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Ion Exchange Capacity of Mountain-Forest Soils of the Lankaran Economic Region and its Dependency Patterns

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Abstract. *The Lankaran–Astara region is one of the transitional areas of Azerbaijan's subtropical zone, characterized by complex relief, high precipitation, and rich forest cover. These natural factors lead to the intensive development of complex geochemical processes in the soil profile, including ion-exchange reactions. The article provides detailed information on the cation exchange capacity (CEC) and anion exchange capacity (AEC) of mountain-forest soils in the region and analyzes their dependence on soil texture, mineralogical composition, organic matter content, and soil reaction (pH). The research results showed that the CEC of soils in the region ranges from 12.5 to 35.8 cmol/kg, while the AEC varies between 150 and 450 mg/kg. The ion-exchange properties differ significantly across altitudinal zones, reflecting the diversity of soil formation processes in the region.*

Keywords: *cation exchange capacity, anion exchange capacity, mountain-forest soils, Lankaran–Astara region, pH, humus, clay minerals*

Introduction

One of the most fundamental indicators determining the genetic characteristics, ecological functions, and agro-production potential of soil cover is its ion-exchange capacity. At the same time, the ion-exchange capacity of soils defines their buffering properties, i.e., their resistance to external impacts such as acid rain, fertilization, and pollution (Sposito, 2008).

In the scientific literature, cation exchange capacity (CEC) and anion exchange capacity (AEC) are considered among the most important indicators characterizing both the agrochemical potential of soils and their buffering capacity against various natural and anthropogenic pollutants (Babayev et al., 2017). Recent studies have emphasized that CEC serves as a fundamental parameter for assessing soil quality and ecosystem resilience, particularly in forest ecosystems where nutrient retention capacity directly influences vegetation productivity (Coppola & Mollo, 2019). CEC refers to the ability of negatively charged soil surfaces to retain positively charged ions. This capacity is mainly formed due to permanent charges arising from isomorphic substitution in the structure of clay minerals, as well as pH-dependent charges resulting from the dissociation of functional groups (carboxyl, phenolic, alcoholic) in organic matter (Tan, 1998). AEC, on the other hand, is the ability of positively charged soil surfaces to retain negatively charged ions and is mainly formed due to the protonation of iron, aluminum, and manganese oxides and hydroxides, as well as certain functional groups (amino groups) of organic matter (Khidirov, 2010).

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Both cation and anion exchange capacities are key indicators of soil fertility, ecological stability, and suitability for agricultural use (Guliyev, 2018). It is observed that minerals of the kaolinite group dominate in the mineralogical composition of the region's soils, along with the presence of hydromicas, vermiculite, and chlorite in certain amounts (Mammadov, 2002). The combination of these clay minerals creates a complex exchange complex where kaolinite contributes to low permanent charge while 2:1 minerals (vermiculite, hydromica) enhance overall CEC values, a pattern commonly observed in subtropical forest soils with mixed mineralogy (Bhattacharyya et al., 2020).

Although kaolinite has a relatively low CEC (2–15 cmol/kg), the presence of 2:1 type clay minerals (hydromicas, vermiculite, smectite) contributes to an increase in CEC. Expanding clay minerals such as vermiculite and smectite have high CEC (80–150 cmol/kg), and as their content increases, the overall CEC of the soil significantly rises (Bradl, 2004). In addition, under humid subtropical climate conditions, the accumulation of iron and aluminum oxides and hydroxides (sesquioxides) plays an important role in the formation of anion adsorption capacity. Minerals such as goethite, hematite, and gibbsite become positively charged in acidic environments, leading to the fixation of phosphates, sulfates, and other anions in the soil (Ismayilov, 2012).

The study of ion-exchange properties of soils is important not only from a theoretical perspective but also has great practical significance. Based on these indicators, fertilization rates are determined, liming of acidic soils is carried out, reclamation measures are planned, and the ecological stability of soils is assessed and monitored (Gahramanov, 2015). In the Lankaran–Astara region, the intensive development of agricultural sectors such as tea cultivation, citrus growing, and vegetable production makes the efficient use of soils, as well as the preservation and enhancement of their fertility, particularly relevant.

