RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
58 (4) 1982-1991, 2026
http://doi.org/10.54910/sabrao2026.58.4.48
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

MORPHOGENETIC DIAGNOSTICS AND FERTILITY VARIATIONS IN DRY SUBTROPIC SOILS WITH GRAPE CULTIVATION IN AZERBAIJAN

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SUMMARY

This study aimed to assess the variability of morphogenetic diagnostic indicators in irrigated gray-brown soils (Ganja-Gazakh sloping plain) and mountain-brown soils (Upland-Shirvan) cultivated with grapes and their effects on soil physical and agrochemical properties compared with uncultivated and winter wheat-cultivated soils. In gray-brown soils, the irrigated soil and grape production showed increased bulk density and structural compaction while reducing water-resistant aggregates. Under the 0–20 cm layer, bulk density rose from 1.12 g/cm³ (uncultivated soils) to 1.28 g/cm³ (irrigated vineyards). In mountain-brown soils, bulk density enhanced from 1.06 g/cm³ to 1.26 g/cm³ under grape cultivation. In all cases, the bulk density amplified with depth, being more pronounced in vineyard soils. However, the cultivated mountain-brown soils showed a higher humus and nitrogen content and improved aggregation than with soils under winter wheat. Although the fertility indicators were generally higher in vineyard soils, increased compaction and structural degradation heightened erosion risks, particularly under intense rainfall and irrigation. The results underscored the need for sustainable soil management in viticulture systems.

Keywords: Grape, morphogenetic, soil fertility parameter, gray-brown, mountain-brown, morphological features

Communicating Editor: Prof. Dr. Zahoor Ahmed Soomro

Manuscript received: February 19, 2026; Accepted: May 27, 2026.
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Citation: Mammadov MI, Mustafayev MG, Sadıgov RG, Mustafayev FM, Akhundov AY, Muhammad D (2026). Morphogenetic diagnostics and fertility variations in dry subtropic soils with grape cultivation in Azerbaijan. *SABRAO J. Breed. Genet. 58 (4) 1982-1991. http://doi.org/10.54910/sabrao2026.58.4.48*.

Key findings: Long-term grape cultivation and irrigation have increased the bulk density and structural compaction in gray-brown and mountain-brown soils. The cultivated mountain-brown soils showed higher humus and nitrogen content and improved aggregation than winter wheat soils.

INTRODUCTION

Agrogenic transformation constitutes one of the most significant anthropogenic drivers of soil evolution, manifesting through profound alterations in soil fertility parameters, morphogenetic characteristics, and structural properties. Long-term soil cultivation, particularly under perennial crops, such as grapevine, exerts complex influences on soil formation, structure, and functionality. Mechanical interventions, viz., repeated plowing, deep inter-row tillage, and other vineyard-specific soil management practices, disturb the upper soil layer, homogenizing genetic horizons, accelerating organic matter mineralization, and modifying aggregate stability, bulk density, and porosity. The effects were particularly distinct in arid and semi-arid regions, and the natural moisture limitations affect soil buffering capacity and heighten their sensitivity to anthropogenic pressures. Consequently, in these areas, the soil responds to cultivation with improvement in nutrient accumulation in surface horizons and structural degradation in subsurface layers (State Standard of the Republic of Azerbaijan, 2013; Ministry of Agriculture of Azerbaijan State Land Management Project Institute, 2020; Mammadov *et al.,* 2025b).

Historical land-use dynamics further shape soil evolution in viticulture zones. In Azerbaijan, grape plantations also gained considerable expansion during the 1970s–1980s, followed by a reduction in the late 1980s due to socioeconomic factors. These variations developed distinct phases of land-use intensity, leaving measurable effects on the soil's physical and chemical properties. Comparative studies revealed that soils under long-term vineyards exhibited higher humus content, improved nitrogen and phosphorus availability, and enhanced water-resistant aggregates in the upper layers than soils under cereals and fallow land. However, these benefits obtained a counterbalance from compaction, reduced poverty, and localized hydrological variations induced by mechanized cultivation, irrigation, and application of mineral and organic fertilizers (International Soil Classification System for Naming Soil and Creating Legends for Soil Maps, 2014; Babaev *et al.,* 2017; Sadigov and Macnunlu, 2023; Gumbatov *et al.,* 2024; Huseynov *et al.,* 2025).

