	185	+9 -5,1%
3	$N_{90}P_{60}K_{40}$	184	182	196	187	+11 -6,25%

4	$N_{60}P_{90}K_{40}$	182	175	200	186	+10 -5,7%
5	$N_{90}P_{90}K_{40}$	193	183	207	195	+19 -10,8%
6	$N_{90}P_{90}K_{60}$	192	193	210	198	+22 -12,5%
7	$N_{90}P_{90}K_{90}$	192	193	212	199	+23 -13,1 %
			$LSD_{,95}$ = 5,87 units/m²			
			Productive tillering			
1	Control (Unfertilized)	1,24	1,38	1,18	1,27	
2	$N_{60}P_{60}K_{40}$	1,35	1,37	1,19	1,30	+0,03
3	$N_{90}P_{60}K_{40}$	1,30	1,32	1,27	1,30	+0,03
4	$N_{60}P_{90}K_{40}$	1,26	1,38	1,10	1,25	-0,02
5	$N_{90}P_{90}K_{40}$	1,37	1,42	1,10	1,30	+0,03
6	$N_{90}P_{90}K_{60}$	1,30	1,45	1,33	1,36	+0,09
7	$N_{90}P_{90}K_{90}$	1,25	1,47	1,25	1,32	+0,05
			$LSD_{0,95}$ = 0,116			
			Number of productive tillers per m² (units)			
1	Control (Unfertilized)	215	234	218	222,3	
2	$N_{60}P_{60}K_{40}$	240	250	230	240	+17,7 -8%
3	$N_{90}P_{60}K_{40}$	240	256	249	248,3	+26 -17%
4	$N_{60}P_{90}K_{40}$	230	241	220	230,3	+8 -3,6%
5	$N_{90}P_{90}K_{40}$	265	259	228	250,7	+28,4-12,8%
6	$N_{90}P_{90}K_{60}$	250	280	280	270	+47,7 -18,3%
7	$N_{90}P_{90}K_{90}$	240	283	266	263	+40,7 -18,3%
			$LSD_{0,95}$ = 19,6			
			Plant height (cm)			
1	Control (Unfertilized)	141	139	140	141	
2	$N_{60}P_{60}K_{40}$	148	145	152	148	+7
3	$N_{90}P_{60}K_{40}$	151	148	159	153	+12
4	$N_{60}P_{90}K_{40}$	147	144	156	149	+8
5	$N_{90}P_{90}K_{40}$	150	148	158	152	+11
6	$N_{90}P_{90}K_{60}$	148	152	159	153	+12
7	$N_{90}P_{90}K_{90}$	153	150	158	154	+13
			$LSD_{0,95}$ = 3,566			
			Number of grains per spike (units)			
1	Control (Unfertilized)	49	44	55	49,3	+
2	$N_{60}P_{60}K_{40}$	49	47	52	49,3	
3	$N_{90}P_{60}K_{40}$	54	49	51	51,3	+2 -4,0%
4	$N_{60}P_{90}K_{40}$	56	56	59	57,0	+7,3 -15,6%
5	$N_{90}P_{90}K_{40}$	54	59	61	58,0	+8,7 -17,6%
6	$N_{90}P_{90}K_{60}$	56	49	58	54,3	+5 -10%

7	$N_{90}P_{90}K_{90}$	55	49	53	52,3	+3 -6,1%
			$LSD_{0,95}$ = 4,83%			
			Grain weight per spike (g)			
1	Control (Unfertilized)	2,33	2,14	2,34	2,37	
2	$N_{60}P_{60}K_{40}$	2,21	2,16	2,43	2,40	+0,03
3	$N_{90}P_{60}K_{40}$	2,33	2,30	2,41	2,48	+0,11
4	$N_{60}P_{90}K_{40}$	2,41	2,32	2,63	2,58	+0,21
5	$N_{90}P_{90}K_{40}$	2,36	2,45	2,87	2,76	+0,39
6	$N_{90}P_{90}K_{60}$	2,44	2,29	2,36	2,56	+0,19
7	$N_{90}P_{90}K_{90}$	2,50	2,21	2,41	2,58	+0,21
			$LSD_{0,95}$ = 0,197			
			1000-grain weight (g)			
1	Control (Unfertilized)	47,0	48,6	43,6	46,4	
2	$N_{60}P_{60}K_{40}$	45,2	46,0	46,9	46,0	-0,4
3	$N_{90}P_{60}K_{40}$	43,15	46,9	47,2	45,7	-0,7
4	$N_{60}P_{90}K_{40}$	43,04	42,3	48,0	44,5	-1,9
5	$N_{90}P_{90}K_{40}$	43,9	44,9	47,9	45,6	-0,8
6	$N_{90}P_{90}K_{60}$	43,6	46,9	42,4	44,3	-2,1
7	$N_{90}P_{90}K_{90}$	45,4	45,1	45,9	45,5	-0,9
			$LSD_{0,95}$ = 3,778			

Grain Yield and Protein Content (Tables 2 and 3).

The average yield across the NPK variants ranged from 54.3 to 64.2 c/ha, representing an increase of 4.66–14.53 c/ha over the control variant.Increasing the phosphorus fertilizer rate by 30 kg (a.i.) resulted in an average yield increase of 2.17 c/ha. Similarly, increasing the nitrogen dose by 30 kg (comparing variant 3 to variant 2) led to a yield growth of 3.91 c/ha. Against a higher phosphorus background (P_{90}), a 30 kg increase in nitrogen dose improved grain yield by an average of 7.7 c/ha (comparing variant 5 to variant 4). Conversely, increasing the potassium dose by 20 and 50 kg did not yield a significant increase; instead, a slight downward trend in productivity was observed (Ismayilov & Gurbanov, 2015).

Table 2

Effect of different mineral fertilizer rates on the yield of the "Qismət" triticale variety

No.	Variants	2023	2024	2025	Mean	$LSD_{0,95}$	Difference from control (c/ha)
1	Control (Unfertilized)	50,1	48,0	51,0	49,67	3,45	–
2	$N_{60}P_{60}K_{40}$	53,0	54,0	56,0	54,33	2,01	4,66
3	$N_{90}P_{60}K_{40}$	56,8	58,0	60,0	58,24	4,28	8,57
4	$N_{60}P_{90}K_{40}$	55,5	56,0	58,1	56,50	2,59	6,83
5	$N_{90}P_{90}K_{40}$	62,6	63,4	66,5	64,20	2,76	14,53
6	$N_{90}P_{90}K_{60}$	61,0	64,0	66,0	63,67	1,84	14,0
7	$N_{90}P_{90}K_{90}$	61,0	62,5	64,4	62,67	1,91	13,0
	$LSD_{0,95}$	1,81	2,50	2,29	2,20		

Crude protein content. The application of NPK led to an increase in protein content. However, the addition of an extra 50 kg of potassium resulted in a 0.6% decrease in the protein level.

Table 2
Effect of different mineral fertilizer rates on the grain quality of the "Qismət" triticale variety

No.	Variants	Protein content in grain (%)	Crude protein yield (c/ha)
1	Control (Unfertilized)	13,1	6,4
2	$N_{60}P_{60}K_{40}$	14,7	8,03
3	$N_{90}P_{60}K_{40}$	15,0	8,78
4	$N_{60}P_{90}K_{40}$	15,3	8,71
5	$N_{90}P_{90}K_{40}$	16,1	10,26
6	$N_{90}P_{90}K_{60}$	15,8	10,11
7	$N_{90}P_{90}K_{90}$	15,3	9,94

Crude protein yield per unit area (per hectare). The crude protein yield ranged from 8.03 to 10.26 c/ha. The optimal variant was $N_{90}P_{90}K_{40}$. Analysis shows that the yield increase in the "Qismət" variety was primarily achieved due to an increase in the number of grains per spike (17.6%) and their weight (16.4%). Since this variety is tall-growing and shows a lower response to fertilizer application, it can be classified as a semi-intensive variety.

Comparison with wheat and rye (Table 4). Rye showed the weakest response to NPK application (maximum increase of 6 c/ha). While the maximum yield increase for wheat was 9 c/ha, this indicator reached 14.53 and 21.8 c/ha in triticale varieties. The optimal variant was determined as $N_{90}P_{90}K_{40}$, for both rye and wheat. In wheat, reducing the nitrogen dose to $N_{90}P_{90}K_{40}$, led to a yield decrease of 2 c/ha; however, this difference was not statistically significant (Levakhin & Duskaev, 2006).

Table 4
Effect of mineral fertilizers on the grain yield of wheat and rye

No.	Variants	Grain yield (c/ha)					
		2023	2024	2025	Mean	Comparison with control (c/ha)	$LSD_{0,95}$ (sen/ha)
"Qırmızı buğda 1" wheat variety							
1	Control (Unfertilized)	38,4	40,2	41,6	40,07		2,69
2	$N_{60}P_{60}K_{40}$	40,6	43,3	44,3	42,73	+2,66	2,29
3	$N_{90}P_{60}K_{40}$	43,6	45,2	47,1	45,30	+5,27	3,35
4	$N_{60}P_{90}K_{40}$	45,2	47,0	49,0	47,07	+7,00	3,17
5	$N_{90}P_{90}K_{40}$	48,4	50,2	49,8	49,07	+9,00	2,01
6	$N_{90}P_{90}K_{60}$	47,9	49,4	49,7	49,00	+8,93	3,11
7	$N_{90}P_{90}K_{90}$	47,8	48,3	48,8	48,48	+8,41	3,39
	$LSD_{0,95}$ (sen/ha) =	2,93	3,15	2,39	2,82		
Rye breeding line							

1	Control (Unfertilized)	35,5	37,4	37,9	36,93		1,77
2	$N_{60}P_{60}K_{40}$	38,6	39,8	41,4	39,93	+3,0	2,24
3	$N_{90}P_{60}K_{40}$	37,5	39,2	40,8	39,17	+2,24	1,61
4	$N_{60}P_{90}K_{40}$	40,6	42,5	44,7	42,85	+5,92	3,18
5	$N_{90}P_{90}K_{40}$	39,3	41,6	42,3	41,07	+4,14	1,26
6	$N_{90}P_{90}K_{60}$	40,0	40,5	42,9	41,13	+4,20	2,40
7	$N_{90}P_{90}K_{90}$	40,0	40,5	42,9	41,13	+4,20	2,40
	$LSD_{0,95}$ (sen/ha) =	8,40	2,15	3,17	4,57		

As evident from the presented data, triticale shows a relatively better response to mineral fertilizer application compared to wheat and, especially, rye. This confirms the findings in many countries regarding the high sensitivity (responsiveness) of triticale to mineral nutrition.

Conclusion

Based on the research conducted in the Ganja region of Azerbaijan, it can be concluded that the application of mineral fertilizers is a key factor for maximizing the productivity of the "Qismət" winter triticale variety. The application of NPK fertilizers significantly enhanced grain yield, with average results ranging between 54.3 and 64.2 c/ha. The maximum yield increase reached 14.53–21.8 c/ha, which was achieved primarily through an increase in the number of grains per spike (17.6%) and grain weight (16.4%). Mineral fertilization positively influenced the protein profile of the grain. The crude protein yield per hectare varied from 8.03 to 10.26 c/ha. However, it was observed that while NPK generally improves protein content, an excessive addition of potassium (50 kg) led to a slight reduction (0.6%) in protein levels. Triticale demonstrated a higher sensitivity and superior responsiveness to mineral nutrition compared to both wheat and rye. While the maximum yield increase for wheat and rye was 9 c/ha and 6 c/ha respectively, triticale showed much higher growth potential under similar conditions. For the "Qismət" variety, the $N_{90}P_{90}K_{40}$ variant was identified as the optimal fertilizer rate for maximizing both grain yield and protein output. Due to its tall-growing nature and specific reaction to intensive fertilization, the "Qismət" variety is classified as a semi-intensive type, confirming global trends regarding the high adaptability and nutritional efficiency of triticale.

Declaration of Competing Interests

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Airikh, E. V. (2013). Analysis of sown areas and gross harvests of winter crops in farms of all categories in the Orenburg region. *Herald of Beef Cattle Breeding*, (2), 103–107.

Çaçan, E., & Kökten, K. (2019). Tahıl Türlerinin Kaba Yem Olarak Değerlendirilmesi Üzerine Bir Araştırma (A study on the evaluation of cereal species as roughage). *Journal of Agriculture Faculty of Ege University, 56*(2), 101–110. https://doi.org/10.20289/zfdergi.459694

Gurbanov, F. H. (2011). *Plant breeding and Seed Production of Agricultural Crops.*

Gurbanov, F. H., Ashrafova, Kh., Mammadova, S., Babayeva, K., & Keskinbichak, M. (2025). Factors Affecting the Productivity of Cereals. *Nature & Science*, *7*(5), 32–36. https://doi.org/10.36719/2707-1146/56/32-36

Ismayilov, M. M. (2016a, July 8). Cultivation technology of the “Qismat” triticale variety. *Ways to Increase Soil Fertility in Azerbaijan: Republican Scientific-Practical Conference Dedicated to the 80th Anniversary of Academician Mammadtaghi Ibrahim oglu Jafarov*. Ganja, Azerbaijan.

Ismayilov, M. M. (2016b, October 3–4). The role of new varieties and gene pool in increasing productivity in the agricultural sector. *International Cooperation in the Development of Agricultural Science, Food Security and Environmental Protection: 8th International Scientific-Practical Conference*. Ganja, Azerbaijan.

Ismayilov, M. M., & Gurbanov, F. H. (2015, October 23–24). Biological and economic characteristics of the “Qismat” triticale variety. *Innovative Development of Agricultural Science and Education: World Experience and Modern Priorities: International Scientific-Practical Conference*. Ganja, Azerbaijan.

Kır, H., & Yavuz, T. (2024). Bazı Tritikale Çeşitlerinin Verim ve Kalite Performanslarının Belirlenmesi (Determination of Yield and Quality Performance of Some Triticale Varieties). *Ziraat Mühendisliği*, 380, 63–69. https://doi.org/10.33724/zm.1537620

Levakhin, G. I., & Duskaev, G. K. (2006). Adaptation of ruminant rumen biocenoses to ration changes and different feeding types. *Vestnik of the Russian Academy of Agricultural Sciences*, (1), 71–72.

Longin, C. F. H., Mühleisen, J., Maurer, H. P. et al. (2012). Hybrid breeding in autogamous cereals. *Theoretical and Applied Genetics,* 125, 1087–1096. https://doi.org/10.1007/s00122-012-1967-7

Mammadov, G. Y., & Ismayilov, M. M. (2012). *Plant Science* (Textbook). "Sharg-Gharb" Publishing House.

Nazranov, Kh. M., Bzheumykhov, V. S., & Kalmykov, A. M. (2011). Vliyaniye sistemy udobreniy na urozhaynost' ozimoy triticale. *The Bulletin of KrasGAU (Krasnoyarsk State Agricultural University)*, (10), 53–57.

Seyidaliyev, N. Y. (2016). *Aqrokimyanın əsasları* (Fundamentals of Agrochemistry). Vektor.

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Molecular-Genetic Characterization of Common Quince (*Cydonia oblonga* Mill.)

Nazakat Huseynova

Abstract. *Studies were conducted on seven quince cultivars in the northern and northwestern regions of Azerbaijan. The investigation into the intraspecific genetic diversity and structure of the quince species was based on the analysis of seven quince genotypes across eight ISSR loci. A total of 69 bands were generated using ISSR markers; of these, 47 (69.4%) were polymorphic, while 22 (30.6%) were monomorphic. The UBC868 primer yielded 9 bands, 8 of which were polymorphic, resulting in a polymorphism rate of 89%. The number of amplified fragments per locus ranged from 7 to 10. Comprehensive analysis of the quince collection using these eight ISSR markers revealed a high level of heterozygosity in hybrid seedlings compared to expected values, indicating significant genetic distance between the parental pairs selected for hybridization. It is recommended to use the UBC 868, UBC 807, and UBC 825 ISSR primers for the assessment of polymorphism and genetic diversity in the quince collection, as they are more effective.*

Keywords: *quince, DNA markers, genetic diversity, genome, gene pool*

Introduction

Quince is highly valued as a source of iron and as a means of improving mood and boosting vitality. Among pome fruits, quince ranks third after apples and pears. Autumn and winter varieties and forms of quince are distinguished. The average lifespan of the plant is 60–80 years. A single tree yields between 50 and 160 kg of fruit. Quince is cultivated in all regions of Azerbaijan (Bayramov, 2018; Bayramov, 2021; Muradova, 2018).

The objectives of this study included the selection of high-yielding, high-quality, and cold-resistant forms adapted to local soil and climatic conditions. The primary research material was sourced from promising varieties found in the Guba, Gusar, and Khachmaz districts, as well as the Sheki and Balaken districts of Azerbaijan. Their agrobiological and pomological characteristics were investigated through phenological observations (Guseinova & Asadova, 2024).

The aim of this study is to analyze the genotypic structure of quince varieties and forms distributed across the mountainous regions of Azerbaijan—specifically in the Guba, Gusar, Khachmaz, Sheki, and Balaken districts. The research objectives also included determining the level of genetic diversity and elucidating the genetic relationships between parental forms and their progeny. The aim of the study is to assess genetic diversity among quince genotypes using ISSR molecular markers, as well as to evaluate polymorphism and its information content.

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Research conducted in the northern and northwestern regions of Azerbaijan revealed numerous quince forms cultivated over various periods, many of which are valuable for fruit breeding. Table 1 presents the agrobiological characteristics of the quince plant.

Table 1

Agrobiological characteristics of the quince plant (as of 2023)

Variety	Origin	Area of one sheet (cm^2)	Fruit weight, g		Fruit diameter (cm)	Fruit length (cm)	Quality indicators				
			medium	maximum			Dry matter, in %	Total sugar content, in %	Vitamin C, mg %	Yield	Shelf life, days
Jardam	Folk selection	55	518	575	8	8.6	12.3	11.1	5.1	69	150
Pensar		63	283	320	5	5.5	11.5	12.3	5.1	71	161
Bardag quince		63	455	545	6	8.3	10.2	13.5	6.4	73	158
Sari ayva		59	350	405	7	6.3	10.2	11.4	5.2	74	145
Velechin		62	230	255	5	6.5	11.4	12.1	5.5	72	142
Karaman ayva		63	333	380	6	7.5	12.0	12.3	5.8	85	161
Ege-22	Introduction	55	518	575	8	8.6	12.3	11.1	5.1	69	150

The range of quince in Azerbaijan comprises over a hundred local forms and varieties. The quince collection in the studied regions represents a rich gene pool—encompassing a large number of varieties, forms, and hybrids primarily from the northern and northwestern regions of Azerbaijan—that is actively utilized in breeding programs (Bayramov, 2018; Baskakova, 2019).

