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Mineralogical and geochemical indicators to determine the usage of Abbasabad bentonite, Saveh, Iran

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ABSTRACT

Bentonite is a rock type primarily composed of the clay mineral montmorillonite. Due to its unique properties, bentonite has a wide range of applications across various industries. The Abbasabad bentonite deposit is located within the Urmia-Dokhtar volcanic belt, and its parent rock is Eocene andesite. A total of 29 samples were analyzed for their major oxides using the X-ray fluorescence (XRF) method, and 25 samples were subjected to qualitative and quantitative mineralogical analysis via X-ray diffraction (XRD). The mineralogical composition of Abbasabad bentonite consists of 19% quartz, 16% plagioclase, 6% potassium feldspar, 16% calcite, 17% cristobalite, 21% clay minerals, with the remaining 5% comprising other minerals. Additionally, 44% of the bentonite samples demonstrated an enrichment in quartz and clay minerals, while 100% of the samples exhibited a depletion of plagioclase and potassium feldspar compared to the parent andesite rock. Approximately 86% of the original andesite rock has undergone alteration into dacite, rhyolite, and trachyte rocks due to the process of chemical weathering. Based on the ratio of CaO to Na2O (equal to 3.79), Abbasabad Bentonite is classified as a calcium-type bentonite. The comparison of the chemical weathering index suggests that the bentonite is a result of intense weathering processes. Furthermore, the results of a student's t-test comparing the chemical composition of Abbasabad bentonite to that used in agriculture, livestock, poultry, drilling, and ceramic industries indicate that Abbasabad bentonite is suitable for agricultural applications.

Keywords: *Geochemistry, Bentonite, Mineralogical index, Enrichment index, Abbasabad Saveh.*

1. Introduction

Bentonite is a type of rock primarily composed of the clay mineral montmorillonite. Montmorillonite belongs to the smectite group and forms as a result of the chemical weathering of volcanic rocks. Bentonite itself originates from the diagenetic alteration of volcanic glass in aquatic environments, hydrothermal alteration of volcanic material, and from smectite-rich sediments in saline lake (playa) and sabkha settings [1, 2]. Due to its distinctive properties such as softness, swelling capacity, colloidal behavior, water absorption, plasticity, adhesiveness, and stickiness, bentonite is utilized in a wide range of industrial applications [3, 4]. Currently, over 100 industrial uses for bentonite have been documented [5, 6]. These include, but are not limited to: drilling muds, binders in foundry sands, liners for preventing water infiltration in dams, canals, and ponds, clarification agents for liquids (especially fruit juices), water purification, smoothing agents for paraffin and other liquids, iron ore pelletizing, animal feed additives, carriers in paints and agrochemicals, fillers in paper and paint industries, soap and detergent production, ceramic body and glaze formulation, agricultural pesticides, pharmaceuticals, filtration media, catalysts, decolorizing agents for industrial, petroleum, and edible oils, separation of gums from gasoline, treatment of acid sludge from oil refining, use in sericulture, and fire suppression or wall sealing in coal mines to prevent spontaneous combustion [7, 8, 9].

The chemical composition of bentonite derived from volcanic rocks can vary between geographic regions, though it tends to be consistent within any single locality [10]. In general, the levels of sodium and potassium oxides are low in bentonites from Iran, the United States, and India [11], with sodium typically present in higher concentrations than potassium [12]. Among bentonite deposits, those dominated by calcium are more common than sodium-rich types. The exchangeable cations in bentonite include sodium, potassium, magnesium, lithium, and hydrogen [13]. Based on their chemical composition and swelling capacity, bentonites can be classified into several types: Na-Ca bentonites (moderate swelling), Ca-bentonites (low swelling), Na-bentonites (high swelling), and K-bentonites (low swelling) [1].

Bentonites have a volcanic origin and typically form along fault zones in a region [14, 15], primarily through the alteration of volcanic rocks and tuffs [16, 17]. This study investigates the various applications of bentonite from the Abbasabad region in Saveh by analyzing its mineralogical composition, chemical characteristics, and geological origin.