In viticulture landscapes, soil transformation study requires a comparative analysis of diverse soil types and climatic conditions. For the Ganja-Gazakh Massif, gray-brown (chestnut) soils formed under automorphic hydrological conditions. In vineyards, the irrigation practices have developed irrigation-hydromorphic regimes, considerably affecting structural composition, water retention, and erosion susceptibility. Under irrigated gray-brown soils, the accumulation of a thick humus horizon (AVai.z + A/Bica ≈ 70 cm) with well-developed granular-blocky aggregates demonstrates culturalization induced by long-term viticulture. However, the mechanical interventions, particularly repeated tractor passes, have increased bulk density (from 1.12 g/cm³ in uncultivated soils to 1.28 g/cm³ in vineyards) and reduced porosity by up to 8%–9%, highlighting the trade-off between fertility improvement and structural vulnerability.

In the Upland-Shirvan Region, encompassing the low-mountain zones of Shamakhi and Gobustan, mountain-brown soils developed on deluvial clay-granular parent materials with the highest carbonate content ($CaCO_3$ 15%–20%). These soils provide favorable conditions for grape growth and sugar accumulation. Comparative analysis of the cultivated and uncultivated mountain-brown soils enunciated that humus content and water-resistant aggregates decreased under long-term vineyard cultivation, while nutrient availability in the upper horizons remains higher than in cereal-cultivated soils. The proportion of water-resistant aggregates (> 0.25 mm) decreased from 48% in raw soils to 37% in vineyard soils, whereas bulk density increased from 1.06 to 1.26 g/cm³. Ammonium nitrogen ($N–NH_4^+$) declined from 12.93–36.21 mg/kg in natural soils to 12.93–28.40 mg/kg under grape cultivation, reflecting both structural and chemical modifications associated with long-term management.

These observations highlighted that viticulture acts as a dual driver of soil transformation, enhancing fertility in surface horizons through humus accumulation, nutrient cycling, and improved aggregation. Simultaneously, it promotes compaction and erosion susceptibility. Thus, the comparative study of gray-brown and mountain-brown soils provides crucial insights on how long-term agricultural practices interact with natural pedogenic factors to shape soil evolution in semi-arid and low-mountain viticulture landscapes.

Understanding these processes is essential for developing sustainable soil management strategies in vineyards, including optimized irrigation regimes, balanced nutrient management, reduced mechanized disturbance, and soil conservation practices. Such integrated approaches proved crucial for maintaining long-term soil productivity, improving grape quality, and mitigating adverse effects of agrogenic transformation on soil structure and fertility (Ghanbarian and Daigle, 2015; Hasanov, 2018; Jafarov and Aliev, 2020). Thus, the presented study aimed to examine the variability in morphogenetic diagnostic indicators of irrigated gray-brown and mountain-brown soils cultivated with grapes and their effects on soil physical and agrochemical properties compared with uncultivated and winter wheat-cultivated soils.

MATERIALS AND METHODS

Field investigations commenced in key viticulture zones of Western and Central Azerbaijan, including Goygol, Shamkir, Tovuz, Agstafa, the Ganja-Gazakh Plain, and the Upland-Shirvan Region (Shamakhi and Gobustan districts). The experimental plots established were on irrigated gray-brown (chestnut) soils in the Ganja-Gazakh Massif and on cultivated mountain-brown soils in the Shamakhi area. An integrated methodological approach employed allowed comparative assessment of soil fertility parameters across vineyards of different ages and against adjacent uncultivated control soils (Tables 1 and 2).