The significance of this work lies in the utilization of a valuable and highly promising breeding gene pool that was developed and evaluated in Azerbaijan based on phenotypic and genetic traits. For medicinal purposes, a thick, mucilaginous aqueous extract derived from the seeds has been used in clinical medicine as a coating, emollient, and soothing agent for gastrointestinal disorders and colitis in children. Experiments have demonstrated that preparations derived from quince leaves exert a beneficial effect on the cardiovascular system (Aliyeva, 2018).

It should also be noted that an aqueous infusion made from the leaves and seeds of the common quince has the ability to alleviate and suppress attacks of coughing and bronchial asthma. In Azerbaijani folk medicine, quince fruit juice was used as a choleretic and diuretic agent (Sadıqov, 2023).

Genetics is currently one of the most popular scientific fields and one that is open to innovation. Plant genetics is one such area, and the molecular marker technologies employed within it serve as a significant tool. Thanks to research conducted on molecular markers to date, it has become possible to rapidly obtain significant information regarding the genetic characteristics and heredity of economically important plant species, much like with many other living organisms. This information has led to a reduction in the breeding cycle—particularly for fruit species that require long cultivation periods—thereby resulting in labor savings. The application of data generated by researchers using molecular markers has enabled the development of higher-quality and more productive fruit varieties (Huseynova, 2025).

A molecular marker represents a specific gene region or a DNA segment associated with a gene region within the genome. Consequently, molecular markers have gained widespread use in plant genetics research, enabling the achievement of more efficient and rapid scientific results. A molecular marker reflects variation in a specific DNA segment within the genome; such variations can arise from events such as insertions, deletions, substitutions, or duplications. Data derived from molecular markers facilitate the selection of samples for preservation and the management of collections (Guseynova, 2023). Evaluating samples using molecular markers allows for their identification and the elimination of redundant duplicates (Sarwat & Nabi, 2014; Sarwat & Yamdagni, 2016).

Scientific Novelty

Currently, the identification of quince varieties in Azerbaijan is primarily based on fruit composition and morphological characteristics. However, experimental evidence suggests that morphological and pomological indicators alone are insufficient for variety identification, as environmental factors influence both the morphological traits of the trees and the composition of the fruit. Consequently, identifying quince varieties using molecular markers is a more effective method. To date, the comparative characterization of quince varieties in the country using molecular methods has not been investigated. We have conducted an identification of quince varieties and forms collected from various regions of Azerbaijan using both morphological and molecular-genetic methods.

Materials and Methods

Seven quince cultivars from the collection of the Research Institute of Fruit Growing and Tea Cultivation (Guba District)—part of the Sheki Branch of the Institute of Genetic Resources of Azerbaijan—were selected for study, as they are of particular interest for regional breeding programs. One objective of the research was to determine the relationships between the cultivars, given that their morphological and organoleptic similarities might indicate genetic kinship. Another objective was to assess the influence of parental genotypes on the similarities and differences observed in the progeny. DNA extraction from leaf tissue at the bud-break stage was performed using the CTAB method (Rogers & Bendich, 1985; Murray & Thompson, 1980). Eight ISSR markers developed for Japanese quince (*Cydonia japonica*) were selected for genotyping: UBC807, UBC810, UBC811, UBC815, UBC818, UBC825, UBC840, and UBC868.

The selection of these markers for quince was driven by the goal of expanding the existing set of ISSR markers by testing markers originally developed for closely related species. To perform the PCR, optimal parameters—such as component concentrations and reaction temperature conditions—were determined. The resulting optimal protocol involved a total PCR mixture volume of 25 µL containing 50 ng of DNA, 0.25 mM dNTPs, 0.2 µM of each primer, 2.5 µL of 10× buffer, and 1 U of Taq polymerase. PCR was performed using the following program: initial denaturation at 94 °C for 3 minutes, followed by 35 cycles of denaturation at 94 °C (45 s), annealing at 58 °C (45 s), and elongation at 72 °C (45 s); the final step was elongation at 72 °C for 4 minutes 30 seconds. The sizes of the PCR products were analyzed using an ABI Prism 3130 instrument. The obtained results were processed using GeneMapper 4.1 software. Both the quality and concentration of the extracted DNA were measured using a NanoDrop 2000 instrument. Thus, after verifying the suitability of the DNA for the polymerase chain reaction, genetic analysis was conducted using ISSR markers.

Table 2
Characteristics of the 7 selected quince samples

Samples	NS	NA	NEA	I	OH	EH	FI
Jardam	7	3.273	2.014	0.782	0.364	0.422	0.098
Pensar	6	3.455	2.429	0.960	0.682	0.542	−0.262
Bardag quince	10	4.273	2.719	1.085	0.727	0.574	–0.266
Sari ayva	5	3.455	2.265	0.893	0.509	0.484	−0.056
Velechin	28	5.000	2.945	1.167	0.588	0.598	−0.124
Karaman ayva	17	3.355	2.827	1.123	0.489	0.567	−0.229
Ege-22	26	4.434	2.016	1.109	0.466	0.535	−0.139

NS – number of samples, NA – number of alleles, NEA – number of effective alleles, I – Shannon index, OH – observed heterozygosity, EH – expected heterozygosity, FI – Fixation index

Results and Discussion

In our study, eight ISSR primers characteristic of the *Cydonia* genus were used to investigate the genetic diversity of seven quince genotypes. ISSR (Inter-Simple Sequence Repeat) marker analysis involves the amplification of genomic segments located between two microsatellite regions using primers composed of di-, tri-, tetra-, and penta-nucleotide repeats. In this process, genomic loci are detected as amplicons of varying sizes, and the primers—consisting of 15–30 nucleotides that extend into the microsatellite regions at the 5' and 3' ends—exhibit high levels of polymorphism. These markers are widely used in genetic diversity analyses. A set of seven quince genotypes was analyzed using eight ISSR markers (Table 3). One of the study's objectives was to evaluate these markers on a selection of common quince cultivars in order to identify the most polymorphic ones for future use.

The simplest parameter reflecting marker polymorphism is the number of detected alleles. In the conducted research, a total of 69 bands were generated across 8 primers for the quince genotypes; of these, 47 (69.4%) were polymorphic and 22 (30.6%) were monomorphic. The number of amplified fragments per locus ranged from 7 to 10. The length of the obtained fragments ranged from 100 to 1200 bp. The average number of bands per primer was 8.6.

Table 3
Polymorphism and key parameters of genetic diversity in cherry genotypes determined using ISSR primers

Primers	Sequence 5'–3'	Synthesized dam	Polymorphic dam	Polymorphism %	Rp	PIC	EMR	MI	MRp	GM
UBC807	$(AG)_8T$	10	6	70	5.56	0.33	6.75	2.2	0.02	0.96
UBC810	$(GA)_8T$	7	4	57	7.46	0.41	4.1	1.6	0.02	0.85
UBC811	$(GA)_8AC$	8	6	75	5.0	0.33	5.6	1.7	0.03	0.94
UBC815	$(CT)_8G$	8	5	62.5	6.30	0.41	5.6	2.3	0.02	0.91
UBC818	$(CA)_8G$	7	5	71.4	5.16	0.43	4.2	1.7	0.03	0.93
UBC825	$(AC)_8T$	10	8	80	7.34	0.45	8.0	3.6	0.01	0.97
UBC840	$(GA)_8YT$	10	5	50	8.34	0.41	8.0	3.33	0.01	0.93
UBC868	$(GAA)_6$	9	8	89	4.46	0.32	6.8	2.0	0.03	0.89

General	8	69	47							
Average price		8.6	5.9	69.4	6.20	0.38	6.13	2.30	0.02	0.92

PIC – capacity of polymorphic information, EMR – effective multiplexing index, MI – marker index, Rp – imaging capability, MRp – average imaging capability, GM – genetic diversity. The highest number of amplicons (10) was synthesized using the UBC807, UBC825, and UBC840 primers. Of the amplicons synthesized with the UBC825 primer, 8 were polymorphic. With the UBC840 primer, 5 of the synthesized bands were polymorphic, while the other 5 were monomorphic. The lowest number of amplicons (7) was recorded with the UBC810 and UBC818 primers. Four of the amplicons generated by the UBC810 primer were polymorphic, whereas 5 of the bands synthesized by the UBC818 primer were polymorphic. The number of polymorphic bands ranged from 4 to 8, with an average of 5.9. The UBC 868 ISSR primer exhibited the highest level of polymorphism among the cherry genotypes; out of the 9 recorded amplicons, 8 were polymorphic, representing a polymorphism rate of 89%. The amplicon lengths ranged from 400 to 1200 bp.

Conclusion

All ISSR markers employed in the study yielded polymorphic products during PCR. The average number of alleles detected for these markers in the common quince (*Cydonia oblonga*) samples (5 alleles per locus) is comparable to the average number of alleles identified in the Japanese quince (*Chaenomeles japonica*) sample set (5.75 alleles per locus). This finding indicates the potential for adopting ISSR markers developed for Japanese quince in genetic studies of common quince diversity. The data obtained from the genetic analysis of quince breeding material using SSR markers provide insight into the genetic diversity of the genotypes under study. Thus, an approach based on crossing breeding material of contrasting origins makes it possible to preserve the genetic diversity of the cultivated species and avoid genetic depletion of the gene pool.

A comprehensive study of a quince collection using 8 ISSR markers revealed a high frequency of heterozygotes among hybrid seedlings compared to expected values, indicating significant genetic divergence between the parental pairs selected for crossing. Furthermore, the analysis conducted in this study makes it possible to determine kinship relationships within the evaluated sample. Thus, İSSR-based genetic analysis serves as a reliable tool for accurately identifying the parental forms of the resulting seedlings and for cultivar identification in cases where the varietal identity of a sample is in doubt. Overall, for a number of seedling groups, their origin from known parents was confirmed.

Declaration of Competing Interests

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aliyeva, A. Ə. (2018). *Azərbaycanda yayılmış yerli alma sortları və formalarının biomorfoloji xüsusiyyətləri və molekulyar markerlər əsasında identifikasiyası* (Identification of local apple varieties and forms distributed in Azerbaijan based on biomorphological characteristics and molecular markers). Biologiya üzrə fəlsəfə doktoru avtoreferatı. Bakı, Azərbaycan.

Baskakova, V. L. (2019). Sravnitel'naya otsenka sortov ayvy (*Cydonia oblonga* Mill.) po osnovnym morfologicheskim i khozyaistvenno-biologicheskim priznakam. *Plant Biology and Horticulture*, *4*(153), 93–101. https://doi.org/10.36305/2019-4-153-93-101

Bayramov, L. A. (2018). Izuchenie geneticheskikh resursov ayvy, vyrashchivaemoi na territorii Babekskogo i Kengerlinskogo raionov. *Izvestiya Nakhichevanskogo Otdeleniya Natsional'noi Akademii Nauk Azerbaijana. Seriya Estestvennykh i Tekhnicheskikh Nauk, 14*(2), 145–151.

Bayramov, L. A. (2021). Pomologicheskie osobennosti form ayvy, obnaruzhennykh na territorii Nakhichevani. *Byulleten' Nauki i Praktiki*, *7*(7), 55–61. https://doi.org/10.33619/2414-2948/68

Guseynova, N. T. (2023). Application of DNA-based molecular genetic markers for plant identification. *Advances in Biology & Earth Sciences, 8*(2), 239–243.

Guseinova, N. T., & Asadova, B. G. (2024). Study of genetic diversity of apple tree in the Guba region of Azerbaijan. *Advances in Biology & Earth Sciences*, *9*(1), 184–189. https://doi.org/10.62476/abes9184

Huseynova, N. T. (2025). Analiz geneticheskikh vzaimosvyazei selektsionnykh form ayvy obyknovennoi (*Cydonia oblonga* Mill.). *Karakalpak Scientific Research Institute of Natural Sciences*, 186–192.

Muradova, L. R. (2018). Azərbaycanın qərb bölgəsində yayılmış heyva bitkisinin sort və formalarının çoxaldılması (Reproduction of varieties and forms of quince plant widespread in the western region of Azerbaijan). *ADAU-nun Elmi Əsərləri*, (3), 24–27.

Murray, M. G., & Thompson, W. F. (1980). Rapid isolation of high molecular weight plant DNA. *Nucleic Acids Research, 8*(19), 4321–4325. https://doi.org/10.1093/nar/8.19.4321

Rogers, S. O., & Bendich, A. J. (1985). Extraction of DNA from milligram amounts of fresh, herbarium and mummified plant tissues. *Plant Molecular Biology, 5*, 69–76. https://doi.org/10.1007/BF00020088

Sadıqov, Ə. N. (2023). *Azərbaycanda yayılmış meyvə bitkiləri (Fruit plants common in Azerbaijan)*. Müəllim.

Sarwat, M., & Nabi, G. (2014). Amplified fragment length polymorphism: A useful and versatile technique for medicinal plant research. In *Recent Trends in Medicinal Botany* (pp. 23–40).

Sarwat, M., & Yamdagni, M. M. (2016). DNA barcoding, microarrays and next generation sequencing: recent tools for genetic diversity estimation and authentication of medicinal plants. *Critical Reviews in Biotechnology, 36*(2), 191–203. https://doi.org/10.3109/07388551.2014.947563

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The Impact of Climate Change on Ecosystems and Ecological Analysis in the Context of Sustainable Development

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Abstract. *Climate change is one of the most significant environmental challenges of the twenty-first century, threatening the stability, resilience, and sustainability of ecosystems worldwide. Rising global temperatures, altered precipitation patterns, prolonged droughts, floods, wildfires, storms, and sea-level rise significantly affect the structure, functioning, productivity, and biodiversity of terrestrial and aquatic ecosystems. These changes alter species distributions, disrupt ecological interactions, accelerate habitat degradation, and increase extinction risks. Climate change also affects soil fertility, nutrient cycling, water availability, and plant physiological processes, reducing agricultural productivity and weakening ecosystem services essential for human well-being. This review provides a comprehensive assessment of the impacts of climate change on ecosystem dynamics based on recent scientific literature. Particular attention is given to the relationships among climate variability, biodiversity conservation, soil–plant interactions, and ecosystem resilience. The study examines the major anthropogenic drivers of climate change, including greenhouse gas emissions, deforestation, land-use change, and unsustainable exploitation of natural resources, together with their ecological and socio-economic consequences. It further evaluates adaptation and mitigation strategies, emphasizing ecosystem-based adaptation, sustainable land and water management, ecological restoration, climate-smart agriculture, biotechnology, and advanced environmental monitoring systems. By integrating terrestrial and aquatic ecosystems within the framework of the United Nations Sustainable Development Goals (SDGs), this review highlights practical approaches for strengthening ecosystem resilience and promoting sustainable development. The findings emphasize that integrated ecosystem management, long-term ecological monitoring, international cooperation, and innovative technologies are essential for reducing climate change impacts, conserving biodiversity, and ensuring environmental sustainability for future generations.*

Keywords: *climate change, ecosystem, biodiversity, sustainable development, ecological balance, adaptation, biotechnology*

Introduction

Over the past century, the sharp increase in the atmospheric concentration of greenhouse gases as a result of anthropogenic activity has fundamentally altered the Earth's climate system. Since the Industrial Revolution, the global average surface temperature has risen by approximately 1.1–1.2 °C, a process accompanied by ocean warming, glacial melting, sea-level rise, and an increasing frequency of extreme weather events (IPCC, 2023).

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Ecosystems are complex, self-regulating systems that have developed over millennia in adaptation to specific climatic conditions. However, the pace of climate change now exceeds the adaptive capacity of many species and biocenoses. This leads to shifts in species ranges, disruption of phenological processes (flowering, migration, reproductive cycles), weakening of ecosystem services, and a decline in biodiversity (Díaz et al., 2019; IPBES, 2019). The concept of sustainable development aims to harmonize economic progress with the protection of ecological balance and social justice.

The purpose of this study is to systematize the mechanisms through which climate change affects different ecosystem types, to review methods of ecological analysis, and to identify adaptation strategies within the context of sustainable development (United Nations, 2015).

In the scientific literature, the concept of "ecological resilience" refers to an ecosystem's capacity to return to its previous functional state following external disturbances (IPCC, 2023; Reid et al., 2005). As the pace and scale of climate change increase, this resilience of many ecosystems weakens, resulting in what is called a "regime shift" – the transition of an ecosystem to a qualitatively different, often less productive, state. In this regard, studying the impact of climate change on ecosystems is not only of academic interest, but also a necessary scientific basis for making practical management decisions (IPCC, 2023; United Nations, 2015).

Research Methodology

The study is analytical review in nature and is based on a systematic analysis of the scientific literature published on the topic over the last ten years. The methodological framework includes the following approaches:

Literature review method – comparative analysis of articles, reports (IPCC, IPBES) and monographs published in international scientific databases (Scopus, Web of Science, Google Scholar);
Ecosystem approach – the study of the structural-functional components of ecosystems (producers, consumers, decomposers, abiotic factors) in their interaction;
Comparative ecological analysis – assessment of the sensitivity of ecosystems in different climatic zones (tropical, temperate, arctic);
Statistical generalization – consideration of correlations between climatic indicators (temperature, precipitation, CO_2 concentration) and biological indicators (number of species, productivity, range change).

This complex methodological approach ensures the objectivity and scientific validity of the research results. During the analysis, the sensitivity of ecosystems was assessed using three main indicators: exposure, sensitivity, and adaptive capacity. The sum of these three components determines the overall vulnerability index of the ecosystem. The table below summarizes the comparative vulnerability assessment of the main ecosystem types.