2. Geology of the area

The Abbasabad bentonite deposit is situated in the central segment of the Urmia-Dokhtar magmatic belt, which represents the most significant zone in Iran for the formation of hydrothermal, magmatic, and weathering-related non-metallic mineral deposits, including bentonite (Fig. 1). Extending approximately 1,500 kilometers from the northwest to the southeast of Iran, this belt was formed as a result of subduction processes associated with calc-alkaline magmatism [18]. In addition to bentonite, this region hosts related mineralization's such as kaolinite and copper-gold (Cu-Au) deposits, particularly concentrated

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in the central section of the belt. The characteristic lithology of the Urmia-Dokhtar belt are predominantly Eocene to Miocene andesitic volcanic rocks, accompanied by intrusive bodies ranging in composition from diorite to granite [19]. These volcanic rocks occur at shallow depths as intrusive masses, lava flows, pyroclastic materials, and ignimbrites, and exhibit a compositional spectrum from basalt to rhyolite (Fig. 2).

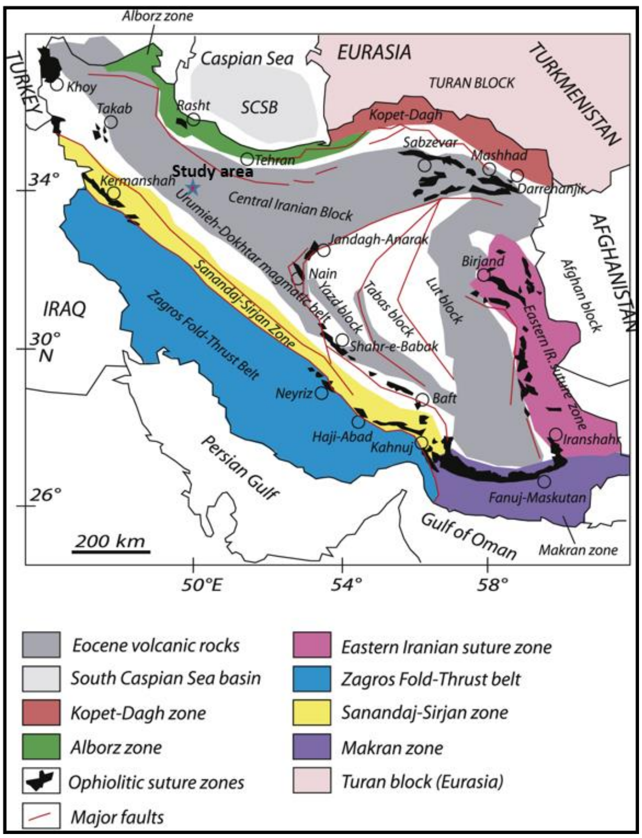
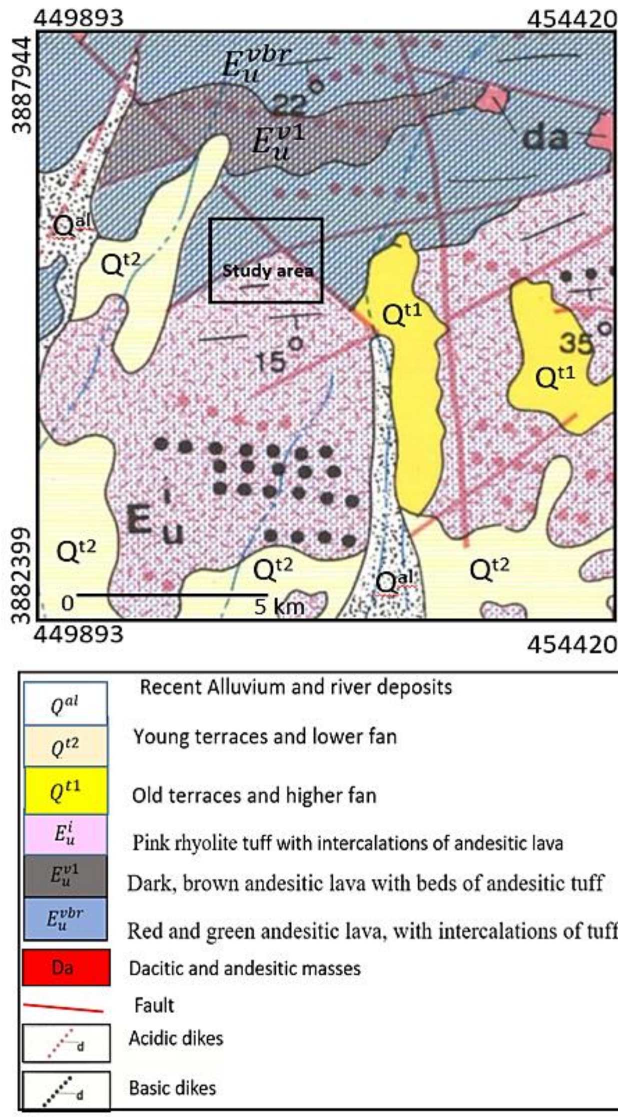


Fig. 1. Geological belts of Iran [18].