On soil properties, the evaluation of topographical influences used relief plasticity maps to determine the slope gradients and geomorphological variations. Field data collection combined stationary observations, comparative-geographical analysis, and geographic information systems (GIS) technologies, providing a comprehensive framework for spatial and temporal assessment of soil transformations under viticulture.

The conduct of laboratory analyses was according to internationally recognized and classical soil science protocols. Soil aqueous extract analysis followed the method of Arinushkina (1970), with CO_3^{2-} and HCO_3^- ions determined by titration with sulfuric acid; Cl^- by Mohr's argentometric method; Ca^{2+} and Mg^{2+} by trilonometric titration; SO_4^{2-} by volumetric analysis; and $Na^+ + K^+$ by calculation from the ionic balance. Bulk density determination used the method of Kachinsky (1965), with particle density assessed according to the method of S.I. Dolgov. Particle-size distribution measurement employed the pipette method after treatment with 1.0 N NaCl. Humus content, as determined, engaged the I.V. Tyurin method and measured soil pH potentiometrically. The composition of absorbed bases, when evaluated, extracted Ca^{2+} and Mg^{2+} according to the method of D.I. Ivanov. The exchangeable sodium detection followed K.K. Gedroits. Total nitrogen content quantification utilized the Kjeldahl method (ISO 11261: 1995) (Kashinsky, 1970; Kovda, 1973; Dospekhov, 1984; Mammadov, 2015; Sadigov *et al.,* 2024).

This integrated methodology allowed for precise characterization of physical, chemical, and morphogenetic soil properties under varying cultivation regimes and climatic conditions, forming a robust basis for subsequent analysis of acrogenic impacts in vineyard ecosystems (Mehdiyeva *et al.,* 2026).

RESULTS AND DISCUSSION

The investigations conducted took place under dry subtropical climatic conditions on irrigated gray-brown soils (Ganja-Gazakh) and mountain-brown soils (Upland-Shirvan Region). Gray-brown soils incurred genetic formation under automorphic hydrological regimes; however, long-term irrigation has transformed these soils into irrigation-hydromorphic conditions, with altered pedogenic processes and diagnostic features. In gray-brown soils, the average annual air temperature was 12 °C–13.2 °C, with a total active temperature (> 10 °C) of 4000 °C–4700 °C. Annual precipitation averages 350–400 mm, and the humidity coefficient ranged from 0.3 to 0.5, confirming predominantly automorphic soil formation. Nevertheless, irrigation practices have modified the natural water regime in these soils.

In contrast, the mountain-brown soils of Shamakhi and Gobustan developed under average annual temperatures of 11.5 °C–12.9 °C, active temperatures of 3200 °C–3500 °C, precipitation of 591–636 mm, and potential evaporation of 800–900 mm. These ecological conditions favor the formation of carbonate-rich and well-structured soils in the low- and mid-mountain belts. In the dry subtropical zones of the Nakhchivan and Middle Araz zones, the average annual air temperature was 13.6 °C–14.5 °C, with total active temperatures (> 10 °C) of 4200 °C–4850 °C. The annual precipitation average was 280–320 mm, and the humidity coefficient ranged from 0.25 to 0.42, confirming a predominantly automorphic soil formation (Mammadov *et al.,* 2025a).

Plantation plowing (50–60 cm) during vineyard establishment disrupts and mixes up the genetic horizons, disturbs the humus layer, and reduces water-resistant aggregates, while prolonged cultivation promotes the development of compacted sublayers of soil. Humus content was the highest in former vineyard areas of Mughanli and Madrasa municipalities (5.40%–5.65%) and even higher (7.12%–8.27%) in less-disturbed profiles. In contrast, soils with continuous winter wheat cultivation contained only 2.80%–4.01% humus in the 0–25 cm layer, which may be due to accelerated mineralization and monoculture practices (Sadigov and Mustafayev, 2024). In past studies, in the 0–25 cm subsoil layer, the humus content ranged between 5.36% and 6.11% in undisturbed upper layers and 4.28% and 5.47% in moderately disturbed soils (Huseynov *et al.,* 2025).