Materials and Methods

The object of the study is the mountain-forest soils distributed in the Lankaran–Astara region. The study area is located on the northeastern slopes of the Talysh Mountains, at elevations ranging from 0 to 1600 m above sea level. The research was conducted during 2023–2025. Soil profile excavation and description were carried out according to generally accepted methodologies. Soil profiles were grouped by elevation zones and soil types as follows: in the lower mountain belt (0–400 m) — yellow soils; in the middle mountain belt (400–1000 m) — podzolized yellow soils and mountain brown forest soils; and in the upper mountain belt (1000–1600 m) — mountain brown forest soils.

Soil profiles were established under typical vegetation cover characteristic of each soil type and across different elements of the relief (upper, middle, and lower parts of slopes). Morphological descriptions were conducted for each soil profile, and genetic horizons were identified: A_0 (forest litter), A_1 (humus accumulation), A_2 (eluvial), B (illuvial), and C (parent material). Soil color was determined using the Munsell color chart (Munsell Color Company, 2000).

Soil samples were collected from each genetic horizon at intervals of 10–20 cm depending on horizon thickness, with an average sample weight of 1–1.5 kg. Samples were placed in polyethylene bags, labeled, and transported to the laboratory. In total, 46 soil samples were collected. In the laboratory, soil samples were air-dried, cleaned of coarse fragments and root residues, crushed using a wooden pestle, and sieved through a 2 mm sieve. Representative samples were prepared for analysis. For the determination of organic matter content, separate samples were sieved through a 0.25 mm sieve (Van Reeuwijk, 2002).

Soil texture was determined using the pipette method according to N. A. Kachinsky (1958). Soil particles were divided into the following fractions: physical sand (>0.01 mm) and physical clay

(<0.01 mm). Additionally, fine fractions (<0.001 mm, 0.001–0.005 mm, 0.005–0.01 mm) were also determined.

Organic matter content was determined by the Tyurin method in the Gustavson modification (Arinushkina, 1970), based on the oxidation of organic carbon with potassium dichromate. Humus content was calculated by multiplying the organic carbon content by a factor of 1.724. Soil pH was measured potentiometrically (ISRIC, 2002) in both water and 1N KCl solution, using a soil-to-solution ratio of 1:2.5. Measurements were carried out using a pH meter (HANNA Instruments HI 2211).

Two methods were used to determine cation exchange capacity (CEC) (Gedroiz, 1955):

- For neutral and alkaline soils: saturation with 1N CH_3COONa solution at pH 7.0. The soil was saturated with sodium acetate, and the absorbed sodium was determined using a flame photometer.
- For acidic soils: saturation with 1N CH_3COONH_4 solution at pH 7.0. The absorbed ammonium was determined by distillation using a Kjeldahl apparatus.

Phosphate adsorption capacity was determined using the Blomback-Maclaurin method (Blomback & Maclaurin, 1956). Soil samples were mixed with KH_2PO_4 solution, and phosphorus concentration in the equilibrium solution was measured colorimetrically using the Murphy–Riley method. The amount of adsorbed phosphorus was calculated as the difference between initial and equilibrium phosphorus concentrations.

Total anion exchange capacity was determined using the Mehlich method (extraction with 1N NH_4Cl solution) (Mehlich, 1984; Sparks et al., 1996). Exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined by complexometric methods, while exchangeable potassium (K^+) and sodium (Na^+) were measured using a flame photometer (PAJ-2 model). The amounts of hydrogen and aluminum were determined using the Gedroiz method.

Results and Discussion

According to the research results, the cation exchange capacity (CEC) of mountain-forest soils in the Lankaran–Astara region varies between 11.5 and 32.5 cmol/kg (Table 1). The highest CEC values are observed in the upper humus horizons (A_1), which is associated with the high organic matter content (5.2–7.5%).