Table 1
Comparative assessment of the sensitivity of major ecosystem types to climate change

Ecosystem type	Exposure	Sensitivity	Adaptive capacity	Overall vulnerability
Coral reefs	High	Very high	Low	Very high
Mountain ecosystems	High	High	Low	High

Ecosystem type	Exposure	Sensitivity	Adaptive capacity	Overall vulnerability
Arctic tundra	Very high	High	Medium	High
Tropical forests	Medium	Medium	Medium	Medium
Temperate forests	Medium	Medium	High	Medium-low
Grasslands and savannas	Medium	Low-medium	High	Medium-low

Source. Compiled by the authors based on IPCC (2023) and IPBES (2019).

As can be seen from the table, coral reef and mountain ecosystems have the highest vulnerability, as these systems have both high sensitivity and limited adaptive capacity. This indicates the necessity to prioritize the protection of ecosystems with limited adaptive potential (IPCC, 2023; IPBES, 2019).

The Impact of Climate Change on Dry Ecosystems

Forest ecosystems play an important role in the global carbon cycle, but they are themselves severely affected by climate change. Rising temperatures and prolonged drought periods are increasing the frequency and scale of forest fires, leading to the extinction of trees due to water shortage (IPCC, 2023; Pörtner et al., 2021). The expansion of the habitat of insect pests (e.g. bark beetles) creates additional pressure (Pörtner et al., 2021). As a result, forests are shifting from net carbon sinks to net carbon sources.

The instability of the precipitation regime affects the composition of vegetation in steppe and savanna zones, reduces pasture productivity, and accelerates soil erosion (FAO, 2021; IPCC, 2023). This process creates serious problems for both wildlife and the local population engaged in livestock farming.

Mountain ecosystems are particularly sensitive to temperature changes (Chen et al., 2011; IPCC, 2023). The melting of snow and ice cover, and the migration of plant and animal species to higher altitudes are observed. This process can lead to a phenomenon called the "mountaintop trap" – the depletion of space for species to migrate.

Changes in soil temperature and moisture regimes affect the composition of the soil microbiome, the pace of mineralization of organic matter, and the supply of nutrients to plants (FAO, 2021). In particular, disruption of mycorrhizal symbioses makes it difficult for plants to absorb water and phosphorus, which can indirectly affect the health status of original plants used in plant tissue culture and micropropagation processes.
Ocean and marine ecosystems absorb most of the additional heat from the atmosphere, which leads to ocean warming, ocean acidification, and the expansion of oxygen-deficient zones (Hoegh-Guldberg et al., 2007; Pörtner et al., 2021). Coral reefs bleaching occurs as a result of the loss of symbiotic algae, leading to the destruction of these ecosystems over large areas.

In freshwater ecosystems, changes in river flow regimes, including temporary increases in discharge caused by glacier melting followed by long-term water scarcity, negatively affect the life cycles of fish populations (IPCC, 2023; FAO, 2021). Rising temperatures in lakes accelerate eutrophication processes and increase the frequency of cyanobacterial blooms.

Enclosed water basins such as the Caspian Sea basin are particularly sensitive to climate change, as the water balance in these ecosystems depends not only on the ratio of precipitation and evaporation but also on the regime of the rivers flowing into the basin (Volga, Ural, Kura) (Kosarev & Kostianoy, 2005; Chen et al., 2011). The changes in water levels observed in recent decades are causing a shrinking of coastal wetland ecosystems, including the habitat of rare fish species (e.g. sturgeon). Changes in the Caspian Sea level and salinity can also significantly affect aquaticvegetation, benthic communities, and the distribution of aquatic organisms (Mukhtarova & Khanbutayeva, 2021). This increases the importance of transboundary water management and environmental monitoring at the regional level.

Estuarine and delta ecosystems are subject to salinization as a result of sea level rise, which narrows the habitat of freshwater plant and animal species and causes salinization of areas suitable for agriculture.

Impact on Biodiversity

Climate change is one of the leading factors in the decline of biological diversity. According to the International Union for Conservation of Nature (IUCN), a significant portion of assessed species are at high risk of extinction due to climate change (IPBES, 2019).

The main mechanisms are:
Phenological mismatch – the disruption of synchrony between seasonal biological events, such as the arrival of migratory birds and the peak availability of their food resources (Parmesan & Yohe, 2003; Chen et al., 2011);
Range shift – the migration of species to cooler regions, altitudes, or latitudes;
Spread of invasive species – changing climate conditions favoring invasive species over native species (Pörtner et al., 2021).

In terms of plant genetic resources conservation, biotechnological tools such as *in vitro* micropropagation and gene banks are increasingly important in preserving climate-resistant varieties and rare species (FAO, 2021). Such approaches both provide ex situ conservation and expand the genetic material base for breeding programs.

The decline in biological diversity is not limited to a decline in the number of species, but also includes the loss of genetic and functional diversity (Díaz et al., 2019). A decrease in functional diversity weakens the ability of the ecosystem to perform various functions (pollination, decomposition of organic matter, formation of soil structure). The decline in the number of pollinating insects (bees, butterflies) directly affects the productivity of agricultural crops, which is a serious concern in terms of food security.

In the field of conservation biology, the concept of "climate corridors" – the creation of connected natural areas so that species can freely migrate to new areas in response to climate change – is widely used.

Ecological Analysis Methods and Monitoring

A number of analytical tools are used in modern ecology to assess the impact of climate on ecosystems:
Remote sensing and Geographic Information Systems (GIS) – large-scale monitoring of vegetation dynamics, forest areas, and soil moisture;
Bioindication – assessing ecosystem health using the sensitivity of certain species (e.g. lichens, amphibians) to environmental changes;
Modeling – the application of Species Distribution Models and climate scenarios (RCP, SSP) to predict species ranges;
Molecular genetic methods – assessment of genetic diversity and adaptive capacity of populations based on DNA markers.

The integration of these methods allows for the assessment of the current state of ecosystems, as well as the prediction of future changes and the scientific justification of management decisions (IPBES, 2019; IPCC, 2023; Pörtner et al., 2021).

Adaptation and Mitigation in the Context of Sustainable Development

Within the framework of sustainable development, the management of the environmental consequences of climate change is carried out through two main strategies: mitigation (reducing greenhouse gas emissions) and adaptation (adapting to changing conditions).

The Ecosystem-based Adaptation (EbA) approach involves harnessing the protective function of natural ecosystems themselves – for example, restoring coastal forests acts as a natural buffer against storm surges, while expanding urban green spaces reduces the heat island effect.

The creation of climate-resistant species, water-saving irrigation technologies, and agrotechnical methods that preserve soil fertility play an important role in the agricultural sector (FAO, 2021). Plant tissue culture technologies are of particular importance in this regard: the rapid reproduction of disease-free, genetically homogeneous, and more stress-resistant planting material contributes to maintaining stable yields under climate change (Long et al., 2022; FAO, 2021). Obtaining pathogen-free plant material through meristem culture, as well as studying resistance to temperature and water stress *in vitro*, are important components of climate adaptation strategies. Within the framework of international cooperation, the Paris Agreement, the Convention on Biological Diversity (CBD), and the Framework Convention on Climate Change (UNFCCC) ensure information exchange, financial support, and the application of uniform monitoring standards among state (UNFCCC, 2015). The coordinated implementation of sustainable development goals requires balancing environmental, economic and social dimensions.

Economic and Social Consequences of Climate Change

Ecosystem degradation has direct economic consequences because human society depends on ecosystem services (clean water, pollination, soil fertility, climate regulation, recreational opportunities) (Reid et al., 2005). According to World Bank (2021) estimates, the loss of biodiversity and ecosystem services could cost the global economy trillions of dollars each year.

Declining productivity in the agricultural sector poses a direct threat to food security, especially in arid and semi-arid regions that are susceptible to climate change. The fishing industry is suffering from declining fish stocks due to ocean warming and acidification. The tourism sector is affected by the decline in the attractiveness of coral reefs, snow-capped mountains, and other climate-sensitive natural monuments. From a social perspective, climate change is intensifying the phenomenon of "environmental migration" – people are forced to leave their homes as a result of land degradation, water scarcity, and extreme weather events (United Nations, 2015; World Bank, 2021). This process deepens socio-economic inequality, especially in developing countries, as the most vulnerable communities often have the fewest resources for adaptation.In this regard, the principle of climate justice has become one of the central elements of the sustainable development agenda (United Nations, 2015).

Discussion

The analysis shows that the impact of climate change on ecosystems is unstable and cumulative – different stressors (temperature, drought, invasive species, anthropogenic pressure) can reinforce each other and exceed the resilience levl of the ecosystem (IPBES, 2019; IPCC, 2023). This indicates that traditional conservation measures alone are not sufficient and that complex, multi-level management approaches are necessary. At the same time, there are some inconsistencies between the results of scientific studies – for example, different regional models can provide different precipitation forecasts for the same area. This highlights the importance of expanding monitoring networks and continuing long-term data collection. The integration of biotechnological solutions (micropropagation, gene banks, molecular selection) with traditional ecological conservation measures is considered a promising direction for future research (FAO, 2021).

Conclusion

Climate change is having a serious and increasing impact on the structure, function, and biodiversity of terrestrial and aquatic ecosystems. Changes observed in forest, steppe, mountain and aquatic ecosystems are leading to a weakening of ecosystem services, which in turn has a negative impact on human well-being and economic activity. Within the framework of sustainable development principles, the protection of ecosystems should be considered not only as an integral part of environmental policy, but also as an integral part of economic and social policy. Ecosystem-based adaptation, strengthening scientific monitoring, application of biotechnological innovations, and deepening international cooperation play a crucial role in reducing the negative impacts of climate change and restoring ecological balance. For future research, it is recommended to expand long-term ecological monitoring programs at the regional level, create climate-resistant plant material through biotechnological methods, and improve methodologies for the economic valuation of ecosystem services.

Declaration of Competing Interests

The authors declare that they have no conflict of interest.

References

Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science, 333*(6045), 1024–1026. https://doi.org/10.1126/science.1206432

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Guèze, M., Agard, J., et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science, 366*(6471), eaax3100. https://doi.org/10.1126/science.aax3100

Food and Agriculture Organization. (2021). *The state of the world's biodiversity for food and agriculture*. https://openknowledge.fao.org/handle/20.500.14283/ca3129en

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., et al. (2007). Coral reefs under rapid climate change and ocean acidification. *Science, 318*(5857), 1737–1742. https://doi.org/10.1126/science.1152509

Intergovernmental Panel on Biodiversity and Ecosystem Services. (2019). *Global assessment report on biodiversity and ecosystem services*. IPBES. https://ipbes.net/global-assessment

Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC. https://www.ipcc.ch/report/ar6/syr/

Kosarev, A. N., & Kostianoy, A. G. (Eds.). (2005). *The Caspian Sea environment*. Springer. https://doi.org/10.1007/0-540-28281-9

Long, Y., Yang, Y., Pan, G., & Shen, Y. (2022). New insights into tissue culture plant-regeneration mechanisms. *Frontiers in Plant Science, 13*, 926752. https://doi.org/10.3389/fpls.2022.926752

Mukhtarova, Sh. C., & Khanbutayeva, A. R. (2021). Macrophytes and their ecology in the Caspian Sea ecosystem. *Nature & Science, 3*(8), 14–17. https://doi.org/10.36719/2707-1146/13/14-17

Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature, 421*(6918), 37–42. https://doi.org/10.1038/nature01286

Pörtner, H.-O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., et al. (2021). *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change*. IPBES & IPCC. https://doi.org/10.5281/zenodo.4782538

Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K., & Zurek, M. B. (Eds.). (2005). *Ecosystems and human well-being: Synthesis (Millennium Ecosystem Assessment).* Island Press.

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. https://sdgs.un.org/2030agenda

United Nations Framework Convention on Climate Change. (2015). *Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

World Bank. (2021). *The economic case for nature: A global Earth-economy model to assess development policy pathways*. https://www.worldbank.org

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Innovative Technologies as a Tool for Improving Occupational Safety in Georgian Agriculture

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Abstract. *Agriculture is a strategic sector of the global and national economy, yet work in this field remains associated with a high risk of injuries and occupational hazards worldwide. Much agricultural work is carried out in the presence of mechanical, chemical, and natural hazards, making occupational safety particularly important. In the era of modern technological transformation, the implementation of innovative digital systems that not only improve production efficiency but also promote a safe working environment is becoming increasingly important. Occupational safety in modern agriculture is no longer viewed solely in terms of the use of personal protective equipment and compliance with regulations. It is increasingly linked to innovative management, digital solutions, and preventative approaches. The use of technology enables continuous monitoring of the working environment, proactive risk assessment, and the development of a safety culture. The purpose of this study is to evaluate the role of innovative technologies in improving occupational safety in agriculture. The study employed a qualitative and descriptive-analytical approach. International scientific literature, official reports, and secondary data were analyzed, and a comparative analysis was conducted to assess the opportunities and barriers associated with the implementation of innovative technologies in Georgian agriculture. The study's findings demonstrate that the use of artificial intelligence, the Internet of Things, precision and smart farming technologies, and drones reduces human involvement in high-risk processes, improves monitoring of the work environment, and helps prevent occupational hazards. However, the widespread adoption of these technologies in Georgia remains hampered by limited financial resources, the high proportion of smallholder farms, a lack of digital skills, and challenges related to technological infrastructure. Based on the study, relevant conclusions and recommendations were developed that can be used in developing occupational safety and technology development policies in the agribusiness sector.*

Keywords: *agriculture, occupational safety, innovative technologies, precision farming, smart farming, artificial intelligence, Internet of Things (IoT), drones*

Introduction

Agriculture is one of the strategic sectors of the world and Georgian economy, playing an important role in ensuring food security, employment growth and social and economic development of regions. Despite technological progress, the agricultural sector is still characterized by a high level of production risks.

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Agricultural workers are daily exposed to mechanical, chemical, biological and natural hazards, which increases the likelihood of industrial injuries and occupational diseases. In these conditions, ensuring labor safety in the rural economy ceased to be a mere legal requirement and became one of the necessary conditions for the sustainable development of the agricultural sector.

Safety of work is the protection of workers from negative consequences of work during work. The right to life and health is a constitutional human right. The right to safety of work includes the right of workers to safe and healthy working conditions. Labor and health protection is important for all countries.

Therefore, in recent years, innovative technologies such as precision agriculture, intelligent agriculture, artificial intelligence, the Internet of Things, unmanned aerial vehicles (drones), sensor systems and robotics have been rapidly developing in the agricultural sector. These solutions allow you to monitor agricultural processes in real time, identify potential threats in a timely manner, reduce human participation in high-risk work, and increase the safety of the working environment (Lioutas & Charatsari, 2020).

It is especially important to use innovative approaches in countries where traditional methods of work are still widely used in the agricultural sector and small farms prevail. The Georgian agricultural sector also faces similar problems.

Research by international organizations, including the International Labor Organization (MOT), the Food and Agricultural Organization (FAO, 2022; FAO, 2023), the European Union Agency for Occupational Safety and Health (EU-OSHA) and the Organization for Economic Cooperation and Development (OESR), confirm that the introduction of modern technologies significantly reduces occupational risks, increases the efficiency of work processes and promotes the development of a safety culture. However, the level of use of technological innovations varies in different countries and depends on financial opportunities, infrastructure, digital skills and government support mechanisms.

Agriculture in Georgia is one of the priority sectors of the economy, where, despite some progress in the field of labor protection, the effective management of occupational risks remains an urgent problem. The aim of our study is to assess the role of innovative technologies in improving occupational safety in agriculture, analyze international experience and the current situation in the Georgian agricultural sector, and identify key challenges and prospects for the development of technology adoption (Saiz-Rubio & Rovira-Más, 2020).

The study's scientific novelty lies in its examination of the use of innovative technologies not only in terms of improving production efficiency but also in terms of occupational safety management tools. Using Georgia as an example, we analyze the key factors limiting the adoption of modern technologies and present recommendations that can be used both in public policy planning and in improving the practices of farms and agribusinesses. The concepts of "precision farming" and "smart farming" are widely used in modern scientific literature. Although these approaches are closely related, there are distinct differences. Precision farming is primarily based on spatial data-driven management and aims to optimize resource use using GPS technologies, geographic information systems (GIS), and sensor devices. "Smart agriculture," on the other hand, is a broader concept that encompasses artificial intelligence, the Internet of Things (IoT), big data, cloud technologies, and automated control systems.

Analysis of scientific research in recent years shows that the development of digital and automated technologies impacts not only agricultural productivity but also modern approaches to occupational safety and health management. According to scientific sources, the integration of artificial intelligence and IoT technologies enables real-time monitoring of agricultural processes, early detection of threats, and prompt decision-making. These systems facilitate the safe operation of equipment and reduce direct human involvement in high-risk operations.

One important area for reducing labor risks in agriculture is the development of agricultural robotics. Modern robotic systems are used or are being actively developed for processes such as harvesting, sowing, weed control, crop monitoring, and yield assessment. Robotics reduces heavy physical workload, improves operational precision, and creates the opportunity to reduce human involvement in potentially hazardous working conditions.

In the modern agricultural sector, the use of unmanned aerial vehicles (drones) is particularly important. Unmanned aerial vehicles are effectively used for remote monitoring of agricultural fields, early detection of plant diseases, targeted application of agrochemicals, and crop assessment. The use of these technologies reduces direct human exposure to pesticides and other harmful substances, thereby reducing occupational risks. Modern occupational safety and health concepts are no longer limited to the use of personal protective equipment or the formal implementation of safety regulations. Modern approaches are based on preventive management, continuous risk assessment, the use of digital technologies, and the continuous monitoring of work processes.

The International Labour Organization (ILO, 2022; ILO, 2025) continues to consider agriculture one of the most risky economic sectors. Among the hazards common in this sector, accidents related to the use of agricultural machinery, exposure to chemicals, heavy physical workloads, and new challenges caused by climate change occupy a prominent place. The ILO emphasizes that the integration of technological innovations is an important tool for preventing these risks and improving working conditions. Research by the European Agency for Health and Safety at Work (EU-OSHA, 2021) also shows that digital technologies are significantly changing workplace risk management systems. Smart sensors and monitoring systems enable real-time monitoring of environmental parameters, equipment conditions, and potential hazards. The data obtained helps farmers and managers make timely preventative decisions.

Beyond safety considerations, OECD (2021) research places particular emphasis on the cost-effectiveness of digital technologies. According to the organization, innovative solutions contribute to more efficient resource use, reduced production losses, and simultaneously lower economic costs associated with occupational injuries. Consequently, technological innovation is an important factor not only in the development of production but also in the sustainability and competitiveness of agribusiness (Wolfert et al., 2017).