Bentonite deposits in Iran are primarily concentrated in six distinct regions: Semnan-Trud, Alborz-Azerbaijan, Eastern Iran, Tafresh-Talkhab, and Zagros. The Abbasabad bentonite deposit, in particular, is associated with Cenozoic volcanic activity [10] and is situated within the Tafresh-Talkhab bentonite zone (Fig. 3). Iran's bentonite deposits are concentrated in six areas: Semnan-Trud, Alborz-Azerbaijan, Eastern Iran, Tafresh-Talkhab and Zagros. The Abbasabad bentonite are mainly related to Cenozoic volcanic activities [10] and is located in Tafarsh-Talkhab bentonite zone (Fig. 3).

3. Research method

In this study, five primary trenches were excavated in the Abbasabad bentonite deposit, from which a total of 28 samples were collected at various depths and lengths within the bentonite layers (from the surface to the depth of the trench and from the beginning to the end of the trench containing bentonite). Additionally, one sample was obtained from the underlying andesite rock (Fig. 4). A total of 29 samples were subjected to chemical composition analysis using the X-ray fluorescence (XRF) method, while 25 samples were analyzed for their mineralogical composition through a semi-quantitative approach using X-ray diffraction (XRD) [21]. To evaluate the degree of alteration in the bentonites, indices such as the lithological change index, mineralogical enrichment index, and weathering index were applied. Furthermore, to assess the quality of the bentonite, the chemical composition enrichment index was calculated, and the student's t-test was employed to compare bentonite quality across various applications.



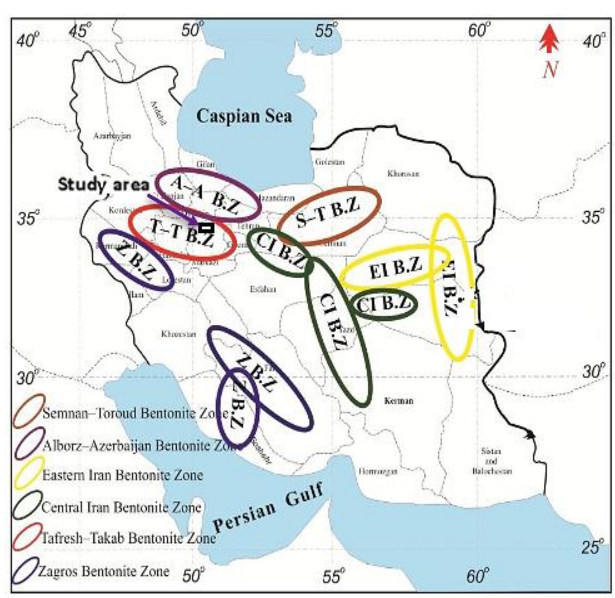


Fig. 3. Distribution of bentonite deposits in Iran [20].

Fig. 4. The trench for taking samples from Abbasabad bentonite.

4. Results and discussion

4.1. Lithological change Index

The mineralogy of bentonite plays a crucial role in understanding its source rocks [22]. This study reveals that the average mineral composition of Abbasabad bentonite consists of 19% quartz, 16% plagioclase, 6% potassium feldspar, 16% calcite, 17% cristobalite (due to the volcanic nature of the rocks in the region and the porphyry texture, it can be said that cristobalite is derived from the crystallization of a glassy matrix) [22], 21% clay minerals, and 5% other minerals (Figs. 5, 6). The distribution of these minerals, as shown in the maximum, minimum, and median values in Fig. 5, indicates that the clay minerals in the bentonite vary between a minimum of 11% and a maximum of 28% across the 25 samples. Furthermore, the average ratio of plagioclase to potassium feldspar is 2.7, suggesting that the bentonite is relatively rich in plagioclase.

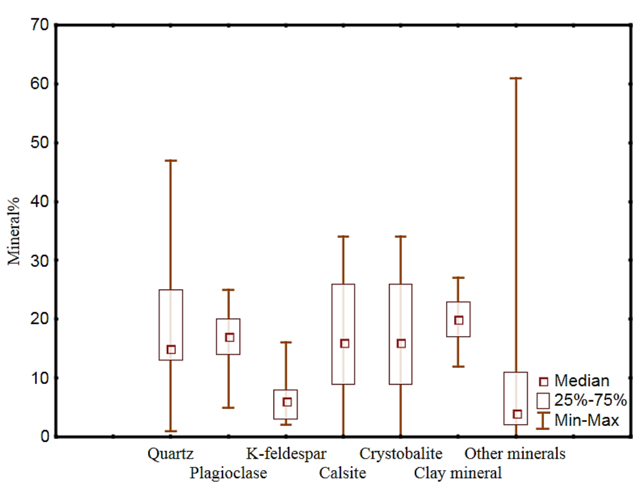


Fig. 5. Description of mineralogical composition of Abbasabad bentonite.