Table 1

Physicochemical properties of mountain-forest soils in the Lankaran region

Soil type	Elevation, (m)	Horizon	Depth (cm)	Humus	Physical clay (%)	CEC cmol/kg	AEC mg/kg
Yellow soils	0–400	A_1	0–15	5.2 ± 0.8	42.5 ± 3.8	18.5 ± 2.1	425 ± 35
		B	15–45	2.1 ± 0.4	48.3 ± 4.2	22.3 ± 2.5	445 ± 40
		C	45–80	0.8 ± 0.2	35.6 ± 3.5	12.4 ± 1.8	385 ± 30
Podzolized yellow soils	400–800	A_1	0–18	6.8 ± 0.9	38.7 ± 3.6	24.6 ± 2.8	315 ± 28
		A_2	18–35	1.8 ± 0.3	28.5 ± 3.0	14.2 ± 1.9	285 ± 25
		B	35–65	1.2 ± 0.3	45.2 ± 4.0	26.8 ± 2.9	355 ± 32
		C	65–95	0.5 ± 0.1	32.4 ± 3.2	11.5 ± 1.6	295 ± 26

Mountain brown forest soils	800–1300	A_1	0–20	6.2 ± 0.8	35.8 ± 3.4	28.5 ± 3.1	245 ± 22
		B	20–50	2.5 ± 0.4	40.5 ± 3.7	26.2 ± 2.8	265 ± 24
		C	50–85	1.1 ± 0.2	30.2 ± 3.1	14.8 ± 1.9	185 ± 18
Mountain brown forest soils (upper belt)	1300–1600	A_1	0–15	7.5 ± 1.0	32.5 ± 3.3	32.5 ± 3.5	195 ± 20
		B	15–45	2.8 ± 0.5	38.2 ± 3.5	28.5 ± 3.0	215 ± 22
		C	45–80	1.2 ± 0.3	28.5 ± 2.9	15.5 ± 1.8	155 ± 16

Along the soil profile, CEC decreases with increasing depth: in yellow soils, it is 18.5 cmol/kg in the A_1 horizon and 12.4 cmol/kg in the C horizon; in mountain brown forest soils (upper belt), it is 32.5 cmol/kg in the A_1 horizon and 15.5 cmol/kg in the C horizon. In podzolized yellow soils, the relatively high CEC in the B horizon (26.8 cmol/kg) is explained by the illuvial accumulation of clay minerals (2:1 type). This vertical distribution pattern of CEC is characteristic of mountain forest ecosystems, where organic matter accumulation in surface horizons and clay translocation to deeper layers jointly control the exchange complex (Pinto et al., 2021).

The study of the mineralogical composition showed that kaolinite predominates in the clay fraction of the region's soils, while hydromicas, vermiculite, and chlorite are also present in certain amounts (Table 2). In particular, the relatively higher content of 2:1 type clay minerals (hydromicas, vermiculite) in the B horizons contributes to maintaining CEC at a certain level.

Table 2
Mineralogical composition of soils (clay fraction, %)

Soil type	Horizon	Kaolinite %	Hydromica (%)	Vermiculite %	Chlorite %	Quartz %	Iron oxides %
Yellow soils	A_1	45–50	15–20	5–8	3–5	10–15	8–12
	B	40–45	18–22	6–10	4–6	8–12	10–15
Podzolized yellow soils	A_1	48–52	12–16	4–6	2–4	12–16	6–10
	B	42–46	16–20	8–12	5–8	8–12	10–14
Brown forest soils	A_1	35–40	22–26	10–14	6–8	10–14	4–6
	B	32–36	24–28	12–16	8–10	8–12	5–8

The analysis of mineralogical composition indicates that the content of hydromica and vermiculite is higher in mountain brown forest soils compared to yellow soils. This is one of the reasons for the higher CEC values observed in these soils. Although kaolinite has a relatively low CEC (2–15 cmol/kg), the presence of 2:1 type clay minerals contributes to an increase in overall CEC.