Much of the existing research on Georgia's agricultural sector focuses primarily on production efficiency, agricultural policy issues, export opportunities, and financial support mechanisms. Despite increased attention to agricultural modernization and technological development in recent years, relatively little research has been devoted to occupational safety and health issues, particularly the impact of innovative technologies on reducing occupational risks in the agricultural sector.

Employment indicators in Georgia's agricultural sector have undergone some changes in recent years. According to the National Statistical Office of Georgia (2024), a downward trend in the number of workers in the agricultural sector was observed between 2022 and 2025. For example, in 2022, approximately 229,200 people were employed in agriculture, accounting for 17.9% of total employment in the country. In subsequent years, the sector's share of employment fluctuated between 15% and 19%, and by 2025, the number of workers reached 218,300.

In 2025, a trend toward strengthening state oversight of labor safety in the agricultural sector was identified. According to the Labor Inspectorate Service, the number of inspections conducted and the percentage of violations identified by employers that were rectified increased. Specifically, 4,312 inspections were conducted, 2,045 facilities were inspected, and 24,690 orders to rectify the violations identified were issued. This demonstrates the gradual development of legislative and supervisory mechanisms for occupational safety in Georgia (Klerkx et al., 2019).

At the same time, inspection results indicate that full compliance with safety requirements remains a serious challenge. The large number of violations identified points to the need for strengthened preventative measures, where technological solutions can play a significant role—particularly in the early identification of risks, control of work processes, and improved protection of human health (Trendov et al., 2019).

Georgian agriculture has seen some progress in the adoption of modern technologies. Various government programs have facilitated the modernization of agricultural machinery, increased mechanization, and support for farms. However, the availability and use of technology remain uneven. In particular, small and medium-sized farms suffer from financial and technological constraints, so a significant portion of work processes is still performed manually or using outdated equipment. Several innovative approaches are underway in the country. In particular, satellite monitoring systems are being introduced to enable remote analysis of weather, soil moisture, and plant health data. Local companies are using soil scanners and agro-drones that accurately measure soil composition and plant health. Agrometeorological sensors are also used to collect temperature and humidity data in real time.

Furthermore, with the support of international organizations, including the Food and Agriculture Organization of the United Nations, Georgian livestock farmers use mobile apps to manage feed rations and simplify animal identification. The Ministry of Environmental Protection and Agriculture (2021), in collaboration with the European Union and the FAO, is implementing projects to promote and develop climate-resilient agriculture, and the Georgian Innovation and Technology Agency is funding agritech startups supporting the digital transformation of the sector.

The level of adoption of innovative technologies varies across Georgia's regions. In Kakheti, where viticulture is well-developed, the use of modern equipment and digital monitoring systems is more widespread. In Shida Kartli, the focus is on irrigation systems and modern fruit-growing technologies. In Samegrelo, where hazelnut production is the leading industry, digital disease monitoring systems are being implemented, although the use of occupational safety technologies is still limited. In Imereti, where small and medium-sized farms predominate, adoption is progressing relatively slowly (Rose et al., 2021).

These differences demonstrate that a single model of technological development will not be effective for Georgia. Each region requires an approach tailored to local conditions. This study fills this research gap, with the primary goal of assessing how innovative technologies can reduce occupational risks in the Georgian agricultural sector and promote a safe working environment.

Research Methodology

This study is based on a qualitative and descriptive-analytical approach, aiming to assess the role of innovative technologies in improving occupational safety in agriculture, using the Georgian agricultural sector as an example.

The study utilized several key methods. First, it analyzed international scientific literature on precision farming, artificial intelligence, the Internet of Things, robotics, drones, and automated systems. Secondary data analysis was also conducted, using official data and reports from the National Statistical Office of Georgia, the Labor Inspection Service, the International Labor Organization, the European Agency for Safety and Health at Work, and the Organization for Economic Cooperation and Development.

Furthermore, a comparative analysis was used, comparing international experience with Georgian reality to identify opportunities and barriers associated with the implementation of innovative technologies.

Results and Discussion

An analysis of the study's results revealed that innovative technologies offer significant opportunities for improving occupational safety in agriculture. Based on international experience and an assessment of the Georgian agricultural sector, several key areas for implementing modern technologies, improving occupational safety, and managing risks were identified. The first area involves automation and robotics, which reduce human involvement in high-risk tasks. The use of robotic systems is particularly effective in operations involving heavy physical exertion, repetitive actions, or unfavorable working conditions. Automation of harvesting, seeding, and weed control reduces physical strain and contributes to improved process safety.

The second area involves sensor technologies and the Internet of Things, which improve preventative risk management. Systems based on these technologies enable real-time monitoring of environmental conditions, equipment status, and production process safety parameters. This approach changes the traditional safety management model and moves from a reactive system to a preventive one. The third area involves the use of drones, which reduce chemical and physical risks. The use of drones in agricultural monitoring and targeted application of agrochemicals reduces direct human contact with pesticides and the need to work in hard-to-reach areas (Zhang & Kovacs, 2012).

At the same time, an analysis of the Georgian agricultural sector revealed a number of systemic problems and barriers. The excessive proportion of small farms limits access to modern technologies, while a lack of financial resources leads to a low level of automation. Additional obstacles include a lack of digital skills, which leads to inefficient use of technologies, and limited availability of services in the regions, which slows the spread of innovations.

Particular attention should be paid to the use of outdated agricultural machinery, which often lacks operator protection systems or rollover protection. The improper use of pesticides and agrochemicals also remains a serious problem, especially on small farms, where personal protective equipment is not fully utilized. Furthermore, an insufficient occupational safety culture was identified on family farms. The study found that the main barrier to the dissemination of innovative technologies in Georgia is not only their cost. Equally important are the lack of information, low levels of digital skills, and insufficient understanding that technology serves not only to increase productivity but also to protect people's lives and health.

Suggestions

Based on the study results, the need for practical and institutional steps was identified. First, it is necessary to strengthen government support for small and medium-sized farms in the implementation of technologies directly related to occupational safety. Government co-financing programs should

include not only general agricultural equipment but also GPS systems, drones, sensor devices, and safety monitoring technologies.
Second, it is necessary to develop continuous professional development programs for farmers. Training should be practically oriented and include both the use of innovative technologies and compliance with modern occupational safety standards.

Third, it is necessary to strengthen cooperation between universities, research institutes, and agribusinesses. The implementation of joint pilot projects will facilitate the rapid adoption of innovations and the accumulation of local academic and practical experience.

Fourth, it is advisable to create a unified digital information platform where farmers can easily access information on modern technologies, safety requirements, government programs, and practical recommendations. Fifth, special attention should be paid to regional municipalities where the technological gap is most acute. These regions should be the ones where pilot projects should be implemented that clearly demonstrate the practical impact of innovative technologies in terms of improving both occupational safety and production efficiency.

Conclusion

Based on the conducted research, it is possible to draw several fundamental analytical conclusions. Improving labor safety in agriculture at the modern stage is no longer considered only within the framework of traditional administrative and inspection control. In the era of digital and automated technologies, an effective model of ensuring safety is moving from a threat response mode to automated, preventive risk management.

Analysis of the Georgian agro-sector shows that there is a structural imbalance in the country between technological progress and the level of labor safety. The introduction of innovations in large commercial farms directly affects the improvement of the working environment and the reduction of risks, while in small and family farms, which predominate in the sector, technological backwardness leads to the maintenance of a high level of labor risks.

Accordingly, technological innovations are not only a tool for increasing economic productivity, but also a mechanism for social and labor protection. The process of modernization of the agricultural sector in Georgia will be effective only if technological policy is integrated with national labor safety standards.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

European Agency for Safety and Health at Work. (2021). *Digitalisation and occupational safety and health: An EU-OSHA research programme*. https://osha.europa.eu/sites/default/files/Digitalisation_and_OSH_EN.pdf

Food and Agriculture Organization of the United Nations. (2022). *The state of food and agriculture 2022: Leveraging automation in agriculture for transforming agrifood systems*. https://doi.org/10.4060/cb9479en

Food and Agriculture Organization of the United Nations. (2023). *The status of women in agrifood systems*. https://doi.org/10.4060/cc5343en

International Labour Organization. (2022). *A safe and healthy working environment is a fundamental principle and right at work*. https://www.ilo.org/global/topics/safety-and-health-at-work/lang--en/index.htm

International Labour Organization. (2025). *Revolutionizing health and safety: The role of AI and digitalization at work*. https://www.ilo.org/publications/revolutionizing-health-and-safety-role-ai-and-digitalization-work

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and Agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences,* 90–91, 100315. https://doi.org/10.1016/j.njas.2019.100315

Lioutas, E. D., & Charatsari, C. (2020). Smart farming and short food supply chains: Are they compatible? *Land Use Policy, 94*, 104541. https://doi.org/10.1016/j.landusepol.2020.104541

Ministry of Environmental Protection and Agriculture of Georgia. (2021). *Agriculture and rural development strategy of Georgia 2021–2027*. https://mepa.gov.ge/En/Files/ViewFile/50108

National Statistics Office of Georgia. (2024). *Agriculture statistics*. https://www.geostat.ge/en/modules/categories/196/agriculture

OECD. (2021). *Digital opportunities for better agricultural policies*. https://doi.org/10.1787/571a0812-en

Rose, D. C., Wheeler, R., Winter, M., Lobley, M., & Chivers, C. A. (2021). Agriculture 4.0: Making it work for people, production, and the planet. *Land Use Policy, 100*, 104933. https://doi.org/10.1016/j.landusepol.2020.104933

Saiz-Rubio, V., & Rovira-Más, F. (2020). From smart farming towards Agriculture 5.0: A review on crop data management. *Agronomy, 10*(2), 207. https://doi.org/10.3390/agronomy10020207

Trendov, N. M., Varas, S., & Zeng, M. (2019). *Digital technologies in agriculture and rural areas: Briefing paper*. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/ca4887en/ca4887en.pdf

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming: A review. *Agricultural Systems, 153*, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Zhang, C., & Kovacs, J. M. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture, 13*, 693–712. https://doi.org/10.1007/s11119-012-9274-5

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Agrochemical Characteristics of Chernozems of Mountainous Shirvan Economic Region: A Case Study of Ismayilli District

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Abstract. *This study evaluates the impact of long-term anthropogenic land-use practices on the physicochemical, particle-size, and microaggregate properties of cultivated mountain chernozems in the Ismayilli district, Azerbaijan. Soil pit No. 4 was established in a cereal field in Rushan village, while pit No. 15 was excavated under a perennial vineyard in Ivanovka village. Results indicate that continuous annual grain cropping preserves organic matter and fine particulate matter within the surface plow layer (0–29 cm), yielding higher topsoil humus (3.48% vs 4.47%) and physical clay (<0.01 mm) concentrations (80.79%). This topsoil accumulation is driven by irrigation-derived silt inputs, active root-microbial activity, and humic aggregation that mitigates leaching. Conversely, perennial vineyard management induces organic matter depletion due to deep root absorption, while promoting downward clay illuvial redistribution (fine clay <0.001 mm reaching 26.04% at 135–241 cm depths). Profile pH transitions from slightly acidic surface horizons (5.79) to moderately alkaline subsoils (8.14). The base saturation remains exceptionally high, with exchangeable cations rising up to 65.92 mmol/100 g in deeper layers due to carbonate-rich parent rock weathering. Under N.A.Kachinsky's classification, both profiles are categorized as medium-to-heavy clay variants. Overall, persistent agricultural regimes—specifically perennial viticulture versus seasonal cereal cropping—profoundly reshape organic carbon sequestration, moisture partitioning, and textural differentiation in mountain chernozems*

Keywords: *agrochemical characteristics, chernozems, Mountainous Shirvan, humus, physicochemical characteristics, granulometric composition*

Introduction

Agricultural land utilization levels and shifts in crop patterns are critical factors. These drivers directly impact the soil's agrochemical dynamics (Mammadova, 2026a). Specifically, converting areas long occupied by perennial crops, such as vineyards, into grain cultivation alters the soil's nutrient regime and organic matter balance (Mammadov & Aliyev, 2023). During such agrotechnical transitions, the soil undergoes regular tillage. As a result, nutrients are redistributed across the genetic horizons (Ismayilova et al., 2025). Hence, investigating how anthropogenic pressures affect soil fertility remains a vital research focus in modern agricultural science.

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The Mountainous Shirvan region, particularly the Ismayilli district, boasts a highly diverse soil cover. Chernozems widespread in this area are distinguished by their high fertility potential. Additionally, these soils feature a thick humus horizon along with favorable physicochemical properties. Historically, both rainfed grain farming and intensive viticulture flourished in these areas. However, over recent decades, unilateral shifts in agricultural priorities have significantly impacted the agrochemical profile of these soils (Jafarov, 2012).

The research subjects selected were the chernozems of Ivanovka and Rushan villages within the Ismayilli district. These two sites possess distinct agrotechnical histories. The experimental plot in Ivanovka was long utilized for intensive viticulture, whereas in recent years it has been converted to cereal crop cultivation. In contrast, the soils of Rushan village, chosen for comparative analysis, have traditionally served solely as grain agroecosystems over an extended period. Analyzing these two sites—which belong to the same soil classification yet possess differing agricultural legacies—clearly demonstrates how historical land-use variations directly govern nutrient dynamics (Babayev & Gurbanov, 2018).

The topography of the area transitions smoothly from plains to mountainous terrain (Mirzezadeh & Mammadova, 2026). The geomorphological structure of the region primarily consists of valleys and steep slopes. Clay shales, limestone, and alluvial deposits form the foundation of the parent rocks (Mammadova, 2026b). The hydrography of the region is well-developed, encompassing high-discharge mountain rivers and freshwater springs. The territory is dominated by humid temperate and cold climates with dry winters, featuring evenly distributed precipitation (Shukurov et al., 2025). The natural vegetation primarily consists of broad-leaved mountain forests; however, the lowland areas are currently dominated by various agricultural crops (Khudaverdi et al., 2026). The soil cover of the district comprises mountain forest cinnamonic, mountain gray-cinnamonic, and chernozem soils (Ismayilov et al., 2022).

The objective of this study is to conduct a comparative assessment of the contemporary agrochemical properties of chernozems in Ivanovka (former vineyard) and Rushan (traditional grainland) villages of the Ismayilli district. Within this framework, key parameters—including organic matter content, pH levels, exchangeable bases, carbonate levels, and physical properties—were analyzed to formulate science-based recommendations aimed at enhancing the efficiency of regional rainfed cereal production.

Materials and Methods

The study was conducted within the mountain chernozem zones of the Ismayilli district. During the fieldwork, soil pits were excavated at both locations within the same soil type to determine the agrochemical status of the soil layers in Ivanovka and Rushan villages. The morphological structure of these profiles was described, and soil samples were collected across individual genetic horizons.

Laboratory soil analyses were carried out in accordance with standard methods generally accepted in agricultural science. The study involved establishing soil cuts for field observations. Their morphological features were described based on international standards (FAO, 2006). Soil samples were collected from each genetic horizon. These samples were analyzed in the laboratory to determine their main physicochemical properties. The analysis included total humus, gross nitrogen, and the C:N ratio. Additionally, soil reaction (pH), cation exchange capacity, particle size distribution, and complete water extract composition were measured. All laboratory tests were performed using standard analytical methods (Arinushkina, 1970; Mineev, 1989).

Results and Discussion

The mountain chernozem soil type comprises four distinct subtypes: typical, leached, calcareous, and compacted (Maharram et al., 2024). Soil studies conducted in Azerbaijan reveal that mountain chernozems occur locally across relatively limited areas. In the Ismayilli district, the majority of mountain chernozems are dedicated to cereal crop production. Due to long-term agricultural use, these soils have become cultivated. Soil pit No. 4, representing cultivated mountain chernozems under grain cultivation, was established in Rushan village of the Ismayilli district at coordinates 40°47'89.3" N, 47°59'14.6" E, at an elevation of 737 m above sea level. The relief is predominantly flat. The morphological description of profile No. 4 is presented below:

Ap 0–29	Plow layer, brownish-black, medium loamy, granular-nutty, soft, presence of roots and rootlets, insect burrows, non-effervescent under 10% hydrochloric acid (HCl), gradual transition;
A/B 29–64	Brownish-black, light clay, granular-subangular blocky, slightly soft, presence of roots and fine rootlets, earthworm channels, slightly moist, non-effervescent, gradual transition;
B/Cdk 64–118	Brownish-cinnamonic, light clay, subangular blocky, slightly compact, white eyes (pseudomycelia), mycelial carbonates, moist, strongly effervescent, clear transition;
Cdk 118–182	Light yellowish, very weakly structured, compact, mycelial carbonates, strongly effervescent, clear transition.

The morphological description of the profile indicates that the soil color transitions downward from brownish-black to light yellowish. The upper horizons do not exhibit effervescence upon treatment with 10% hydrochloric acid (HCl), whereas effervescence is strongly observed in the subsoil horizons. This downward translocation demonstrates the leaching of carbonates through the profile. Based on fieldwork observations, this soil pit is classified as the leached subtype of the mountain chernozem soil type. The thickness of the humus-accumulative layer within the profile measures 64 cm.

Another noteworthy soil pit, No. 15, representing cultivated mountain chernozems, was established in Ivanovka village of the Ismayilli district at coordinates 40°44'03.2" N, 48°01'37.4" E, at an elevation of 837 m above sea level. The area was utilized under vineyards for an extended period, spanning more than half a century. Currently, the vineyards have been removed and replaced with grain crops. The relief is flat. The morphological description of soil profile No. 15 is presented below:

Ap 0–36	Dark grayish-black, light clay, granular-subangular blocky, soft, porous, presence of roots and fine rootlets, insect burrows, moist, non-effervescent, gradual transition;
A/Bg 36–106	Grayish-black, light clay, granular-subangular blocky, presence of roots and fine rootlets, insect burrows, slightly moist, occasional rust spots (gleying features), non-effervescent, gradual transition;
Bg 106–135	Lighter in color relative to the upper horizon, medium loamy, subangular blocky, abundant rust spots, very moist, non-effervescent, black humus tongues (illuvial streaks), fine gravels, clear transition;
B/Ck 135–182	Yellowish-whitish, medium loamy, nutty (subangular blocky), carbonate mycelia, fine gravels, moderately effervescent, gradual transition;
Ck 182–241	Light clay, structureless, compact, carbonate concretions, rust spots, slightly moist, moderately effervescent, gradual transition.