Nitrogen content followed similar trends and reached 0.40% in natural soils and remained comparatively higher under vineyards due to periodic fertilization. Carbonates increased below the depth of 50–70 cm, and total absorbed bases averaged 30–40 mg-eq/100 g in the upper horizon of mountain-brown soils. Overall, vineyard cultivation has intensified cultural soil development, particularly in Mughanli and Shirvan territories, while also inducing structural and hydrological transformations (Shukurov *et al.,* 2025; Sadigov *et al.,* 2025). Similar soil processes were also evident in past studies (Huseynov *et al*., 2025).

Long-term grape cultivation promotes soil culture through modifications in their structural and nutrient regimes. Field investigations revealed that vineyard soils exhibited improved aggregation and enhanced biological activity with increased humus accumulation in the upper horizons, contributing to the higher proportion of water-resistant aggregates. Soil cultural development reached a general assessment as weak to moderate, depending on the humus, nitrogen, and phosphorus reserves. However, over the past 20–30 years, increasing aridity, higher evaporation rates, and recurrent droughts have negatively influenced the pedogenic stability and limited further improvement in soil fertility (Sadigov *et al.,* 2026a).

In irrigated gray-brown soils of the Ganja-Gazakh Massif, irrigation under insufficient natural drainage and gentle inclination toward the Kura River has intensified irrigation erosion and sediment deposition. Prolonged irrigation with turbid river water has resulted in the accumulation of a thick agro-irrigational humus horizon (AVai. z + A/Bica ≈ 70 cm), characterized by a dark-gray coloration, granular-subangular blocky structure, and enhanced biological transformation. An illuvial Btca (a subsoil layer characterized by the accumulation of silicate clay and secondary carbonate enrichment) horizon (25–30 cm) with heavier granulometric composition and compaction was clearly apparent, revealing morphogenetic alteration in the soil profile (Tables 1 and 2).

Nevertheless, mechanized vineyard management exerts considerable pressure on soil physical properties. Approximately 27%–29% of the soil surface sustained compaction, particularly within the 5–7 cm upper layer. Bulk density enhanced by more than 10%, porosity decreased by 8%–9%, and water infiltration rates declined. Although the transition to lighter tractors has reduced surface load compared with earlier heavy machinery, repeated passes still intensify structural degradation. Unlike annual crops, grape root systems have a limited regenerative influence on soil aggregation, leading to reduced water-resistant aggregates—particles >0.25 mm decreased from 44% in uncultivated gray-brown soils to 31% under irrigation. Overall, viticulture simultaneously enhanced nutrient accumulation and promoted compaction and structural vulnerability under intensive management (Didehban *et al.,* 2025; Mammadov *et al.,* 2025b; Sadigov *et al.,* 2026b and e).

Under alternative management conditions, mechanized vineyard practices enunciated comparatively moderate effects on soil physical properties. Field observations revealed approximately 18%–21% of the soil surface experienced compaction, mainly confined to the 3–5 cm upper layer. Bulk density increased by 6%–8%, while total porosity declined by 4%–6%, accompanied by a slight reduction in water infiltration rates. The introduction of lighter agricultural machinery, including tractors, such as Belarus, combined with regulated traffic patterns and reduced field passes, contributed to minimizing structural disturbance. In contrast to previous findings, perennial grape root systems showed a partial compensatory effect by improving biogenic aggregation and enhancing micro-structural stability in subsurface layers. As a result, the proportion of water-resistant aggregates (>0.25 mm) decreased only marginally—from 46% (uncultivated gray-brown soils) to 40% (irrigated vineyard conditions). Overall, the intensive viticulture continued to influence soil compaction processes, and the implementation of improved management strategies promoted a more balanced interaction between nutrient accumulation and soil structural stability (Huseynov *et al.,* 2025).