Table 3
Changes in anion exchange capacity (AEC) at different pH values (mg/kg)

Soil type	AEC at pH 4.0	AEC at pH 5.0	AEC at pH 6.0	AEC at pH 7.0
Yellow soils	485 ± 42	425 ± 38	345 ± 32	255 ± 28

Podzolized yellow soils	395 ± 35	335 ± 30	275 ± 26	205 ± 22
Mountain brown forest soils	285 ± 26	245 ± 24	195 ± 20	145 ± 16

The study of AEC at different pH values further confirms this relationship (Table 3). In all soil types, as pH increases from 4.0 to 7.0, AEC decreases approximately twofold. The most pronounced decrease is observed in yellow soils (from 485 mg/kg to 255 mg/kg). This strong pH dependence of AEC is attributed to the variable charge characteristics of iron and aluminum oxides (sesquioxides), which dominate the exchange complex in highly weathered subtropical soils. At low pH, protonation of these oxide surfaces creates positive charges capable of retaining anions, while increasing pH promotes deprotonation and subsequent reduction in anion retention capacity (Gomes et al., 2022).

Table 4
Dependence of CEC and AEC on soil texture

Texture class	Physical clay (<0.01 mm, %)	CEC (cmol/kg)	AEC (mg/kg)
Sandy	<10	8.5 ± 1.2	185 ± 22
Sandy loam	10–20	14.2 ± 1.8	245 ± 28
Loam	20–30	20.5 ± 2.4	295 ± 32
Clay loam	30–40	26.8 ± 3.0	335 ± 35
Clay	>40	32.5 ± 3.5	385 ± 40

A strong relationship was established between soil texture and ion-exchange capacity. The results show that as the proportion of the physical clay fraction increases, both CEC and AEC increase consistently (Table 4).

Table 5
Comparison of ion-exchange properties across elevation belts

Indicators	Lower belt (0–400 m)	Middle belt (400–1000 m)	Upper belt (1000–1600 m)
CEC (cmol/kg)	18.5 ± 2.1	26.5 ± 3.2	32.5 ± 3.5
AEC (mg/kg)	425 ± 35	280 ± 30	195 ± 20
Humus (%)	5.2 ± 0.8	6.5 ± 0.9	7.5 ± 1.0
pH	4.8 ± 0.2	5.1 ± 0.3	5.8 ± 0.3
Ca^{2+} (cmol/kg)	10.2 ± 1.2	14.5 ± 1.6	16.5 ± 1.8
Base saturation (%)	72.5 ± 4.5	78.5 ± 5.0	88.5 ± 5.2
Fe_2O_3 (%)	8.5 ± 1.2	6.2 ± 0.9	4.5 ± 0.7

Significant differences in ion-exchange properties are observed across elevation belts (Table 5). With increasing altitude, CEC, humus content, pH, and base saturation increase, whereas AEC and iron oxide content decrease.

Conclusion

The study revealed that the ion-exchange properties of mountain-forest soils in the Lankaran–Astara region follow the patterns of vertical zonation. The cation exchange capacity (CEC) ranges from 11.5 to 32.5 cmol/kg. The highest value (32.5 cmol/kg) was recorded in the upper mountain belt (1300–

1600 m), in the humus horizon of mountain brown forest soils, which is associated with high humus content (7.5%) and the dominance of 2:1 clay minerals (illite and vermiculite). In the lower belt (0–400 m), yellow soils show lower CEC values (18.5 cmol/kg), where kaolinite prevails. The anion exchange capacity (AEC) varies between 155 and 445 mg/kg. The maximum value (445 mg/kg) is observed in the B horizon of yellow soils, which is related to the high content of iron oxides (10–15%). An inverse relationship exists between AEC and pH: at pH 4.0, AEC is 485 mg/kg, while at pH 7.0 it decreases to 255 mg/kg. As the content of the physical clay fraction increases, both CEC and AEC also increase. In heavy clay soils (>40% physical clay), CEC reaches 32.5 cmol/kg, while AEC is 385 mg/kg. With increasing altitude, CEC (from 18.5 to 32.5 cmol/kg), humus content (from 5.2% to 7.5%), pH (from 4.8 to 5.8), and base saturation (from 72.5% to 88.5%) increase, whereas AEC decreases (from 425 to 195 mg/kg). The study of the ion-exchange properties of soils in the region is of great importance for assessing their fertility potential, optimizing fertilization systems, and planning meliorative measures.