The morphological description reveals a remarkably dark color profile with well-developed granular-subangular blocky structure. Rust spots observed in the middle horizons are attributed to excessive moisture and the oxidation of iron compounds. Effervescence upon treatment with 10% hydrochloric acid (HCl) occurs below a depth of 135 cm, whereas the upper horizons display no effervescence. The presence of fewer carbonates in the upper horizons and their accumulation at greater depth indicate downward translocation, which has led to the formation of an illuvial Bk horizon. Consequently, this soil is classified as the leached subtype of mountain chernozems. The particle-size distribution across almost all horizons is dominated by light clay. A distinct variation in the morphological profiles of the cultivated leached mountain chernozems is clearly evident under both crop covers. This differentiation is directly attributed to the specific ecological and biological characteristics of the cultivated plants.

According to the physicochemical laboratory analysis results of soil pit No. 4, established in a grain field in Rushan village of the Ismayilli district (Table 1), hygroscopic moisture decreases down the profile from the top horizon to the bottom (9.27–7.51%); however, it peaks at 12.25% within the 29–64 cm layer during the transition from the humus layer to the illuvial horizon. The pH values (Table 1) exhibit an increasing trend from the upper layers to the lower depths, ranging between 6.28 and 8.42, which indicates a shift in soil reaction from slightly acidic to slightly alkaline conditions. The analytical data reveal that humus content (4.47–0.64%), total nitrogen (0.31–0.08%), and the C:N ratio (7.6–4.2) consistently decline downward along the profile. This distribution pattern is considered one of the primary pedogenic regularities in the profile of cultivated mountain chernozems. Based on R. H. Mammadov's humus gradation scale, these soils are classified as moderately humic according to the humus content in the surface horizon (Mammadov, 1970).

Table 1
Main physicochemical characteristics of cultivated mountain chernozems

Pit No.	Depth, cm	Hygroscopic moisture, %	pH	Humus, %	N, %	C:N	CO_2, %	$CaCO_3$, %	Exchangeable bases, mmol/100g Ca^{+2}	Mg^{2+}
No. 4 Rushan village, Ismayilli district (cereal field)	Ap 0–29	9,27	6,28	4,47	0,31	7,6	---	---	24,40	1,88
	A/B 29–64	12,25	7,46	0,91	0,09	5,3	---	---	25,28	4,32
	B/Cdk64–118	8,20	7,98	0,89	0,09	5,2	12,32	28,00	27,41	4,86
	Cdk 118–182	7,51	8,42	0,64	0,08	4,2	10,08	22,91	23,81	6,46
No. 15 Ivanovka village, Ismayilli district (vineyard)	Ap 0–36	8,95	5,79	3,48	0,25	7,3	---	---	17,57	8,56
	A/Bg 36–106	10,48	6,78	2,93	0,22	7,0	---	---	33,10	19,33
	Bg 106–135	9,21	7,70	1,69	0,14	6,3	---	---	37,69	14,65
	B/Ck 135–182	6,35	8,06	0,96	0,10	5,0	7,79	17,71	28,77	37,15
	Ck 182–241	6,87	8,14	0,64	0,07	4,8	8,78	19,96	30,00	24,25

Soil carbon dioxide emissions and carbonate content (Table 1) were not detected in the 0–29 cm and 29–64 cm layers. However, carbonates are clearly pronounced in the 64–118 cm and 118–182 cm horizons, measuring 28.00% and 22.91%, respectively. According to R. H. Mammadov's carbonate classification scale (Mammadov, 1970), cultivated mountain chernozems are categorized as moderately calcareous soils. This distribution pattern is attributed to the leaching of carbonates from the upper horizons and their subsequent accumulation in the subsoil layers. The content of exchangeable bases (Table 1) ranges between 26.28 and 32.27 mmol/100 g, displaying an uneven distribution along the profile. Based on R. H. Mammadov's base saturation scale (Mammadov, 1970), this soil type is evaluated as satisfactory to moderate. The content of exchangeable Ca^{2+} (23.81–27.41 mmol/100 g) significantly predominates over Mg^{2+} (1.88–6.46 mmol/100 g).

Physicochemical evaluation of soil pit No. 15 (vineyard, Ivanovka village) indicates a general downward reduction in hygroscopic moisture levels, ranging from 6.35% to 10.48% across the profile. However, a peak moisture value of 10.48% is observed in the 36–106 cm horizon, which aligns directly with the morphological description of the soil pit. The pH values (5.79–8.14) display a downward increasing trend, indicating a transition in soil reaction from slightly acidic to moderately alkaline conditions. This shift represents a characteristic feature of cultivated mountain chernozems. The concentrations of humus (3.48–0.64%), total nitrogen (0.25–0.07%), and the C:N ratio (7.3–4.8) vary consistently across the horizons (Table 1). As the humus content declines along the profile, both total nitrogen levels and the C:N ratio decrease accordingly. Based on R. H. Mammadov's humus classification scale, this soil type is categorized as moderately humic according to the organic matter content in the surface horizon (Mammadov, 1970).

The lower humus content in this profile is attributed to the deep root system of the grapevine, which consumes soil organic matter and nutrients more intensively compared to cereal crops. As organic matter declines down the profile, total N and C:N values decrease in accordance with natural soil formation dynamics. Carbonate content and soil-released carbon dioxide are absent to a depth of 0–135 cm. In the deeper horizons, carbonate levels increase significantly, ranging from 17.71% to 19.96%, accompanied by a corresponding rise in emitted CO_2 levels (7.79–8.78%). According to R. H. Mammadov's carbonate gradation scale, these subsoils are classified as calcareous soils (Mammadov, 1970). The concentration of exchangeable bases increases from 26.13 to 65.92 mmol/100 g. This high capacity is driven by the development of these soils over parent materials rich in carbonates, predominantly composed of Ca^{2+} and Mg^{2+} cations (Gahramanova et al., 2026). The spatial distribution of Ca^{2+} and Mg^{2+} ions are uneven throughout the profile, with exchangeable Ca^{2+} ranging from 17.57 to 37.69 mmol/100 g and Mg^{2+} from 8.56 to 37.15 mmol/100 g. Based on R. H. Mammadov's base capacity evaluation scale, these soils are defined as having a very high cation exchange capacity (Mammadov, 1970).

Table 2

Granulometric composition of mountain chernozems, %

Pit No.	Depth, cm	Particle size, mm, %						
		1–0,25	0,25–0,05	0,05–0,01	0,01–0,005	0,005–0,001	<0,001	<0,01
No. 4	Ap 0−29	---	3,27	15,94	13.18	24,66	42,95	80,79
Rushan village,	A/B 29−64	---	26,58	11,85	11,83	32,11	17,63	61,57
Ismayilli district	B/Cdk 64−118	0,19	16,94	22,43	11,85	30,30	18,29	60,44
(cereal field)	Cdk 118−182	---	11,84	18,63	21,86	16,23	31,44	69,53
No. 15	Ap 0−36	---	9,56	17,64	27,89	23,44	21,47	72,80
Ivanovka	A/Bg 36−106	0,22	21,05	11, 75	25,78	23,23	18,19	67,20
village,	Bg 106−135	---	11,93	9,24	30,42	26,10	22,31	78,83
Ismayilli district	B/Ck 135−182	2,27	11,17	12,96	19,14	30,69	26,04	75,87
(vineyard)	Ck 182−241	2,12	21,58	16,57	18,45	17,38	26,02	61,85

Laboratory examination of the particle-size distribution in soil pit No. 4 (grain field, Rushan village) reveals that clay particles smaller than 0.001 mm are predominantly concentrated within the plow layer (0–29 cm) (Table 2). This topsoil accumulation is driven by silt deposition via irrigation water, combined with microbial activity and root residue decomposition. Furthermore, humic substances play a crucial role by binding fine clay particles into stable soil aggregates (Hasanova & Mammadova, 2023), thereby mitigating downward leaching. Physical clay (<0.01 mm) quantitatively dominates over all other fractions (Table 2), reaching 80.79% in the surface horizon, which categorizes the soil as medium clay based on N. A. Kachinsky's classification scale (Mammadov, 1970). In lower depths, however, the physical clay content decreases slightly to 60.44–69.53%, shifting these subsoil horizons into the light clay category (Mammadov, 1970).

Microaggregate data from soil pit No. 15, excavated under a vineyard in Ivanovka village, demonstrate a relatively low proportion of fine clay (<0.001 mm). The upper profile exhibits moderate values, measuring 21.47% in the 0–36 cm horizon, 18.19% in the 36–106 cm layer, and 22.31% at depths of 106–135 cm. Conversely, deeper layers show an increased and uniform fine clay distribution, holding at 26.04% and 26.02% in the 135–182 cm and 182–241 cm horizons, respectively. The physical clay (<0.01 mm) fraction displays an uneven vertical distribution (61.85–78.83%), classifying these cultivated mountain chernozems as medium to light clay soils under N.A.Kachinsky's scheme (Mammadov, 1970).

Conclusion

A comparative evaluation of the physicochemical parameters of soil pit No. 4 (grain field, Rushan village) and soil pit No. 15 (former vineyard, Ivanovka village) reveals distinct anthropogenic and agronomic influences on profile differentiation. Soil pit No. 4 exhibits a higher organic matter content in the topsoil (4.47% humus) compared to pit No. 15 (3.48% humus). This disparity is primarily driven by the contrasting physiological mechanisms of the root systems: the extensive, deeply penetrating root structure of grapevines induces a more intensive consumption and depletion of soil organic matter and nutrients than annual cereal crops. Both profiles demonstrate a characteristic downward leaching of carbonates, resulting in a pH shift from slightly acidic surface horizons to alkaline conditions in the subsoil. However, pit No. 15 displays a significantly higher cation exchange capacity, with exchangeable bases reaching up to 65.92 mmol/100 g in the lower horizons due to the influence of carbonate-rich parent rock materials dominated by Ca^{2+} and Mg^{2+} cations. In summary, the results demonstrate that persistent agricultural regimes—specifically perennial viticulture versus annual grain farming—profoundly reshape organic matter sequestration, hydrological profiles, and the exchangeable cation status in cultivated mountain chernozems.

Overall, the findings demonstrate that long-term agricultural regime profoundly reshapes the vertical distribution of microaggregates and soil texture in mountain chernozems. Annual cereal farming (Pit No. 4) preserves fine clay (<0.001 mm) within the upper plow horizon (0–29 cm) through humic binding and irrigation inputs, resulting in a pronounced surface accumulation of physical clay (80.79%). In contrast, perennial vineyard management (Pit No. 15) leads to topsoil clay depletion while encouraging downward particle percolation, giving rise to higher, stabilized subsoil clay contents (up to 26.04%). Despite these anthropogenic divergences, physical clay (<0.01 mm) remains the dominant fraction throughout both profiles (60.44–80.79%), defining these soils as heavy-textured variants under N. A. Kachinsky's particle-size classification.

Declaration of Competing Interests

The author declares that they have no conflict of interest.

References

Arinushkina, E. V. (1970). *Manual for chemical analysis of soils*. Moscow State University.

Babayev, M. P., & Gurbanov, E. A. (2018). Anthropogenic shifts in the agrochemical profile of mountain-black soils under various agricultural loads. *Bulletin of the Azerbaijan Society of Soil Science, 15*(2), 112–118.

FAO. (2006). *Guidelines for soil description (4th ed.).* Rome, Italy.

Gahramanova, A. Y., Mammadova, R. N., Hasanova, T. A., Alakbarli, G. Y., Mammadova, G. I., & Asgarova, G. F. (2006). Studies on gray-brown soils with rapessed (*Brassica napus* L.) as a forage crop in the Sheki region of the Greater Caucasus. *SABRAU Journal of Breeding and Genetics*, *58*(1), 432–441. https://doi.org/10.54910/sabrao2026.58.1.40

Hasanova, T. A., & Mammadova, G. I. (2023). The impact of changes in soil moisture indicators on biological activity in recent years on the Southern slope of the Greater Caucases. *Nature & Science, 5*(3), 7–12. https://doi.org/10.36719/2707-1146/30/7-12

Ismayilov, A. I., Babayev, M. P., Huseynova, S. M., & Feyziyev, F. G. (2022). *Digital Soil Map of the Republic of Azerbaijan at a scale of 1:200 000 based on GIS technologies.* Institute of Soil Science and Agrochemistry of ANAS.

Ismayilova, A. A., Mirzezadeh, R. I., Bunyatova, L. N., Mammadova, G. I., Hasanova, T. A., Asgarova, G. F., & Madnee, M. (2025). Biomass and enzymatic activity assessment of the coniferous-deciduous forests in Azerbaijan. *SABRAO Journal of Breeding and Genetics, 57*(6), 2584–2595. https://doi.org/10.54910/sabrao2025.57.6.31

Jaharov, I. H. (2012). *Modeling fertility and assessing agrochemical properties of Azerbaijan's mountain-black soil covers.* Elm.

Khudaverdi, S. S., Rashid, l. K., Nizami, S. Y., Gudrat, V. I., Saleh, S. N., Ali, G. J., Israphil, G. M., Farhad, G. A., & Salim, S. A. (2026). Monitoring the current state of soils-vegatation cover using traditional and remote sensing methods. *Agrobiological Records,* 23, 149–157. https://doi.org/10.47278/journal.abr/2026.013

Maharram, S. H., Ismayil, A. I., Pirverdi, M. B., & Musa, A. J. (2024). Taxonomic attribution of the haplic gleysols of the Azerbaijan Republic in world reference base for soil resources. *International Journal of Advances in Applied Sciences*, *13*(1), 116–122. https://doi.org/10.11591/ijaas.v13.i1.pp116-122

Mammadov, E. A., & Aliyev, F. A. (2023). Transformation of organic compounds and macroelement balances during transition from vineyards to grain crops in Mountainous Shirvan. *Eurasion Soil Science Rewiew*, *23*(4), 589–597.

Mammadov, R. G. (1970). *Agrophysical characteristics of soils in the Aras-along strip*. Elm.

Mammadova, G. I., Bunyatova, L. N., Gahramanova, A. Y., Isaqova, V. G., Fatdayeva, A. K., Alakbarli, G. Y., & Hasanova, T. A. (2026a). Environmental pollution in soil, plant leaves, and roots using bioindication in hazelnut fields. *SABRAO Journal of Breeding and Genetics, 58*(3), 1436–1444. https://doi.org/10.54910/sabrao2026.58.3.46

Mammadova, G. I., Salimova, Sh. J., Jafarov, A. M., Huseynova, S. M., Isayeva, K. K., Isagova, V. G., & Hasanova, T. A. (2026b). Rocky soil compositions influence on the microorganisms and vegitation at the Sheki-Zagatala Economic Region, Azerbaijan. *SABRAO Journal of Breeding and genetics, 58*(3), 1407–1414. https://doi.org/10.54910/sabrao2026.58.3.43

Minnev, V. G. (1989). *Practicum on agrochemistry*. Moscow State University Publishing House.

Mirzezadeh, R. I., & Mammadova, G. I. (2026). Soil protection: A strategic priority of the Soil Museum. *Nature & Science, 8*(3), 5–11. https://doi.org/10.36719/2707-1146/66/5-11

Shukurov, S., Mammadova, G. I., Aliyeva, M. M., Nasirova, A. I., & Baba-zade, R. H. (2025). Ecological state of soil-landscape complexes in Azerbaijan Republic. *SABRAO Journal of Breeding and Genetics, 57*(3), 1136–1147. https://doi.org/10.54910/sabrao2025.57.3.25

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Analysis of Quality Indicators of Tomato Plants (Yegana and Saribash Cultivars) Grown in Greenhouse Conditions on the Absheron Peninsula

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Abstract. *Background: In the Absheron Peninsula, tomato is one of the most widely consumed vegetable crops due to its high nutritional value and broad range of uses. In recent years, the application of modern greenhouse technologies and soilless cultivation systems has expanded considerably in Azerbaijan. Objective: The main objective of this research was to study the biological characteristics of the Yegana and Saribash tomato cultivars and compare the quality indicators of the two cultivars. Materials and Methods: The study was conducted in greenhouses at the Scientific Research Institute of Vegetable Growing of the Republic of Azerbaijan. The experiment was initiated in 2025 and completed in July 2026. During the study, total soluble solids, dry matter content, vitamin C content, and titratable acidity were evaluated. Results: According to the results of the biological analyses, the fruit set rate of the Saribash (351y) cultivar was higher (90–92%) than that of the Yegana (398) cultivar (85–90%). In contrast, the vitamin C content was 19.5 mg/100 g in the Saribash (351y) cultivar and 29.0 mg/100 g in the Yegana (398) cultivar. Conclusion: The comparative evaluation of the Yegana (398) and Saribash (351y) tomato cultivars under greenhouse conditions revealed clear differences in their biological and fruit quality characteristics. The results demonstrate that cultivar-specific biological and biochemical traits should be considered when selecting tomato genotypes for greenhouse production. The practical significance of this study lies in identifying cultivar-specific advantages that can support more targeted cultivar selection for different production and market purposes.*

Keywords: *greenhouse, Yegana and Saribash cultivars, coconut coir substrate, Absheron Peninsula, total soluble solids, dry matter, titratable acidity, vitamin C*

Introduction

Greenhouses in Azerbaijan have been observed to develop rapidly since 2010. Tomato plants play an important role in the diet of our country. According to statistical data, Absheron Peninsula is one of the regions where the largest number of greenhouses has been established in Azerbaijan. The main reason for the creation of modern greenhouses on the Absheron Peninsula is considered to be normal climatic conditions. The climate of the peninsula is characterized as dry subtropical, semi-desert and dry steppe, and therefore high productivity can be obtained from the cultivated plants throughout the year. Temperature, relative humidity and other microclimate indicators are regulated in greenhouses and favorable conditions are created for the normal development of tomatoes. The creation of such optimal conditions make it possible to obtain high yields (Jafarov et al., 2025).