The percentages of the three key minerals quartz, plagioclase, and potassium feldspar were determined using the modal method (QAPF) [23]. According to the results shown in Fig. 7, the decomposed volcanic rocks include rhyolite, dacite, andesite, basalt, and latite. The analysis indicated that 11% of the primary andesite has altered to latite, 39% to rhyolite, 36% to dacite, and 14% has remained as unaltered andesite, based on the mineral content of quartz, plagioclase, and potassium feldspar. In other words, 86% of the primary andesite rock has undergone mineralogical alteration during the decomposition process. Specifically, 75% of the primary rock has been transformed into acidic rocks, while 25% has changed into intermediate rocks in the Abbasabad bentonite deposit.

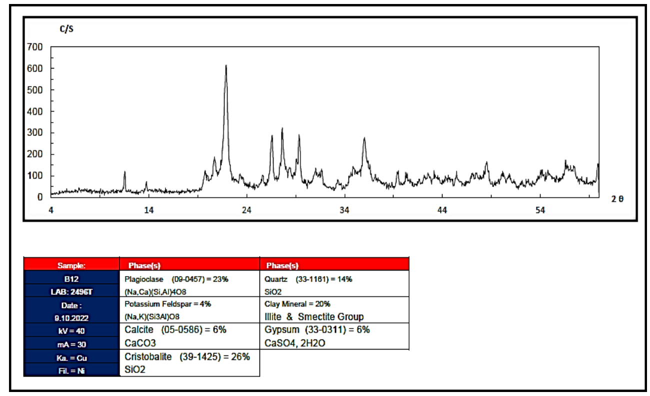


Fig.6. XRD diagram of Abbasabad bentonite with qualitative and quantitative representation (%) of main and secondary minerals in the rock.

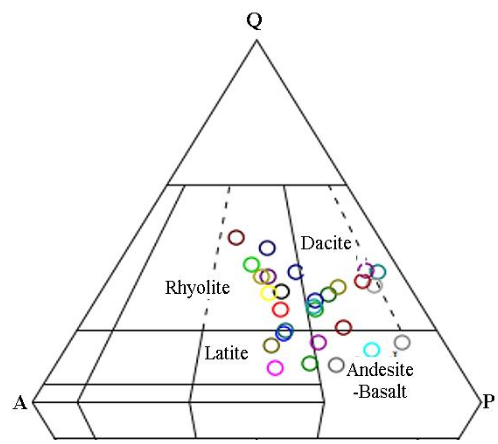


Fig. 7. Lithological composition of Abbasabad bentonite (Q: Quartz; A: Alkali- feldspar; P: Plagioclase).

4.2. Mineralogical enrichment

Mineralogical enrichment is calculated by determining the ratio of bentonite minerals to the minerals of the primary rock (andesite). The mineralogical composition of andesite consists of 14% quartz, 47% plagioclase, 23% potassium feldspar, and 16% clay minerals (Fig. 8A and B). Notably, 100% of the plagioclase and potassium feldspar minerals are depleted in the altered bentonite compared to the primary andesite rock (Fig. 8C, D).

The average mineralogical composition of 25 samples from the Abbasabad bentonite (A) (Table 1) was compared with a reference bentonite (B) [24] using the student's t-test. The calculated t-value is 0.38, while the critical t-value (with 12 degrees of freedom) is 1.78. Since the calculated t-value is smaller than the critical t-value, it can be concluded that the Abbasabad bentonite is comparable to the reference bentonite in terms of mineralogical composition. Furthermore, with a p-value of 0.71, which is greater than the significance level of 0.05, it is confirmed that Abbasabad bentonite qualifies as a true bentonite rock.