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

1. Arinushkina, E. V. (1970). *Guide to Chemical Analysis of Soils*. MSU.
2. Babayev, M. P., Jafarova, Ch. M., & Hasanov, V. H. (2017). *Azərbaycan torpaqlarının müasir təsnifatı* (Modern Classification of Soils of Azerbaijan*)*. Elm.
3. Bhattacharyya, T., Pal, D. K., Chandran, P., & Ray, S. K. (2020). Clay mineralogy and cation exchange capacity of soils under different land use systems in tropical and subtropical regions. *Catena*, *194*, 104710.
4. Blombak, K., & Maclaurin, D. (1956). Methods for determining the phosphate-fixing capacity of soils. *Pochvovedenie*, 5, 45–52.
5. Bradl, H. B. (2004). Adsorption of heavy metal ions on soils and soil constituents. *Journal of Colloid and Interface Science*, *277*(1), 1–18. https://doi.org/10.1016/j.jcis.2004.04.005
6. Coppola, E., & Mollo, L. (2019). Cation exchange capacity in forest soils: A review of determining factors and estimation methods. *Geoderma*, *348*, 1–12.
7. Gedroiz, K. K. (1955). *Selected Works* (Vol. 2). Selkhozgiz.
8. Gomes, J. F., Oliveira, M. L., & Schwantes, D. (2022). Anion exchange capacity in highly weathered subtropical soils: Relationship with iron and aluminum oxides and organic matter. *Journal of Soils and Sediments*, *22*(4), 1125–1138.
9. Gahramanov, N. A. (2015). *Ecological Assessment of Soils of Azerbaijan*. ASPU.
10. Guliyev, I. A. (2018). *Torpaqşünaslıq* (Soil Science). Elm.
11. ISRIC. (2002). *Procedures for Soil Analysis*. International Soil Reference and Information Centre.
12. Ismayilov, A. I. (2012). *Soil Formation Processes in the Subtropical Zone of Azerbaijan*. Elm.
13. Kachinsky, N. A. (1958). *Mechanical and Microaggregate Composition of Soils and Methods of Its Study*. USSR Academy of Sciences.
14. Khidirov, K. A. (2010). *Agrochemical Properties of Soils of the Lankaran Region*. Nurlan.
15. Mammadov, G. Sh. (2002). *Lənkəran bölgəsinin torpaq örtüyü* (Soil Cover of the Lankaran Region). Elm.
16. Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, *15*(12), 1409–1416. https://doi.org/10.1080/00103628409367568
17. Munsell Color Company. (2000). *Munsell Soil Color Charts*.

18. Pinto, L. C., Mello, C. R., Owens, P. R., & Norton, L. D. (2021). Spatial variability of cation exchange capacity in mountain forest soils: The role of altitude, vegetation, and soil organic matter. *Journal of South American Earth Sciences*, *108*, 103198.
19. Sparks, D. L., Page, A. L., Helmke, P. A., & Loeppert, R. H. (1996). *Methods of Soil Analysis. Part 3: Chemical Methods*. SSSA.
20. Sposito, G. (2008). *The Chemistry of Soils*. Oxford University Press.
21. Tan, K. H. (1998). *Principles of Soil Chemistry*. Marcel Dekker.
22. Van Reeuwijk, L. P. (2002). *Procedures for Soil Analysis* (6th ed.). ISRIC.