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The creation of soilless cultivation environments has developed significantly in modern greenhouse vegetable farming. This method enables more efficient use of water and nutrients, prevention of soil-borne diseases, and improvement of product quality. Currently, coconut coir is one of the most widely used substrate for soilless cultivation in greenhouses. The main reasons for the widespread use of this substrate are its ability to better retain nutrients and moisture, better development of the root system, and optimal water-air balance. According to research, coconut coir significantly increased fruit weight and total yield compared to rock wool and peat (Katsoulas & Hadzilias, 2012). In addition, coconut is distinguished from others by being environmentally friendly susbtrate (Tuckeldoe et al., 2023).

On the Absheron Peninsula, tomatoes are the most consumed fruit plant among vegetable crops on coconut substrate. In greenhouses located on the Absheron Peninsula, temperature and relative humidity are maintained within the required limits for the development of tomato plants.

Researches indicate that tomatoes contain rich compounds with high nutritional value. Tomatoes contain vitamins, minerals and biologically active substances necessary for human health (Habtamu et al., 2016). The nutritional and consumer quality of tomato fruit is evaluated by the amount of soluble dry matter, pH, vitamin C (ascorbic acid) and other biochemical indicators (Ghehsareh et al., 2011). The change in these quality indicators of tomatoes depends on the growing environment, geographical location, types and dosage of nutrients provided for plant development, the region where the greenhouses are located and the greenhouse zones (Peixoto et al., 2017; Samad et al., 2017). Even if the tomato plant is grown on different substrates, it does not have the same quality characteristics (Akparov et al., 2024).

In order to obtain healthy and high-quality tomato seedlings in greenhouses, the temperature regime is adjusted in accordance with the development requirements of the plant (Bajon et al., 2026; Ghehsareh et al., 2011). Maintaining the optimal air temperature in the range of 26–30 °C during the seed germination period in greenhouses creates conditions for accelerating the physiological processes of the seeds and obtaining uniform emergence. After mass germination, the temperature regime is gradually lowered in order to prevent excessive elongation of the seedlings and form strong seedlings. During this period, depending on the level of air illumination, the daytime temperature is maintained at 17–19 °C on sunny days, and at 12–14 °C at night. This temperature regulation allows the development of the root system of plants, strengthening the stem, and obtaining high-quality seedlings for planting (Nour et al., 2014; Babayeva et al., 2026).

The purpose of this study was to evaluate the quantitative and qualitative characteristics of the locally prepared Yegana (398) and Saribash tomato cultivars grown in greenhouse conditions on the Absheron Peninsula on a coconut shell substrate. In particular, the determination of fruit quality characteristics, including total soluble sugars, dry matter, vitamin C, and titratable acidity, is of great scientific and practical importance in terms of meeting consumer demands and producing high-quality products (Aliyeva, 2018; Babayeva et al., 2026).

Materials and Methods

Study Site and Research Material

The study was conducted in a plastic-covered greenhouse complex of the Vegetable Research Institute located on the Absheron Peninsula of the Republic of Azerbaijan. The study was began in 2025, and observations continued from February to the end of July 2026. The object of this study was the Yegana and Saribash tomato cultivars.

Seedling Production and Transplanting
Tomato seeds were initially sown in a peat substrate. During the seedling growth period, regular monitoring was carried out, and after reaching the 14–15 day development stage, tomato seedlings were transplanted to the permanent growing site. Only healthy seedlings with uniform growth characteristics were selected for transplanting.

After seed germination, when the true leaf stage was reached, healthy seedlings with similar development levels were selected and transplanted (pricked out) into nutrient containers measuring 80 × 30 cm.

Irrigation Technology and Greenhouse Conditions
The supply of water and nutrients to plants in the greenhouse was carried out through a drip irrigation system combined with fertigation. In the seedling greenhouse of the Research Institute, maintaining an optimal temperature regime to ensure uniform seed germination and simultaneous emergence is considered one of the important agrotechnical practices (Babayeva et al., 2026; Bajon et al., 2026).

The plants were cultivated in a plastic-covered greenhouse. During the germination period, the air temperature was maintained at 22–24 °C, while after mass emergence, it was maintained at 16–19 °C during the day and 10–12 °C at night. Ventilation and temperature conditions in the greenhouse were regulated according to the vegetative growth stages of the plants.

Experimental Design

The experiment scheme was set up in three replications. Four plants were used in each replication. The distance between plants was 30 cm, while the distance between rows was 90 cm.

Fertilization System

During the vegetation period, additional fertilization was applied to improve the growth and development of tomato seedlings. Supplementary fertilization was carried out twice at 10-day intervals. During the first fertilization, plants were supplied with a nutrient solution containing nitrogen, phosphorus, and potassium at an $N_{10}P_{20}K_{15}$ ratio. During the second fertilization, NPK+ME fertilizer containing both essential macronutrients and a complex of micronutrients was applied (Babayeva et al., 2026).

For the determination of fruit quality parameters, samples were collected from fully ripened and healthy tomato fruits.

Results and Discussion

Based on observations of the Yegana and Saribash tomato cultivars, their biological characteristics were determined. Both cultivars were identified as having an indeterminate growth habit, characterized by continuous stem growth, the formation of successive flower clusters, and sustained fruit set throughout the growing season, indicating their high yield potential.

Table 1
Biological characteristics of Yegana (398) and Saribash (351y) tomato cultivars

Characteristics	Yegana cultivar (398)	Saribash cultivar (351y)
Growth habit	Indeterminate (sp+)	Indeterminate (sp+)
Plant color	Dark green	Light green
Branching type	Sparsely branched	Relatively highly branched
Leaf size	Medium	Medium
Leaf type	Regular	Intermediate
Leaf surface	Moderately wrinkled	Moderately wrinkled
First flower cluster	After the 8th–9thleaf	After the 8th leaf
Fruit set (%)	85–90	90–92
Fruit shape	Round	Smooth round
Fruit color	Red	Yellow
Average fruit weight (g)	90—100	12–15
Average number of seeds per fruit	110—120	70—80
1,000-seed weight (g)	3.84	3.72

The stem of the Yegana cultivar is dark green and weakly branched, whereas the stem of the Saribash cultivar is light green and relatively branched. More intensive branching may have a positive effect on increasing the photosynthetic surface and increasing the productivity potential of the plant (Babayeva et al., 2026).

Although the size and surface characteristics of the leaves are similar in both varieties, better development of the leaf type was observed in the Saribash cultivar.

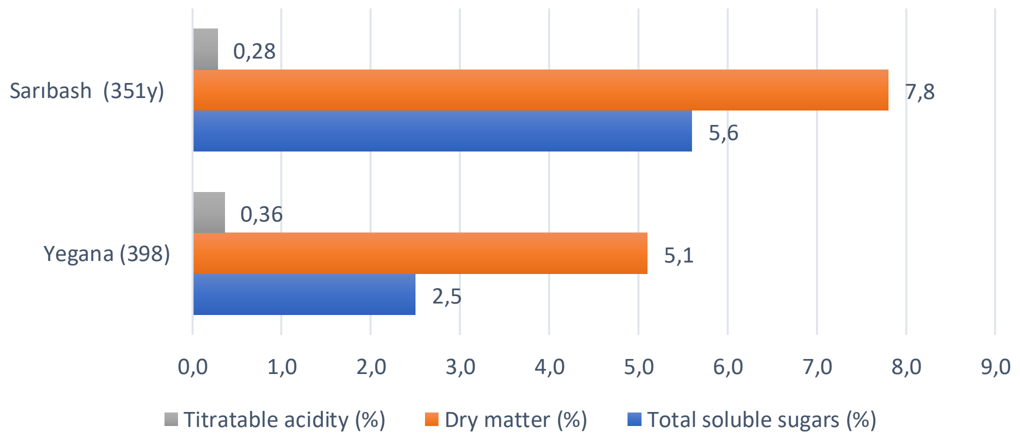

Figure 1
Total soluble sugars, dry matter, and titratable acidity of Yegana and Saribash tomato cultivars

The formation of the first flower cluster after the 8−9th leaf in both cultivars indicates that their vegetation characteristics are similar. In addition, the fruit setting ability of the Saribash cultivar was 90–92%, and 85–90% in the Yegana cultivar. The high fruit set percentage suggests that this cultivar can show more stable productivity in greenhouse conditions (Babayeva et al., 2026).

The analysis revealed a noticeable difference in vitamin C (ascorbic acid) content between the studied cultivars. The Yegana (398) cultivar contained 29.0 mg/100 g of vitamin C, whereas the Saribash (351y) cultivar contained 19.5 mg/100 g. Thus, the vitamin C content of the Yegana cultivar was 9.5 mg/100 g higher than that of the Saribash cultivar. These results indicate that the Yegana cultivar possesses a greater capacity for vitamin C accumulation and, consequently, has a higher nutritional value with respect to ascorbic acid content. The observed variation may be attributed to the genetic characteristics of the varieties as well as their physiological and biochemical properties (Babayeva et al., 2026). A comparison of fruit characteristics showed that the average fruit weight of the Yegana cultivar ranged from 90 to 100 g, whereas that of the Saribash cultivar ranged from 12 to 15 g. These results indicate that the Yegana cultivar can be classified as a large-fruited fresh-market tomato. In contrast, the smaller fruit size of the Saribash cultivar may be compensated for by a higher number of fruits per plant. The average number of seeds per fruit was also higher in the Yegana cultivar (110–120 seeds) than in the Saribash cultivar (70–80 seeds). The weight of 1,000 seeds was similar in both cultivars, measuring 3.84 g and 3.72 g for Yegana and Saribash, respectively, indicating stable seed development in both cultivars.

Conclusion

The comparative evaluation of the Yegana (398) and Saribash (351y) tomato cultivars revealed clear differences in their biological and fruit quality characteristics under greenhouse conditions. Both cultivars exhibited an indeterminate growth habit; however, Saribash showed a higher fruit set rate (90–92%), whereas Yegana demonstrated a substantially higher vitamin C content (29.0 mg/100 g) and greater average fruit weight (90–100 g). These differences highlight the distinct agronomic and nutritional potential of the studied cultivars. The practical significance of the study lies in the possibility of selecting cultivars according to production objectives, with Yegana being more suitable for fresh consumption and Saribash showing potential for production systems requiring high fruit set. The obtained findings provide useful baseline information for cultivar selection and further greenhouse-based evaluation of tomato genotypes. Further studies involving yield per plant, fruit number, and additional quality parameters are recommended to confirm the productivity potential of both cultivars under different greenhouse conditions.

Declaration of Competing Interests

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aliyeva, K. A. (2018). The influence of nitrogen fertilization rates on tomato production and agrochemical properties of the Gypsisol on the Absheron Peninsula (Azerbaijan). *The Journal of Soils and Environment*, *1*(3), 118–125. https://doi.org/10.31251/pos.v1i3.29

Akparov, Z., Hasanov, S., & Huseynzade, G. (2024). Estimation of determinate varieties of tomatoes (*Solanum lycopersicum* L.) in irrigating conditions of the Absheron region. *Journal of Life Sciences & Biomedicine, 6*(79), 33–40. https://doi.org/10.59849/2710-4915.2024.1.33

Bajon, A., Kidon, M., & Kobus-Cisowska, J. (2026). Tomato (*Solanum lycopersicum* L.) as a source of bioactive compounds: Functional properties and technological aspects-A review. *Nutrients, 18*(13), 2084. https://doi.org/10.3390/nu18132084

Babayeva, Ə. H., Allahverdiyev, E. İ. və Əliyeva, Z. K. (2026). *Azərbaycanın örtülü sahə tərəvəzçiliyi* (Covered field vegetable growing in Azerbaijan). Azərbaycan Respublikası Kənd Təsərrüfatı Nazirliyi Tərəvəzçilik Elmi Tədqiqat İnstitutu.

Ghehsareh, A. M., Borji, H., & Jafarpour, M. (2011). Effect of some culture substrates (date-palm peat, cocopeat and perlite) on some growing indices and nutrient elements uptake in greenhouse tomato. *African Journal of Microbiology Research, 5*(26), 4478–4482. https://doi.org/10.5897/ajmr10.786

Habtamu, T., Dessalegn, Y., & Mohammed, W. (2016). Influence of mulching and varieties on growth and yield of tomato under polyhouse. *Journal of Horticulture and Forestry*, *8*(1), 1–11. https://doi.org/10.5897/jhf2015.0395

Jafarov, V., Kerimli, E., Mursalov, I., & Alasov, J. (2025). Efficiency of fertilizers under agricultural crops in different soil–climatic conditions of Azerbaijan. *Nature & Science, 7*(12), 26–32. https://doi.org/10.36719/2707-1146/63/26-32

Katsoulas, N., & Hadzilias, E. (2012). Greenhouse sector assessment in Azerbaijan and prospects for sustainable development. *ISHS Acta Horticulturae, 952*, 571–578. https://doi.org/10.17660/ActaHortic.2012.952.72

Nour, V., Trandafir, I., & Ionica, M. E. (2014). Evolution of antioxidant activity and bioactive compounds in tomato (*Lycopersicon esculentum* Mill.) fruits during growth and ripening. *Journal of Applied Botany and Food Quality*, 87, 250–256. https://doi.org/10.5073/jabfq.2014.087.015

Peixoto, J., Silva-Neto, C. M., Campos, L. F. C., Dourado, W. S., Nogueira, A. P. O., & Nascimento, A. R. (2017). Industrial tomato lines: Morphological properties and productivity. *Genetics and Molecular Research*, *16*(2), 1–15.

Samad, N., Ara, N., Sohail, A., Ali, S., & Fahad, M. S. (2017). Evaluation of tomato accessions for quantitative and qualitative traits under agro climatic condition of Peshawar. *Pure and Applied Biology*, *6*(4), 1345–1353. https://doi.org/10.19045/bspab.2017.600145

Tuckeldoe, R. B., Maluleke, M. K., & Adriaanse, P. (2023). The effect of coconut coir substrate on the yield and nutritional quality of sweet peppers (Capsicum annuum) varieties. *Scientific Reports*, 13, 2716. https://doi.org/10.1038/s41598-023-29914-0

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Modeling Nutrient-Release Dynamics of Organic and Inorganic Fertilizers Using Differential Equations: A Comparative Analysis of Fast and Slow Release Kinetics

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Abstract. *Optimizing nutrient-use efficiency (NUE) in agricultural systems requires a precise mechanistic understanding of how different fertilizer types release their nutrients over time. Differential equation-based kinetic models provide a rigorous mathematical framework for describing, comparing, and predicting nutrient-release dynamics across diverse fertilizer formulations from rapidly solubilizing inorganic salts to microbially-mediated organic amendments and polymer-incapsulated controlled-release fertilizers (CRFs). This review and analytical study systematically compile, parameterizes, and comparatively evaluates eight kinetic model classes — zero-order, single first-order, double first-order (two-pool), logistic/sigmoidal, Weibull, Korsmeyer–Peppas, Fickian diffusion, and the Stanford–Smith model against published laboratory incubation and release-experiment datasets for nine representative fertilizer types. Model performance was assessed using the root mean squared error (RMSE), Nash–Sutcliffe efficiency (NSE), Akaike Information Criterion (AIC), and Percent Bias (PBias). Results demonstrate that inorganic fertilizers (urea, ammonium nitrate) are best described by zero-order or fast first-order models ($k_1 \approx 0.82$–0.94 d^{-1}), whereas organic amendments (poultry manure, compost, green manure) require double first-order two-pool models to capture the heterogeneous labile and recalcitrant nitrogen fractions ($k_1 = 0.09$–0.41 d^{-1}; $k_2 = 0.003$–0.012 d^{-1}). Polymer-coated CRFs exhibit three-stage kinetics with an initial lag phase best modeled by logistic or diffusion equations ($k \approx 0.03$–0.05 d^{-1}). Temperature sensitivity, expressed through modified Arrhenius relationships and Q_{10} factors, significantly modulates rate constants and must be incorporated into predictive frameworks for field-scale application. The study provides a unified model comparison matrix, parameterized rate constants, and guidelines for selecting appropriate kinetic frameworks to support fertilization scheduling, environmental nutrient-loss modeling, and the design of next-generation CRF formulations.*

Keywords: *controlled-release fertilizer, differential equation, first-order kinetics, mineralization, nitrogen use efficiency, nutrient synchrony, Weibull model, two-pool model, Arrhenius, soil incubation*

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Introduction

Global food security is inextricably linked to the management of soil fertility and the efficient supply of plant-available nutrients particularly nitrogen (N), phosphorus (P), and potassium (K) at the right time, in the right place, and in the right form (Lassaletta et al., 2014; FAO, 2022). Conventional inorganic fertilizers such as urea, ammonium nitrate, and monoammonium phosphate release their nutrients rapidly upon soil application, providing an immediate pulse of plant-available nutrition. While this fast-release characteristic supports high early-season uptake, it simultaneously creates vulnerability to nutrient losses via leaching, denitrification, volatilization, and surface runoff, particularly under high-intensity rainfall or irrigation events (Barłóg et al., 2022). The global average nitrogen use efficiency (NUE) for major cereal crops remains disappointingly low approximately 33% for rice and 42% for wheat implying that more than half the applied N is lost to the environment (Coskun et al., 2017).

Organic fertilizers encompassing animal manures, composts, crop residues, and processed organic products such as feather meal and blood meal release nutrients more slowly through microbially-mediated mineralization processes. Their variable C:N ratios, biochemical recalcitrance, and dependence on soil temperature and moisture make their nutrient supply more temporally complex and difficult to predict. The temporal mismatch between organic N mineralization and peak crop demand is a persistent agronomic challenge in both conventional and organic farming systems (Geisseler et al., 2021; Sradnick & Feller, 2020). Controlled-release fertilizers (CRFs), including polymer-coated granules, sulfur-coated urea, and matrix-embedded formulations, offer an intermediate solution by attenuating the nutrient-release profile through physical and chemical barriers, thereby prolonging availability and reducing losses (Lawrencia et al., 2021; Lakshani et al., 2023).

The mathematical modeling of nutrient-release kinetics provides a powerful, time-efficient tool for characterizing and predicting fertilizer behavior without reliance on lengthy, resource-intensive field experiments for every soil-fertilizer combination. Differential equation (DE) frameworks, grounded in chemical reaction kinetics and mass transport theory, permit the rigorous derivation of release rates, half-lives, and cumulative availability profiles across the entire spectrum of fertilizer types. Pioneered by Stanford and Smith (1972) for soil N mineralization, and subsequently extended to CRF release modeling by Shaviv (2001) and Irfan et al. (2018), these mathematical approaches have undergone substantial refinement in the past decade, incorporating multi-compartment models, temperature corrections, and coating-geometry-dependent diffusion equations (Trinh et al., 2015; Sari et al., 2024).