This study demonstrates that the Abbasabad bentonites have a volcanic origin, dating to the Eocene epoch. The volcanic rock present in the deposit is andesite, composed of quartz, plagioclase, potassium feldspar, calcite, cristobalite, and clay minerals, and is classified as a calcium-type bentonite. While some bentonites may share similar lithological and mineralogical compositions with those of Abbasabad, they differ in terms of their formation processes. For instance, the Eocene-aged bentonites of the Tashtab Mountains (Khor), located east of Isfahan, are derived from basalt and andesite, and contain clay, quartz, calcite, and cristobalite minerals to those found in Abbasabad bentonite. However, unlike Abbasabad bentonite, the Tashtab bentonites are of the sodium type and are formed through hydrothermal processes [25].

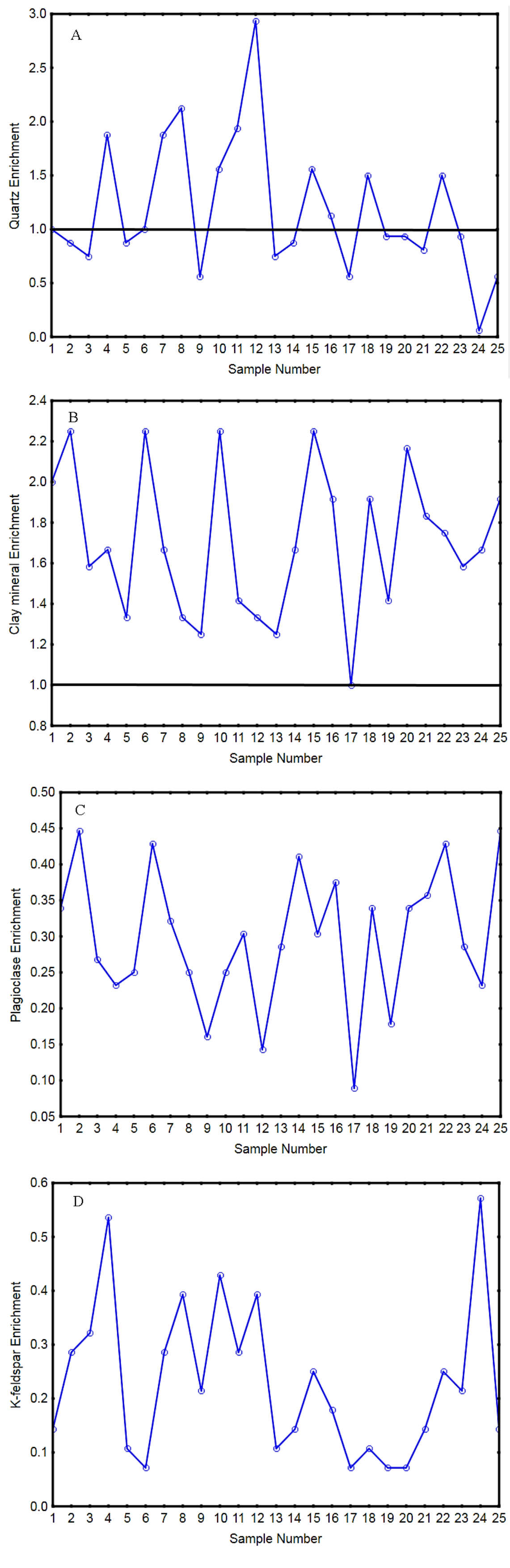


Fig. 8. Enrichment of bentonite minerals related to andesite mineral.

4.3. Bentonite chemical composition

Table 2 and Fig. 9 provide a summary of the chemical composition and statistical analysis of 29 bentonite samples from the study area. The results indicate that the average values of Na_2O and CaO, which are crucial for determining the type of bentonite, are 1.82% and 6.90%, respectively. This gives a CaO to Na_2O ratio of 3.79, confirming that the Abbasabad bentonite is of the calcium-rich type. The minimum and maximum ratios of CaO to Na_2O are 2.41 and 8.63, respectively. A comparison of the chemical composition of Abbasabad bentonite with that of bentonites from other countries is presented in Table 3. This comparison reveals that the chemical composition of Abbasabad bentonite is similar to that of bentonite from England, with both being primarily of the calcium type. In all the regions considered, the amount of sodium bentonite is comparable and lower than that of calcium bentonite. Additionally, the concentrations of aluminum oxide and silicon dioxide exceed 10% and 50%, respectively (Fig. 10).