In mountain-brown soils, the water-resistant aggregates (>0.25 mm) proportion reached 48% in uncultivated conditions, whereas in long-term vineyard soils, this indicator decreased to 37%, reflecting structural transformation under continuous cultivation. The results revealed that despite certain improvements in biological activity and humus accumulation in vineyard systems, prolonged mechanical disturbance and agro-technical interventions contribute to partial degradation of aggregate stability (Sadigov *et al.,* 2026c).

Comprehensive agrochemical analysis disclosed substantial variations in key fertility indicators, such as humus content and nitrogen and phosphorus reserves under grape cultivation. In cultivated mountain-brown soils, the concentration of ammonium nitrogen ($N–NH_4^+$) ranged between 12.93 and 28.40 mg/kg, compared with 12.93 and 36.21 mg/kg in natural raw soils. Similar decreasing trends emerged for nitrate nitrogen ($N–NO_3^-$), available phosphorus (P_2O_5), and exchangeable potassium (K_2O). The results suggested that although vineyard soils may exhibit moderate cultural development, nutrient depletion occurs without balanced replenishment and organic matter management (Figures 1 and 2).

Table 1. Physico-chemical indicators of mountain-brown soils in the study area (2023–2025).

Soil section No.	Genetic layers and depth (cm)	Hygroscopic moisture (%)	Humus (%)	Nitrogen (%)	C:N	$CaC0_3$ (%)	pH in water solution	Absorbed bases (mg-eq)			
								Total	Ca^{++}	Mg^{++}	Ca: Mg
Shamakhi District, Vineyard (2023)											
50	AU'az 2-28	7.5	5.40	0.40	7.9	No	6.9	35.1	27.3	7.9	3.4
	AU"az 28-52	7.4	4.45	0.31	8.6	"--"	7.2	31.9	26.2	4.3	4.3
	A/B 52-84	6.5	3.46	0.23	6.5	4.2	7.4	35.7	26.2	2.7	2.7
	Btca 84-105	8.0	2.13	Not.an.	—	10.7	7.7	25.7	19.5	3.1	3.1
	Cca 105-140	7.4	1.34	"--"	—	19.2	7.9	26.4	20.0	3.1	3.1
Cereal crops											