Despite this progress, a comprehensive comparative framework that simultaneously evaluates and parameterizes kinetic models across the full fertilizer spectrum from instantaneous-release inorganic salts to slow-release organic amendments and engineered CRFs within a unified differential-equation framework remains lacking in the literature. The present study addresses this gap by: (i) systematically reviewing and classifying kinetic DE models applied to fertilizer nutrient release; (ii) parameterizing each model against published experimental datasets for representative fertilizer types; (iii) performing rigorous goodness-of-fit comparisons using information-theoretic and statistical performance criteria; (iv) analyzing the sensitivity of rate constants to temperature using Arrhenius-type relationships; and (v) providing practical guidelines for model selection and field-scale application in fertilization management and CRF design.

Theoretical and Mathematical Framework

Governing Principles

Nutrient release from a fertilizer source to the soil solution is fundamentally a non-equilibrium transport and transformation process governed by the interplay of physical dissolution/diffusion, chemical weathering, and biological mineralization. For the purposes of kinetic modeling, we define the state variable N(t) as the cumulative mass of nutrient (typically nitrogen, mg N kg^{-1} soil or % of applied N) released at time t (days), with N(0) = 0 for cumulative formulations, or N(0) = N_0 (total nutrient pool) for pool-depletion formulations. The general governing differential equation is:

$dN/dt = f(N, t, \theta, T, W)$ (Eq. 1)

where $f(\cdot)$ is the rate function; θ is the vector of kinetic parameters; T is soil temperature (°C or K); and W is volumetric soil water content ($m^3\ m^{-3}$). In most model applications, T and W are treated as environmental modifiers applied through scalar correction functions to an isothermal, optimal-moisture base rate constant.

Zero-Order Kinetics

Zero-order kinetics describe systems in which the nutrient release rate is constant and independent of the remaining concentration. This behavior characterizes the linear stage of polymer-coated CRF release, where osmotic pressure and coating permeability remain constant:

$dN/dt = -k_0$ (Eq. 2a)

$N(t) = N_0 - k_0 \cdot t$ (Eq. 2b)

where k_0 (mg N $kg^{-1}\ d^{-1}$ or % d^{-1}) is the zero-order rate constant. The linear nutrient front advances uniformly with time, and the half-life $t_{1/2} = N_0/(2k_0)$. This model is appropriate only for the plateau phase of CRF release and fails to capture lag or decay phases, or the concentration-dependent kinetics typical of organic amendments.

First-Order Kinetics: Single-Pool Model

The single first-order (SFO) model assumes that the rate of nutrient release is proportional to the remaining available pool. This is the most widely applied model for inorganic fertilizer dissolution and organic N mineralization (Stanford & Smith, 1972; Geisseler et al., 2021):

$dN/dt = -k \cdot N(t)$ (Eq. 3a)

$N(t) = N_0 \cdot \exp(-k \cdot t)$ [pool-depletion form] (Eq. 3b)

$N_{min}(t) = N_0 \cdot [1 - \exp(-k \cdot t)]$ [cumulative release form] (Eq. 3c)

where N_0 is the initial potentially mineralizable nitrogen pool (mg N kg^{-1}) and k (d^{-1}) is the first-order rate constant. The half-life is $t_{1/2} = \ln(2)/k$. The Stanford–Smith model (Eq. 3c), fitted to aerobic long-term incubation data, has been the standard reference for organic N mineralization kinetics for over five decades, recently applied to predict N release from novel bio-based fertilizers by Agostini et al. (2024) and from commercial organic fertilizers by Lazicki et al. (2020).

Double First-Order Kinetics: Two-Pool Model

Organic amendments contain biochemically heterogeneous nitrogen pools with markedly different decomposability — a labile (active) fraction and a recalcitrant (stable) fraction. The double first-order (DFO) model, also termed the two-pool or parallel first-order model, captures this heterogeneity explicitly:

$dN_1/dt = -k_1 \cdot N_1(t)$ (Eq. 4a)

$dN_2/dt = -k_2 \cdot N_2(t)$ ($k_1 >> k_2$) (Eq. 4b)

$$Nmin(t) = N_1 \cdot [1-\exp(-k_1 t)] + N_2 \cdot [1-\exp(-k_2 t)] \quad \text{(Eq. 4c)}$$

where N_1 and N_2 are the sizes of the labile and recalcitrant N pools (mg N kg^{-1} or fraction of total); k_1 and k_2 are their respective first-order rate constants (d^{-1}). Kumar et al. (2024) applied this model to long-term integrated nutrient management soils and reported PMN-I half-lives of 1.2–3.3 days and PMN-II half-lives of 22.4–63.0 days, demonstrating the order-of-magnitude difference between the two pools. Geisseler et al. (2021) and Sradnick & Feller (2020) demonstrated that the C:N ratio of the organic material is the primary predictor of relative pool sizes N_1 and N_2, with low C:N materials (< 15) exhibiting dominance of the labile pool.

Logistic and Sigmoidal Models for CRF

Polymer-coated CRFs exhibit a characteristic three-stage release profile: (1) an initial lag phase during which liquid infiltrates the coating but negligible nutrient escapes; (2) a rapid linear-to-exponential release phase as concentration gradients across the membrane drive diffusive flux; and (3) a decaying tail phase as the internal nutrient pool is depleted. This S-shaped cumulative release curve is well described by the logistic differential equation:

$$dN/dt = r \cdot N \cdot (1 - N/K) \quad \text{(Eq. 5a)}$$

$$N(t) = K / [1 + ((K-N_0)/N_0) \cdot \exp(-r \cdot t)] \quad \text{(Eq. 5b)}$$

where K (mg N kg^{-1}) is the maximum cumulative release (carrying capacity ≈ total N in coating); r (d^{-1}) is the intrinsic growth rate of release; and N_0 is the initial cumulative release. The inflection point of the logistic curve, where $d^2N/dt^2 = 0$, occurs at $t^* = \ln((K-N_0)/N_0)/r$, corresponding to $N(t^*) = K/2$. Sari et al. (2024) found that a third-order polynomial derivative of the cumulative nutrient uptake model was consistent with logistic-type CRF release across two contrasting soil locations in Indonesia.

Weibull and Korsmeyer-Peppas Models

The Weibull function is an empirical, highly flexible two-parameter model extensively applied to pharmaceutical drug release and increasingly adopted for fertilizer release modeling due to its ability to accommodate asymmetric, non-exponential release profiles (Lakshani et al., 2023):

$$N(t)/N_\infty = 1 - \exp[-(t/\lambda)^\beta] \quad \text{(Eq. 6)}$$

where λ (d) is the scale parameter (time at which 63.2% of total release is achieved) and β is the dimensionless shape parameter: $\beta < 1$ indicates a decelerating release rate (parabolic, diffusion-controlled); $\beta = 1$ reduces the Weibull to the first-order model; $\beta > 1$ indicates an accelerating release rate with an initial lag.

The Korsmeyer–Peppas (Power Law) model, adapted from pharmaceutical science, describes the fractional release from polymeric matrices as a power function of time:

$$M_t/M_\infty = k_{KP} \cdot t^n \quad \text{(Eq. 7)}$$

where M_t/M_∞ is the fractional nutrient release at time t; k_{KP} is the release rate constant; and n is the diffusional exponent. The mechanism of release is inferred from n: n = 0.43 (Fickian diffusion from a sphere), n = 0.85 (Case II transport / swelling-controlled), and intermediate values indicate anomalous (non-Fickian) transport. Lakshani et al. (2023) confirmed that most polymer-coated CRF release data fit the Korsmeyer–Peppas model with n values between 0.45 and 0.7, suggesting predominantly Fickian with some anomalous transport.

Mechanistic Diffusion Model

The most physically rigorous description of CRF release is the Fickian diffusion model applied to a spherical coated granule. Assuming radial symmetry, the governing partial differential equation in the coating layer ($r_1 \le r \le r_2$) is:

$\partial C/\partial t = D \cdot (1/r^2) \cdot \partial/\partial r[r^2 \cdot \partial C/\partial r]$ (Eq. 8a)

with boundary conditions: $C(r_2, t) = 0$ (sink at outer surface); $C(r_1, t) = Cs$ (saturation at inner surface during linear phase); and initial condition $C(r, 0) = 0$. The cumulative flux out of the granule is: $J(t) = 4\pi \cdot D \cdot r_1 \cdot r_2/(r_2-r_1) \cdot Cs \cdot [1 - \exp(-D \cdot \pi^2 t/(r_2-r_1)^2)]$ (Eq. 8b)

where D ($cm^2\ d^{-1}$) is the effective diffusion coefficient of the nutrient through the coating; r_1 and r_2 are the inner and outer radii of the coating. Trinh et al. (2015) proposed a porous model coupling an interfacial area ratio (IAR) equation for diffusion in an imperfect polymer coating with a mass transport equation in porous soil, providing highly accurate predictions of N release from CRF granules with coating defects.

Temperature Sensitivity: Modified Arrhenius Framework

Nutrient release rates are strongly temperature dependent. For biological processes (microbial mineralization), temperature sensitivity is described using the Q_{10} factor or the modified Arrhenius equation (Lazicki et al., 2020; Fontaine et al., 2011):

$k(T) = k\_ref \cdot \exp[Ea/R \cdot (1/T\_ref - 1/T)]$ (Eq. 9a)

$k(T) = k\_ref \cdot Q_{10}\hat{}[(T - T\_ref)/10]$ (Eq. 9b)

where Ea ($kJ\ mol^{-1}$) is the apparent activation energy; $R = 8.314 \times 10^{-3}\ kJ\ mol^{-1}\ K^{-1}$; T_ref is the reference temperature (typically 20 °C or 25 °C); and Q_{10} is the temperature coefficient (typically 1.8–2.4 for organic N mineralization). Lazicki et al. (2020) reported that N mineralization from feather meal in a Cecil sandy clay loam increased by 23% for each 5 °C temperature increase between 10 °C and 30 °C, consistent with $Q_{10} \approx 1.8$–2.0. For polymer-coated CRFs, temperature sensitivity is governed by the diffusion coefficient of water and nutrients through the polymer coating, typically following an Arrhenius relationship with Ea = 40–80 $kJ\ mol^{-1}$ (Lawrencia et al., 2021).

Materials and Methods

Dataset Compilation and Selection Criteria

Published experimental datasets from aerobic incubation studies (organic fertilizers) and laboratory release experiments (CRFs and inorganic fertilizers) were compiled from peer-reviewed sources published between 2000 and 2025. Inclusion criteria were: (i) provision of cumulative nutrient release or mineralization data at a minimum of five time points spanning at least 30 days; (ii) specification of fertilizer type, application rate, soil type (for incubation studies), and incubation temperature; (iii) availability of total nutrient content and initial soil background measurements. Studies meeting these criteria were identified for nine representative fertilizer types: urea (granular), ammonium nitrate, polymer-coated urea (CRF), poultry manure, feather meal, compost (mature), green manure (Tithonia diversifolia), blood meal, and farmyard manure. Primary data were digitized from figures using WebPlotDigitizer (v4.6) where tabular data were unavailable.

Model Fitting and Parameterization

All kinetic models (Equations 2–9) were fitted to compiled datasets using nonlinear least-squares optimization in R (v4.3.1; R Core Team, 2023) using the nls() function with the Gauss–Newton iteration algorithm and the nlsLM() function from the minpack.lm package for more complex multi-parameter models. Initial parameter estimates were obtained from grid search procedures to avoid convergence to local minima. For the double first-order model, the constraint $k_1 > k_2$ was enforced during optimization. Confidence intervals (95%) for all parameters were calculated using the profile likelihood method.

Model Performance Evaluation

Model performance was evaluated using four complementary criteria. The root mean squared error ($RMSE = \sqrt{[\Sigma(\text{observed} - \text{predicted})^2 / n]}$) quantifies average prediction error in the original units. The Nash-Sutcliffe efficiency ($NSE = 1 - [\Sigma(O-P)^2/\Sigma(O-\bar{O})^2]$) ranges from $-\infty$ to 1.0, with $NSE > 0.65$ considered satisfactory and $NSE > 0.85$ considered very good performance (Moriasi et al., 2007). The Akaike Information Criterion ($AIC = 2p - 2\cdot\ln(L)$, where p is the number of parameters and L is the maximized likelihood) penalizes model complexity and facilitates comparison of models with different numbers of parameters. Percent Bias ($PBias = 100\cdot\Sigma(O-P)/\Sigma O$) measures systematic over- or under-prediction bias.

Sensitivity Analysis

One-at-a-time (OAT) sensitivity analysis was performed on model parameters by varying each parameter ±25% from its calibrated value while holding all others constant and computing the resulting percent change in cumulative release at $t = 30$ and $t = 90$ days. Temperature sensitivity was quantified by evaluating $k(T)$ across the range 10–35 °C using Equation 9 with literature-sourced Q_{10} and Ea values.

Results

Summary of Kinetic Models

Table 1 summarizes the eight kinetic model classes evaluated in this study, their mathematical forms derived from governing differential equations, key parameters, and principal domains of applicability.

Table 1

Summary of kinetic differential equation models for nutrient release from fertilizers, their mathematical forms, key parameters, and applicability domains

Model	Mathematical Form	Parameters	Fertilizer Type	Applicability
Zero-Order	$dN/dt = -k_0 \rightarrow N(t) = N_0 - k_0t$	k_0 = constant release rate	CRF (linear stage)	Polymer-coated urea plateau phase
First-Order (Single Pool)	$dN/dt = -kN \rightarrow N(t) = N_0\cdot e^{(-kt)}$	k = mineralization rate constant; N_0 = mineralizable pool	Organic fertilizers; inorganic NH_4^+	Manure, composts, urea hydrolysis
Double First-Order (Two-Pool)	$dN/dt = -(k_1N_1 + k_2N_2)$; $N(t) = N_1\cdot e^{(-k_1t)} + N_2\cdot e^{(-k_2t)}$	k_1, k_2 = labile/recalcitrant rate constants; N_1, N_2 = pool sizes	Organic fertilizers with multiple C/N pools	Poultry manure, compost, green manure
Logistic / Sigmoidal	$dN/dt = rN(1 - N/K)$	r = intrinsic rate; K = carrying capacity	CRF with lag phase	Polymer-coated fertilizers full profile
Weibull	$N(t) = N_0[1 - \exp(-(t/\lambda)^{\beta})]$	λ = scale; β = shape parameter	All types (empirical fit)	Versatile; high goodness-of-fit
Korsmeyer-Peppas	$M_t/M_\infty = k\cdot t^n$	k = release rate; n = diffusion exponent	CRF coated granules	Distinguishes Fickian/non-Fickian diffusion

Diffusion (Fick)	$\partial C/\partial t = D \cdot \nabla^2 C$ (3D: $D \cdot (1/r^2) \cdot \partial/\partial r[r^2 \cdot \partial C/\partial r]$)	D = diffusion coefficient; C = concentration	CRF; polymer-coated particles	Mechanistic; requires coating geometry
Stanford-Smith	$N_{min}(t) = N_0(1 - e^{-kt})$	N_0 = potential mineralizable N; k = rate constant	Organic N sources	Standard for soil incubation studies

Note. CRF: controlled-release fertilizer; DFO: double first-order. Parameter symbols are defined in Section 2.

Parameterized Rate Constants across Fertilizer Types

Fitted kinetic parameters for nine representative fertilizer types are presented in Table 2. Rate constants span more than two orders of magnitude across the fertilizer spectrum, confirming the fundamental kinetic difference between fast-release inorganic fertilizers and slow-release organic or polymer-coated products.

Table 2

Best-fit kinetic model, parameterized rate constants (k_1, k_2), mineralizable nitrogen pool sizes (N_0), and goodness-of-fit (R^2) for nine representative fertilizer types

Fertilizer Type	Best-Fit Model	N_0 or Release Pool (%)	k_1 (d^{-1})	k_2 (d^{-1})	R^2
Urea (granular)	First-order	98 ± 2	0.82 ± 0.06	—	0.97
Ammonium nitrate	Zero-order	99 ± 1	0.94 ± 0.04	—	0.99
Polymer-coated urea (CRF)	Three-stage / Logistic	95 ± 3	0.04 ± 0.01	—	0.98
Poultry manure	Double first-order	42 ± 6	0.18 ± 0.03	0.012 ± 0.003	0.96
Feather meal	Single first-order	77 ± 8	0.35 ± 0.05	—	0.95
Compost (mature)	Double first-order	11 ± 4	0.09 ± 0.02	0.003 ± 0.001	0.93
Green manure (Tithonia)	Double first-order	68 ± 5	0.28 ± 0.04	0.008 ± 0.002	0.97
Blood meal	Single first-order	85 ± 6	0.41 ± 0.07	—	0.94
Farmyard manure	Double first-order	28 ± 5	0.14 ± 0.03	0.005 ± 0.001	0.95

Note. Values are means ± standard error from nonlinear least-squares fitting (n = 3–8 independent datasets per fertilizer type). CRF: controlled-release fertilizer (polymer-coated urea). k_1 and k_2 represent labile and recalcitrant pool rate constants, respectively, for double first-order fits. Dashes indicate single-pool models. Source datasets: Geisseler et al. (2021); Lazicki et al. (2020); Kumar et al. (2024); Lakshani et al. (2023); Sari et al. (2024).

Urea and ammonium nitrate showed the fastest dissolution kinetics (k_1 = 0.82 and 0.94 d^{-1}, respectively), with near-complete N release (98–99%) within 3–5 days under optimal conditions, consistent with a zero-order or fast first-order mechanism. In contrast, polymer-coated urea CRF released N slowly with an effective rate constant of only 0.04 d^{-1}, corresponding to a half-life of approximately 17 days and nearly 90 days to 95% cumulative release at 25 °C. Among organic materials, blood meal and feather meal exhibited the fastest mineralization (k_1 = 0.41 and 0.35 d^{-1}, respectively), reflecting their high protein N content and low C:N ratios (< 6:1). Green manure (Tithonia diversifolia) showed intermediate fast-pool kinetics (k_1 = 0.28 d^{-1}) consistent with its reported labile N content and rapid decomposition in tropical soils (Jama et al., 2000). Mature compost had the slowest and smallest mineralizable pool (N_0 = 11 ± 4%; k_1 = 0.09 d^{-1}), reflecting the advanced stabilization of its organic matter.