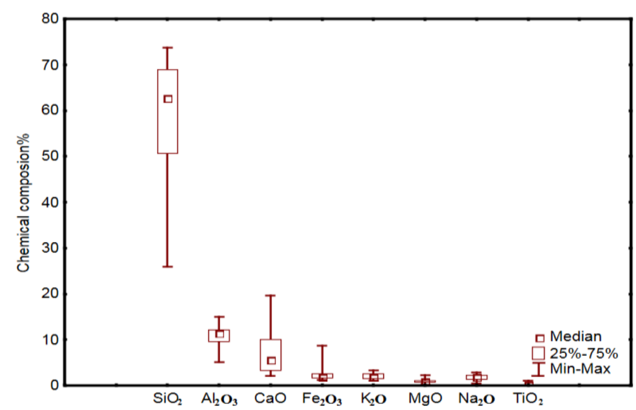


Fig. 9. Statistical description of the chemical composition of Abbasabad bentonite.

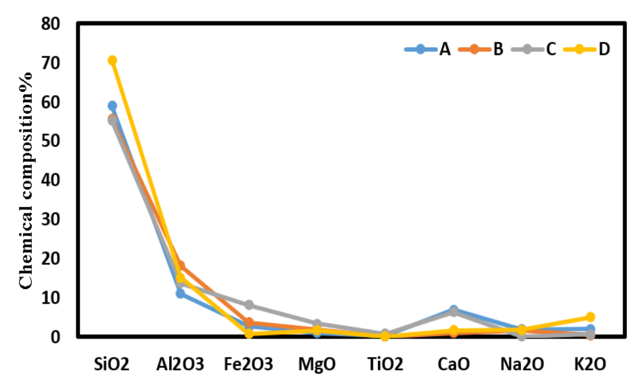


Fig. 10. Chemical composition comparison of Abbasabad bentonite with bentonite of other countries (A: Abbasabad; B: Wyoming US.; C: England; Central Anatoly Turkish) [26].

4.4. Weathering index

The Chemical Weathering Index (CIW) is used to quantify the extent of chemical weathering by employing the ratio $100 \times Al_2O_3 / (Al_2O_3 + CaO + Na_2O)$ [27]. Potassium is excluded from the formula, as it may be introduced into the rock during potassic metasomatism [27]. The CIW index for the Abbasabad bentonite shows values ranging from a minimum of 11 to a maximum of 26, with an average of 17 (Fig. 11). The triangular diagram (Al_2O_3-CaO-Na_2O) illustrates the progression of chemical weathering (Fig. 11). A higher CIW value indicates an increase in chemical weathering, depletion of alkaline and alkaline earth elements, and the replacement of immobile elements [28]. The comparison of the CIW index in Abbasabad bentonite suggests that the bentonite horizon experienced intense chemical weathering during its formation (Fig. 12).

Table1. Mineralogical composition of Abbasabad bentonite (A) and base bentonite (B).

	Quartz	Plagioclase	K-feldspar	Calcite	Cristobalite	Clay mineral	Other composition
A	19	16	6	16	17	21	5
B	19	2	0	0	4	34	41

Table 2. Statistics summary of chemical composition percentage in Abbasabad bentonite (unite to %).

	Mean	Median	Minimum	Maximum	Standard deviation	Skewness	Kurtosis
SiO_2	59	63	26	74	12	-1.01	0.46
Al_2O_3	11	20	5.14	15	2.18	-0.67	0.62
CaO	6.90	5.51	2.11	19	4.47	1.07	0.70
Fe_2O_3	2.60	1.94	1.18	8.67	1.89	2.26	1.43
K_2O	2.00	1.76	1.03	2.70	0.64	5.33	-1.13
MgO	0.96	0.85	0.47	2.20	0.39	1.84	3.31
Na_2O	1.82	1.92	0.44	2.88	0.68	-0.39	-0.72
TiO_2	0.21	0.10	0.08	1.10	0.26	2.56	5.79

Table 3. Standard chemical composition of four main usages of bentonite**.**

	Ceramics	Drilling	Livestock	Agriculture
SiO_2	47.67	57.58	69.80	60.80
Al_2O_3	37.33	13.30	11.88	11.60
CaO	0.7	6.09	1.73	2.50
Fe_2O_3	0.03	0.69	0.10	0.40
K_2O	0.08	2.38	0.96	2.30
MgO	0.27	2.80	1.42	2.50
Na_2O	0.12	2.78	2.10	2.00
TiO_2	1.55	0.29	0.47	0.50

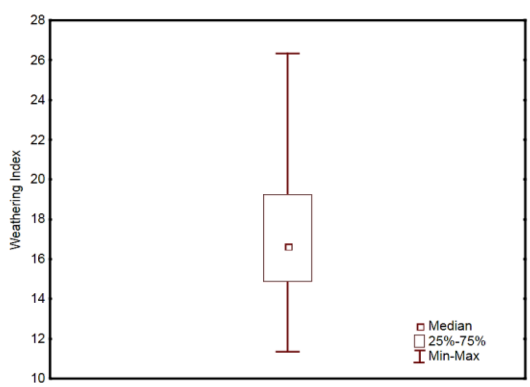


Fig. 11. Weathering index (CIW) in Abbasabad bentonite.