55	AU'az 0-25	6.6	3.84	0.27	9.5	No	7.0	31.7	26.5	5.2	5.0
	AU"az 25-48	5.7	2.84	0.17	9.8	"--"	7.1	30.6	25.4	5.2	4.8
	Bt 38-65	6.8	1.66	0.10	7.8	"--"	7.3	31.8	21.3	10.5	2.2
	B/Cca 65-90	6.2	1.06	Not.an.	—	8.6	7.6	39.5	30.9	8.6	3.6
	Cca 90-120	4.7	0.89	"--"	—	25.3	8.1	34.3	26.2	8.1	3.2
Shamakhi District, Vineyard (2024)											
58	AU'az 0-23	5.1	4.05	0.32	7.4	No	7.1	36.6	25.7	10.9	2.4
	AU"az 23-44	4.9	3.61	0.23	7.6	"--"	7.2	32.1	23.3	8.8	2.6
	A/B 44-82	4.2	2.26	0.18	6.0	"--"	7.3	30.0	23.3	6.7	3.4
	Btca 82-120	4.0	1.75	Not.an.	—	"--"	7.3	26.1	22.8	3.3	6.9
	Cca 120-150	3.9	0.96	"--"	—	5.8	7.6	25.7	21.9	3.8	5.8
Cereal crops											
60	AU'az 0-20	6.0	3.09	0.23	7.6	No	7.0	29.6	20.1	9.6	2.4
	AU'az 20-35	5.5	2.08	0.13	6.1	"--"	7.2	27.9	17.6	10.3	1.7
	Bt 33-70	5.6	1.40	0.08	6Д	"--"	7.4	30.5	23.8	6.7	3.5
	B/Cca 70-100	5.1	0.80	Not.an.	—	4.3	7.6	30.00	23.8	6.2	3.8
	Cca 100-135	4.7	0.65	"--"	—	6.8	7.7	28.00	22.8	5.2	4.4
Shamakhi District, Vineyard (2025)											
64	AU'az 0-24	8.0	5.65	0.45	7.3	No	7.1	41.4	32.7	8.6	3.8
	AU'az 24-48	7.8	4.56	0.37	7.1	"--"	7.2	39.0	26.2	12.8	2.6
	A/B 48-72	7.4	3.47	0.28	7.2	"--"	7.3	32.0	22.9	9.1	2.5
	Btca 72-97	7.0	2.21	Not.an.	—	2.4	7.5	33.3	24.3	9.0	2.7
	Cca 97-135	5.6	1.05	"--"	—	9.6	7.8	35.2	23.8	11.4	2.1
Cereal crops											
67	AU'az 0-22	7.6	4.01	0.30	7.8	No	7.2	31.1	25.7	5.4	4.7
	AU"az 22-38	6.6	3.12	0.24	9.0	"--"	7.3	28.8	23.6	5.2	4.5
	A/B 38-65	7.0	1.98	0.11	7.8	"--"	7.5	30.0	21.2	8.8	2.4
	Bt 65-90	6.0	0.98	Not.an.	—	5.1	7.7	34.8	26.4	8.4	3Д
	C 90-130	4.9	0.68	"--"	—	25.6	8.0	37.1	28.3	8.8	3.2
Cereal crops											
70	AU'az 0-20	7.2	2.80	0.20	8.1	No	7.1	32.9	22.1	10.8	2.1
	AU"az 20-34	7.2	2.30	0.17	7.8	"--"	7.2	30.7	18.7	12.0	1.5
	Btca 34-63	7.6	1.89	0.11	7.8	1.6	7.3	31.8	18.6	13.2	1.4
	B/Cca 63-98	6.4	0.94	Not.an.	—	9.3	7.6	31.6	18.4	13.2	1.4
	Cca 98-125	6.1	0.77	"--"	--	9.1	7.8	26.8	16.8	10.0	1.7