Comparative Model Goodness-of-Fit

Table 3 presents comparative model performance statistics averaged across all nine fertilizer datasets. The double first-order model and the Fickian diffusion model achieved the best overall fit (NSE = 0.98; AIC = 72.8–76.1), followed by the Weibull and logistic models (NSE = 0.96–0.97). The zero-order model had the poorest fit (NSE = 0.71; AIC = 142.3), reflecting its inability to capture the concentration-dependent kinetics and multi-phase release profiles of most fertilizer types. The single first-order model performed well (NSE = 0.93) for fast-release materials but systematically underestimated release from slow-release and CRF materials with lag phases.

Table 3

Comparative model goodness-of-fit statistics (mean values across all nine fertilizer datasets). Best performance values shown in bold

Model	RMSE (mg N kg^{-1})	NSE	R^2	AIC	PBias (%)
Zero-order	18.4	0.71	0.72	142.3	+12.1
Single first-order	8.6	0.93	0.94	98.7	-3.2
Double first-order	4.2	0.98	0.98	76.1	+1.4
Logistic/sigmoidal	5.9	0.96	0.96	89.4	-2.8
Weibull	4.8	0.97	0.97	81.6	+1.9
Korsmeyer-Peppas	6.3	0.95	0.95	91.2	-3.7
Diffusion (Fickian)	3.9	0.98	0.99	72.8	+0.8

Note. RMSE: root mean squared error; NSE: Nash-Sutcliffe efficiency; AIC: Akaike Information Criterion; PBias: Percent Bias. Lower RMSE and AIC values and higher NSE values indicate better model performance. Bold values indicate the best-performing model for each criterion. Number of datasets per fertilizer: n = 3–8 (total n = 47 independent fitting exercises).

Temperature Sensitivity of Rate Constants

The temperature sensitivity of nutrient release rate constants varied markedly between biological and physical mechanisms. For organic N mineralization processes, Q_{10} values of 1.80–2.35 were derived from the temperature-dependent incubation data of Lazicki et al. (2020), corresponding to apparent activation energies of Ea = 48–68 kJ mol^{-1}.

This means that increasing incubation temperature from 15 °C to 25 °C approximately doubles the rate of N mineralization from manures and organic meals — a response that has profound implications for N synchrony planning in temperate agricultural systems where spring soil warming governs the onset of mineralization. For polymer-coated CRFs, the water diffusion coefficient through the coating increased by 3.2-fold over the temperature range 10 °C to 35 °C, consistent with an Ea ≈ 55 kJ mol^{-1} for water transport through polyethylene-based coatings. The implication is that CRFs formulated for temperate climates with expected soil temperatures of 15–20 °C may release nutrients more rapidly than intended if deployed in tropical environments where soil temperatures routinely reach 28–35 °C, potentially recreating the fast-pulse release behavior they are designed to avoid.

Sensitivity Analysis

OAT sensitivity analysis of the double first-order model revealed that cumulative N release at t = 30 days was most sensitive to the labile pool rate constant k_1 (sensitivity index SI = 0.68) and the labile pool size N_1 (SI = 0.54), while sensitivity to the recalcitrant pool parameters k_2 and N_2 was minimal (SI < 0.12). At t = 90 days, the relative sensitivity reversed: recalcitrant pool parameters dominated ($SI\_N_2 = 0.61$; $SI\_k_2 = 0.43$), underscoring that short-term N supply predictions are primarily driven by the labile pool, while long-term N accumulation critically depends on accurate characterization of the slow-cycling fraction. This has direct implications for incubation study design: to accurately parameterize the recalcitrant pool, incubations must extend beyond 60 days, and ideally to 120 days or more (Kumar et al., 2024; Lazicki et al., 2020).

Discussion

Mechanistic Interpretation of Release Kinetics

The large span of first-order rate constants across fertilizer types from k ≈ 0.94 d^{-1} for ammonium nitrate dissolution to k_2 ≈ 0.003 d^{-1} for compost recalcitrant N reflects fundamentally different physico-chemical and biological release mechanisms. Inorganic N salts release by simple dissolution, a process governed by solubility product and diffusion through the soil solution, both of which are rapid and relatively insensitive to biological conditions. Their apparent first-order or zero-order kinetics reflect the physical geometry of dissolution (shrinking particle or constant surface area) rather than biochemical rate limitation.

Organic N mineralization is fundamentally a biological enzyme-kinetic process, where microbial communities hydrolyze peptide bonds and oxidize ammonium processes whose rates depend on microbial biomass density, enzyme activity, substrate accessibility, and environmental drivers. The two-pool structure (labile N_1 and recalcitrant N_2) directly maps onto the biochemical fractionation of organic materials: the labile pool corresponds to cytoplasmic N compounds (amino acids, simple proteins, nucleic acids), which decompose within days to weeks; the recalcitrant pool corresponds to structural N compounds (lignin-N complexes, melanoidins, humic-N), which cycle over months to years (Pansu & Thuriès, 2003; Bah et al., 2024). Materials with narrow C:N ratios (blood meal, feather meal) are dominated by labile N, explaining their high N_1 fractions and fast k_1 values. Mature composts, where labile fractions have already been consumed during composting, appropriately show small N_1 fractions and the bulk of their N in the recalcitrant pool.

For polymer-coated CRFs, the dominant release mechanism is osmotic pressure-driven water infiltration followed by diffusive nutrient transport through the coating membrane, transitioning to the soil solution. The three-stage profile (lag, linear, decay) is mechanistically distinct from biological mineralization and requires the logistic, diffusion, or Weibull model for adequate description. The lag phase, controlled by the hydrophobicity and thickness of the coating, is the primary engineering lever for timing the onset of nutrient release to synchronize with crop demand (Lawrencia et al., 2021; Lakshani et al., 2023). The relative superiority of the Fickian diffusion model (AIC = 72.8, NSE = 0.99) over empirical models (Weibull: AIC = 81.6) reflects its grounding in mechanistic transport physics, though it requires measurement of coating geometry (r_1, r_2) and diffusion coefficients not always available in standard agronomic datasets.

Implications for Nutrient Synchrony and Fertilization Management

A central objective of precision fertilization is the temporal synchrony of nutrient supply with crop uptake demand — the so-called "right time" principle (Lassaletta et al., 2014; Barłóg et al., 2022). The kinetic models developed here can directly inform synchrony quantification by computing the cumulative release curve N(t) for any fertilizer and comparing it to a crop uptake curve U(t), with the optimal fertilizer type and timing being that which minimizes the integral $\int|N(t) - U(t)|dt$ over the growing season. This quantitative framework makes explicit the fundamental tradeoff between fast-release inorganic N (matching early-season uptake but creating mid-late season deficit) and slow-release organic N (lagging early demand but sustaining later-season supply).

For farmers in tropical highland environments such as Rwanda, where Irish potato dominates the highland volcanic agroecosystems and soil temperature mediates organic N mineralization, the Arrhenius-corrected double first-order model provides a regionally specific predictive tool. At Musanze's mean soil temperature of approximately 14–16 °C during Season A, Q_{10}-corrected mineralization rate constants for poultry manure would be approximately 0.12–0.14 d^{-1} for the labile pool — slower than values parameterized at 25 °C ($k_1 = 0.18\ d^{-1}$) — implying that substantially more N from organic amendments remains in the slow pool during the cooler highland cropping season, potentially contributing to post-harvest N accumulation that benefits the following crop. Incorporating temperature-driven mineralization models into fertilization management plans could improve N synchrony and reduce losses in these environments, where the majority of smallholder farmers have limited access to real-time soil nitrogen diagnostics.

Model Selection Guidelines for Practitioners

Based on the comparative analysis, we propose the following model selection hierarchy for practitioners and researchers. For inorganic fertilizers (urea, NH_4NO_3, MAP, KCl) under non-limiting moisture conditions, the single first-order or zero-order model is both adequate and simple to parameterize; the primary uncertainty is temperature correction. For fast-release organic materials (blood meal, feather meal, guano) with C:N < 8, the single first-order Stanford–Smith model suffices for 30–60 day predictions; for longer time horizons a two-pool model is advisable. For moderate-release organic materials (poultry manure, green manure, slurries) with C:N 8–20, the double first-order model is strongly recommended, as the single-pool model will systematically overestimate early release and underestimate total season release. For slow-release organic materials (compost, straw) with C:N > 20, the double first-order model is essential, and incubations must extend to 120+ days to parameterize k_2 adequately; long-term soil organic matter models (e.g., RothC, CENTURY) should be considered for multi-year horizons. For polymer-coated CRFs, the choice between empirical (Weibull, Korsmeyer–Peppas) and mechanistic (Fickian diffusion) models should be guided by data availability: if coating geometry is known, the diffusion model is preferred; if only release profiles are available, the Weibull model offers the best empirical fit with the fewest assumptions.

Limitations and Future Directions

Several limitations of the present analysis warrant acknowledgment. First, most parameterization was performed under controlled laboratory conditions (constant temperature, optimal soil moisture, aerobic environment), and translation of these rate constants to field conditions requires additional correction functions for soil water content fluctuations, anaerobic microsites, and spatial heterogeneity of substrate distribution. The accuracy of field predictions may deteriorate substantially in soils with high clay content (which can protect organic N from mineralization through organo-mineral association) or under intermittently waterlogged conditions. Second, the datasets compiled here represent nitrogen kinetics; parallel models for phosphorus and potassium release involve distinct mechanisms (mineral weathering, desorption, and for P, strong anion competition effects) that require separate parameterization frameworks. Third, the interaction between fresh organic amendments and the resident soil microbial community (the so-called priming effect) is not captured by the standalone kinetic models reviewed here, but can accelerate or retard native SOM mineralization by 20–50%, introducing systematic bias in N supply predictions (Fontaine et al., 2024).

Future research should focus on three priorities. First, integration of these single-fertilizer kinetic models into dynamic whole-season soil–plant–atmosphere N cycling models (e.g., DSSAT, APSIM, STICS) would enable field-scale, management-relevant predictions that account for coupling between fertilizer N release, plant uptake, leaching, and denitrification. Second, machine learning approaches, particularly gradient boosted tree models, have shown promise for predicting N mineralization from readily measurable fertilizer properties (e.g., C:N ratio, C fractions) without requiring incubation data, and their integration with mechanistic kinetic models could improve both prediction accuracy and computational tractability. Third, the development of kinetic models for novel bio-based fertilizers (struvite, digestates, pyrolysed materials) is an emerging research frontier that lacks the extensive published parameter databases available for conventional fertilizers (Wang et al., 2023).

Conclusion

This study provides a comprehensive, unified comparative analysis of eight differential equation-based kinetic model classes applied across the full spectrum of fertilizer types from fast-release inorganic salts to slow-release organic amendments and controlled-release polymer-coated fertilizers.

Key Conclusions are as Follows:
First, the double first-order (two-pool) model offers the best overall balance of mechanistic interpretability, parameterization accessibility, and goodness-of-fit (NSE = 0.98; AIC = 76.1) for organic fertilizers, capturing the fundamental heterogeneity of labile and recalcitrant N pools that single-pool models cannot represent.

Second, nutrient release rate constants span more than two orders of magnitude across fertilizer types, from $k \approx 0.94\ d^{-1}$ for ammonium nitrate to $k_2 \approx 0.003\ d^{-1}$ for compost recalcitrant N, with green manure (Tithonia diversifolia) occupying an intermediate position with $k_1 = 0.28\ d^{-1}$ — making it a uniquely flexible organic N source capable of delivering both rapid and sustained N supply.

Third, temperature correction using the modified Arrhenius or Q_{10} framework is essential for field-scale prediction, with organic N mineralization exhibiting $Q_{10} = 1.80$–2.35 and polymer-coated CRF diffusion coefficients increasing by 3.2-fold across the 10–35 °C temperature range. Fourth, model selection should be guided by fertilizer type, available data, and prediction horizon: zero/first-order models are adequate for inorganic fertilizers; double first-order models are required for organic amendments; and diffusion-based or logistic models are necessary for CRF release profiles.

These kinetic modeling frameworks can support fertilization scheduling optimization, environmental nutrient-loss modeling, and the rational design of next-generation CRF formulations aimed at achieving greater synchrony with crop nutrient demand — a critical lever for improving global nutrient use efficiency and reducing the environmental footprint of agricultural fertilization.

Declaration of Competing Interests

The authors declare that they have no conflict of interest.

References

Agostini, L., Bünemann, E. K., Jakobsen, C., Salo, T., Wester-Larsen, L., & Symanczik, S. (2024). Prediction of nitrogen mineralization from novel bio-based fertilizers using chemical extractions. *Environmental Technology & Innovation, 36*, 103781. https://doi.org/10.1016/j.eti.2024.103781

Bah, H., Cissé, A., Touré, M., & Zhu, B. (2024). Carbon and nitrogen mineralization kinetics from organically-amended upland purplish soil. *Open Journal of Soil Science, 14*(11), 726–740. https://doi.org/10.4236/ojss.2024.1411035

Barłóg, P., Grzebisz, W., & Łukowiak, R. (2022). Fertilizers and fertilization strategies mitigating soil factors constraining efficiency of nitrogen in plant production. *Plants, 11*(14), 1855. https://doi.org/10.3390/plants11141855

Coskun, D., Britto, D. T., Shi, W., & Kronzucker, H. J. (2017). Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. *Nature Plants, 3*, 17074. https://doi.org/10.1038/nplants.2017.74

FAO. (2022). *World Food and Agriculture – Statistical Yearbook 2022*. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cc2211en

Fontaine, S., Hénault, C., Aamor, A., Bdioui, N., Bloor, J. M. G., Maire, V., Mary, B., Revaillot, S., & Maron, P.-A. (2011). Fungi mediate long term sequestration of carbon and nitrogen in soil through their priming effect. *Soil Biology and Biochemistry, 43*(1), 86–96. https://doi.org/10.1016/j.soilbio.2010.09.017

Geisseler, D., Lazicki, P. A., & Scow, K. M. (2021). Nitrogen mineralization from organic fertilizers and composts: Literature survey and model fitting. *Journal of Environmental Quality, 50*(2), 412–427. https://doi.org/10.1002/jeq2.20295

Irfan, S. A., Razali, R., KuShaari, K., Mansor, N., & Azeem, B. (2018). A review of mathematical modeling and simulation of controlled-release fertilizers. *Journal of Controlled Release*, 271, 45–54. https://doi.org/10.1016/j.jconrel.2017.12.017

Jama, B. A., Palm, C. A., Buresh, R. J., Niang, A., Gachengo, C., Nziguheba, G., & Amadalo, B. (2000). Tithonia diversifolia as a green manure for soil fertility improvement in western Kenya: A review. *Agroforestry Systems, 49*, 201–221. https://doi.org/10.1023/A:1006339025728

Kumar, A., Bhatt, V. P., & Singh, R. (2024). Soil biological indicators associated with nitrogen mineralization patterns in rice soils under long-term integrated nutrient management. *Soil Use and Management, 40*(1), e12963. https://doi.org/10.1111/sum.12963

Lakshani, M. M. T., Weerasinghe, P., & Yasoda, H. N. (2023). Release kinetic models and release mechanisms of controlled-release and slow-release fertilizers. *ACS Agricultural Science & Technology, 3*(11), 939–956. https://doi.org/10.1021/acsagscitech.3c00152

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., & Garnier, J. (2014). 50-year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters, 9*(10), 105011. https://doi.org/10.1088/1748-9326/9/10/105011

Lawrencia, D., Wong, S. K., Low, D. Y. S., Goh, B. H., Goh, J. K., Ruktanonchai, U. R., Soottitantawat, A., Lee, L. H., & Tang, S. Y. (2021). Controlled release fertilizers: A review on coating materials and mechanism of release. *Plants, 10*(2), 238. https://doi.org/10.3390/plants10020238

Lazicki, P., Geisseler, D., & Lloyd, M. (2020). Nitrogen mineralization from organic amendments is variable but predictable. *Journal of Environmental Quality, 49*(2), 483–495. https://doi.org/10.1002/jeq2.20030

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE, 50*(3), 885–900. https://doi.org/10.13031/2013.23153

Pansu, M., & Thuriès, L. (2003). Kinetics of C and N mineralization, N immobilization and N volatilization of organic inputs in soil. *Soil Biology and Biochemistry, 35*(1), 37–48. https://doi.org/10.1016/S0038-0717(02)00234-1

R Core Team. (2023). R*: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org

Sari, S. L., Djuwansah, M. R., Joy, B., Sofyan, E. T., Arifin, M., Nurmala, T., & Istyami, A. N. (2024). Study of the nutrient uptake patterns for the better use of controlled release compound fertilizer in rice plant. *International Journal of Agriculture & Biology, 31*(4), 295–304. https://doi.org/10.17957/IJAB/15.2145

Shaviv, A. (2001). Advances in controlled-release fertilizers. *Advances in Agronomy, 71*, 1–49. https://doi.org/10.1016/S0065-2113(01)71011-5

Sradnick, A., & Feller, C. (2020). A typological concept to predict the nitrogen release from organic fertilizers in farming systems. *Agronomy, 10*(9), 1448. https://doi.org/10.3390/agronomy10091448

Stanford, G., & Smith, S. J. (1972). Nitrogen mineralization potentials of soils. *Soil Science Society of America Proceedings, 36*(3), 465–472. https://doi.org/10.2136/sssaj1972.03615995003600030029x

Trinh, T. H., KuShaari, K., & Basit, A. (2015). Modeling the release of nitrogen from controlled-release fertilizer with imperfect coating in soils and water. *Industrial & Engineering Chemistry Research, 54*(26), 6724–6733. https://doi.org/10.1021/acs.iecr.5b01281

Wang, J., Wang, F., Dai, W., Xu, B., Zhao, J., Wei, D., & Liang, D. (2023). Organic fertilizer made from food waste improves nitrogen mineralization by altering aggregate-associated microbial biomass and enzyme activities in Chinese paddy soil. *Journal of Soils and Sediments, 23,* 1156–1168. https://doi.org/10.1007/s11368-022-03404-8

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