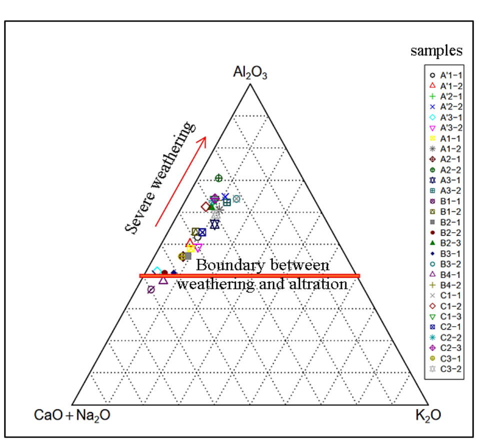


Fig. 12. Weathering index in Abbasabad bentonites.

4.5. Enrichment index

The Enrichment Index is a geochemical parameter used to assess the accumulation of elements or compounds in comparison to reference elements [21]. It allows for the identification of elements that are either enriched or depleted in a specific region. This index is particularly valuable for locating promising areas in mineral exploration [29]. To better classify the Abbasabad bentonite within the region, this index was applied. Fe and Al are used to normalize elements. In this article Fe was used to normalize elements and as reference (neutral oxide) in this method (Equation 1) [30]. In this equation, X represents the concentration of the desired compound in both Abbasabad bentonite and the reference bentonite (Table 3). The quality of the bentonite was then compared with industry standards for various applications, including agriculture, livestock and poultry, drilling, and ceramics (Table 3). The enrichment factors were categorized as follows: very weak enrichment (less than 2), moderate enrichment (between 2 and 5), clear enrichment (between 5 and 20), high enrichment (between 20 and 40), and very high enrichment (greater than 40) (Table 4).

$$EI = \frac{\left(\frac{X}{Fe2O3}\right)sample}{\left(\frac{X}{Fe2O3}\right)Refrence} \quad (1)$$

A statistical average comparison test was employed to determine the similarity or differences in the main chemical composition of Abbasabad bentonite across various applications [32]. The Student's t-test and significance level (P-value) were utilized for this comparison in terms of simple decision-making. The critical Student's t-value (T) is 1.70 with 28 degrees of freedom at a 95% confidence level, and the significance level (P) is set at 0.05. Therefore, if the calculated Student's t-value is lower than the critical t-value and the P-value exceeds 0.05, it indicates that the chemical composition of Abbasabad bentonite is similar to that required for the intended usage. This study found that there is a significant difference between the chemical composition of Abbasabad bentonite (except for SiO_2) and the requirements for ceramic industry, drilling, and livestock and poultry applications (Table 5).

However, the chemical composition of Abbasabad bentonite shows similarity with agricultural usage, particularly in terms of the Al_2O_3, SiO_2, and Na_2O combination. The similarity between Abbasabad bentonite and the chemical composition required for agriculture, ceramics, drilling, and livestock and poultry is 60%, 20%, 20%, and 0%, respectively, at a 95% confidence level. Based on the iron oxide content of the primary rock (andesite) in the study area, it is evident that the enrichment index of SiO_2, Al_2O_3, and Na_2O oxides closely matches that of agricultural bentonite (Table 6). The only notable difference lies in the amount of MgO, while minor differences are observed in the levels of CaO and K_2O (Fig. 13).