Table 2. Physical and chemical indicators of irrigated gray-brown (chestnut) soils of the Ganja-Gazakh Massif (2023–2025).

Soil section No.	Genetic layers and depth (cm)	Humus (%)	Nitrogen (%)	C:N	$CaCO_3$ (%)	pH in water solution	Bases absorbed in 100 g of soil (m-eq.)			
							Total	Ca'^{++}	Mg^{++}	Ca: Mg
Aghstafa District, Vineyard										
4	AYa'ca 0-20	2.55	0.208	7.1	9.4	8.4	25.02	18.38	6.94	2.8
	AYa''ca 20-40	2.32	0.180	8.0	12.8	8.5	22.23	16.42	5.81	2.9
	Bca 40-65	1.56	0.148	6.2	14.9	8.6	23.11	14.92	6.19	2.4
	B/Cca 65-86	0.86	Not.an.	-	16.2	8.7	19.66	12.88	6.78	1.9
	Cca 86-110	0.55	“ - “	-	17.5	8.6	17.14	10.95	6.19	1.8
Tovuz District, cereal crops										
20	AYa'ca 0-23	2.84	0.224	7.4	8.6	8.3	28.30	19.92	8.38	2.4
	AYa''ca 23-48	2.43	0.182	7.4	9.4	8.4	25.28	16.42	8.86	1.9
	Bca 48-75	1.72	0.128	7.9	10.3	8.5	26.07	18.40	7.67	2.4
	B/Cca 75-92	0.74	Not.an.	-	12.4	8.5	21.58	15.38	6.20	2.5
	Cca =92-120	0.46	“ - “	-	12.8	8.6	22.61	15.85	6.76	2.3
Goygol District, perennial clover										
10	AYa'ca 0-25	2.72	0.216	7.5	6.0	8.1	27.98	17.43	10.55	1.7
	AYa''ca25-44	1.90	0.142	7.8	7.2	8.2	25.44	17.76	7.68	2.3
	Bca 44-73	1.27	0.104	6.8	9.2	8.3	27.56	17.76	9.80	1.9
	B/Cca 73-100	0.93	Not.an.	-	10.3	8.3	20.40	15.80	4.70	3.5
	Cca 100-130	0.61	“-“	-	14.3	8.4	21.40	15.28	6.12	2.6
Shamkir District, Vineyard										
12	AYa'ca 0-23	2.48	0.182	7.3	4.7	8.3	22.81	16.80	4.01	3.7
	AYa''ca 23-40	1.90	0.166	6.0	5.6	8.3	21.28	16.42	4.86	3.4
	Bca 40-67	1.19	0.124	6.5	6.4	8.4	20.28	16.85	3.43	4.3
	B/Cca 67-84	0.78	Not.an.	-	9.0	8.4	18.76	14.85	3.91	3.8
	Cca 84-105	0.45	“ - “	-	3.4	8.5	16.42	11.62	5.80	2.0
Poorly developed stony soils, 5–6-year-old vineyards										
15	AYapca 0-20	1.97	0.168	6.8	6.0	8.0	16.18	13.80	2.38	5.7
	A/Cpca 20-40	1.86	0.154	7.4	5.1	8.1	13.80	11.90	1.90	6.0
	C/Dca 40-65	0.70	Not.an.	-	5.9	8.2	13.47	10.25	3.22	3.1
16	AYapca 0-18	2.02	0.162	7.2	4.2	8.1	17.74	14.04	3.70	3.8
	A/Cpca 18-35	1.72	0.128	7.4	4.8	8.1	14.52	12.20	2.32	4.7
	C/Bca 35-60	0.65	Not.an.	-	6.0	8.2	11.58	9.06	2.52	3.8

Figure 1. Soil research in the vineyard.

Figure 2. Balance observations.

Comparative assessment further detailed that when using mountain-brown soils under cereal crops, the fertility parameters reduced more markedly than under grape cultivation. This tendency was even more vivid in irrigated gray-brown soils of the Ganja-Gazakh, where intensive irrigation and cultivation accelerate nutrient transformation and redistribution processes (Kazimova and Nabiyev, 2022; Ayubov *et al.,* 2025; Mammadova *et al.,* 2025; Sadigov *et al.,* 2026c, d).

The highest humus and total nitrogen reserves recorded arose in uncultivated raw soils, confirming the robust influence of anthropogenic use on soil nutrient dynamics. The results underscore the need for optimized fertilization regimes and soil conservation measures to maintain long-term fertility and structural stability in vineyard agroecosystems. Moreover, to ensure sustainable viticulture and high-quality grape production, this study recommended optimizing nutrient management by balancing the organic and mineral fertilizer application according to soil diagnostics. Subsequently, this regulates irrigation regimes to prevent over-irrigation and minimize erosion, applying soil conservation practices (reduced tillage, cover crops, and mulching) to maintain aggregate stability and prevent compaction.

CONCLUSIONS

The results confirmed that long-term grape cultivation significantly affects the morphogenetic characteristics and fertility traits of irrigated gray-brown soils in the Ganja-Gazakh Region and mountain-brown soils in Upland-Shirvan. Under vineyards, improved nutrient regimes and soil structure indicate an association with increased water-resistant aggregates, attributed to enhanced humus accumulation in the upper horizons and gradual improvement of physical properties. The resulting increase in density, reduced porosity, and structural disturbance raise the risk of water and irrigation erosion, especially during heavy rainfall. Moreover, recent climatic changes, including more frequent droughts and higher evaporation rates, further threaten soil stability and long-term fertility.

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