Therefore, the enrichment index further supports the findings from the average comparison test, confirming that Abbasabad bentonite is suitable for agricultural use. The Abbasabad bentonite has been identified as calcium-rich and primarily suitable for agricultural use, based on a comparison of its chemical composition with that of four different usage types through the student's t-test. Sodium bentonite, in contrast to calcium bentonite, is known for its high swelling capacity. When mixed with water, sodium bentonite can expand up to fifteen times its original volume, giving it a significant absorption capacity. This characteristic makes sodium bentonite particularly useful in drilling mud for oil exploration. On the other hand, calcium bentonite, which is non-swelling, does not expand as much as sodium bentonite but retains high absorption properties. In addition to its various applications, calcium bentonite is used as a soil conditioner in agriculture, where it improves soil fertility and productivity by enhancing water retention and nutrient availability [31]. The investigation of the lithological index indicates that the source rock of Abbasabad bentonite is primarily volcanic in origin, consisting mainly of rhyolite and dacite. Under conditions of intense weathering, pelagic feldspar minerals have decomposed into clay minerals, transforming these rocks into calcium bentonite in the Abbasabad region. The chemical analysis of Abbasabad bentonite shows a CaO to Na_2O ratio of 3.79, indicating that it is comparable to calcium bentonite found in England. With a CaO content of 6.90%, Abbasabad bentonite is similar to bentonite used in drilling mud; however, due to the presence of compounds such as SiO_2, Al_2O_3, and Na_2O, it has been determined that Abbasabad bentonite is more suitable for agricultural applications.

Table 4. Enrichment ratio of main chemical compounds in different usages of Abbasabad bentonite mine.

	Ceramics	Drilling	Livestock	Agriculture
SiO_2	0.44	3.15	0.74	1.23
Al_2O_3	0.10	2.42	0.77	1.14
CaO	26	7.39	5.21	3.14
K_2O	0.37	17.25	5.02	4.11
MgO	1.03	0.88	0.49	0.40
Na_2O	4.54	1.67	0.63	0.95
TiO_2	1.84	0.78	1.52	0.00

Table 5. Comparison of Abbasabad bentonite chemical composition with four different usages by student's t- test and significance level (P-value) at 95% probability level.

	Ceramics		Drilling		livestock		Agricultural	
	T	P	T	P	T	P	T	P
SiO_2	0.79	0.43	0.79	0.44	0.65	0.00	0.64	0.52
Al_2O_3	5.70	0.00	5.70	0.00	0.20	0.04	1.50	0.14
CaO	5.44	0.00	5.44	0.00	0.16	0.00	5.54	0.00
Fe_2O_3	33	0.00	33	0.00	0.90	0.01	3.45	0.00
K_2O	14	0.00	14	0.00	13	0.00	12	0.00
MgO	25	0.00	25	0.00	0.21	0.00	20	0.00
Na_2O	7.63	0.00	7.61	0.00	0.24	0.00	1.45	0.16
TiO_2	42	0.00	42	0.00	0.74	0.00	20	0.00

Table 6. Enrichment index of agricultural bentonite and Abbasabad bentonite.

	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	TiO_2
Abbasabad bentonite	1.63	1.47	1.45	1.00	0.98	8.07	5.94	0.56
Agricultural bentonite	1.32	1.29	0.38	1.00	0.2	1.6	5.44	1.32

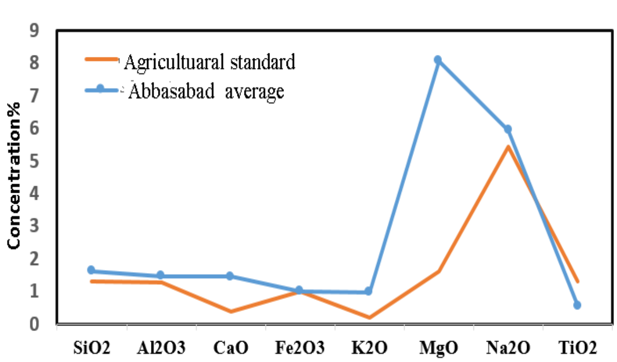


Fig. 13. Changes in chemical composition of Abbasabad bentonite with agricultural standard.

5. Conclusion

The results of the student's t-test, conducted for agricultural, livestock and poultry, drilling, and ceramic industry applications at a 95% confidence level, revealed that the greatest similarity of Abbasabad bentonite is with agricultural, livestock and poultry, and drilling applications, in that order. Therefore, the primary application of Abbasabad bentonite is currently in agricultural programs. Agricultural bentonite plays a significant role in enhancing the performance of crops, both agricultural and horticultural, improving soil productivity, and optimizing the use of chemical and animal fertilizers. Additionally, bentonite sulfur, present in agricultural fertilizers, helps decrease the pH of agricultural land while also increasing both the quantitative and qualitative yield of crops. Calcium bentonite improves water retention and reduces water consumption in arid regions. It is commonly used in the preparation of agricultural fertilizers, particularly bentonite sulfur, which is considered one of the best sulfur fertilizers. Based on the comparison of Abbasabad bentonite with industry standards for bentonite applications, it is recommended that Abbasabad bentonite be utilized primarily for agricultural purposes.

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