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Review Article

Geological Occurrence, Mineralogical Characteristics, Industrial Applications, and Development Potential of Ethiopian Bentonite Deposits: A Review

Kisa Workineh*, Getnet Belachew, Abinet Markos

Geological Institute of Ethiopia, Addis Ababa, Ethiopia

Abstract

Ethiopia hosts substantial bentonite resources totaling over 141.5 million tonnes, distributed across the Cenozoic Afar Depression and the Main Ethiopian Rift. This comprehensive review systematically synthesizes the geological occurrence, mineralogical and chemical characteristics, physical properties, industrial application suitability, and development potential of Ethiopian bentonite deposits. Major deposits include Gewane (77.03 Mm^3 / ~70 Mt), Warseiso (7.01 Mm^3), Ledi (1.78 Mm^3), Hadar Basin (Kada Hadar & Ounda Hadar, 0.93 Mm^3), and Gidicho Island (>9.4 Mt / 3.46 Mm^3), all formed through the low-temperature alteration and diagenesis of Cenozoic volcanic ash and vitric tuff in alkaline lacustrine environments. Mineralogically, X-ray diffraction (XRD) demonstrates that Ethiopian bentonites are predominantly calcium montmorillonite (Ca-montmorillonite) accompanied by minor kaolinite, quartz, albite, and trace zeolites. Complete major oxide geochemistry by XRF reveals SiO_2 contents ranging from 48.78% to 61.93% and Al_2O_3 from 11.06% to 16.40%, with distinct Na_2O/CaO zonation reflecting alkaline depositional water chemistry. Physicochemical testing indicates exceptionally high cation exchange capacity (CEC) values ranging from 77.0 meq/100g (Gidicho) to 82.1 meq/100g (Warseiso), exceeding standard commercial calcium bentonites. Natural swelling indices reach 17.1 mL/2g for Gidicho bentonite, which competes closely with international drilling-mud benchmarks. Beneficiation and chemical activation pathways including sodium carbonate activation for API 13A drilling muds, acid activation (0.8M HCl) for bleaching earth and catalysis, and thermal activation (300 ℃) for surface area expansion (increasing from 57.6 to 81.74 m^2/g) substantially upgrade industrial performance. Systematic evaluation against international standards (API 13A/ISO 13500, UNIDO, JB/T 9227) confirms high suitability for drilling fluids, foundry sands, iron-ore pelletizing, civil engineering sealants, and environmental sorbents. Strategic domestic exploitation can completely replace expensive imports, conserve foreign currency, foster regional industrial growth, and drive value-added mineral export development in East Africa.

Keywords

Bentonite, Montmorillonite, Afar Depression, Industrial Minerals, Acid Activation

*Correspondence: Kisa Workineh (kisaregasa@gmail.com)

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1. Introduction

Bentonite is a versatile industrial clay mineral composed predominantly of smectite-group minerals, primarily montmorillonite [1, 2]. Its unique physicochemical properties including a high specific surface area, permanent layer charge, significant cation exchange capacity (CEC), thixotropic rheology, and remarkable hydration and swelling capacity make it an indispensable raw material in oil and gas drilling, foundry sand binding, iron-ore pelletizing, edible oil refining (bleaching earth), civil engineering barriers, agriculture, and wastewater remediation [1-4]. The fundamental performance of bentonite in these diverse industrial applications is governed by the structural characteristics of its smectite constituent, particularly the nature of the dominant exchangeable interlayer cation (Na^+ vs. Ca^{2+}) and the degree of layer charge substitution [1, 5].

In Ethiopia, extensive Cenozoic volcanism associated with the evolution of the East African Rift System (EARS) created ideal conditions for the formation of substantial bentonite deposits [6-8]. Explosive pyroclastic eruptions deposited vast blankets of vitric volcanic ash and tuff into alkaline lacustrine and fluvio-lacustrine basins throughout the Afar Depression and the Main Ethiopian Rift (MER) [6, 9]. Subsequent diagenetic and low-temperature hydrothermal alteration converted these volcanic glass precursor materials into extensive smectite-rich clay horizons [3, 7]. Historical exploration by the Geological Survey of Ethiopia (GSE) and the United Nations Industrial Development Organization (UNIDO) established a combined calculated reserve of over 86 million m^3 (~140 million tonnes) across major deposits including Gewane, Warseiso, Ledi, Hadar, and Gidicho Island [7, 9, 10]. Recent field mapping and laboratory characterizations have further expanded this resource base with new discoveries in Chacha (Amhara Region), Burji (Southern Ethiopia), and Degele Ruso (Wolayta/Arba Minch) [11-13].

Despite hosting these massive industrial mineral reserves, Ethiopia historically imported thousands of tonnes of processed bentonite and activated bleaching earth annually to meet the growing demands of its domestic petroleum exploration, edible oil refining, steel casting, and construction sectors [7, 14]. This reliance on imported bentonite represents a substantial drain on foreign currency reserves. Unlocking the full economic potential of Ethiopian bentonite requires a rigorous, integrated understanding of deposit geology, spatial distribution, smectite mineralogy, complete major-oxide geochemistry, and physical performance metrics, coupled with targeted beneficiation and chemical activation technologies [3, 8, 15].

This review systematically synthesizes available geological, mineralogical, chemical, and technological datasets for Ethiopian bentonite deposits. The principal objectives are to: (1) evaluate the regional geological framework and deposit genesis; (2) detail the spatial distribution and resource tonnage of major and emerging deposits; (3) characterize smectite mineralogy, major oxide geochemistry, CEC, and swelling behavior; (4) evaluate raw and activated bentonites against international industrial standards (API 13A, ISO 13500, UNIDO, JB/T 9227); (5) outline optimal beneficiation and activation pathways (sodium, acid, and thermal processing); and (6) analyze market dynamics, import substitution opportunities, and strategic development recommendations.

2. Regional Geological Framework and Deposit Genesis

2.1. Tectonic Architecture and Rift Volcanism

The geological architecture of Ethiopia is defined by Precambrian basement rocks overlain locally by Mesozoic sedimentary successions and extensive Cenozoic volcanic and sedimentary sequences associated with the East African Rift System [6, 8]. The evolution of the Ethiopian Rift involved major phases of plume-related continental rifting and intense volcanism. According to Kazmin (1975), significant volcanic episodes occurred during the Oligocene (~30–31 Ma), the Miocene (~16–20 Ma), and the Pliocene to Quaternary [16]. These volcanic pulses generated enormous volumes of rhyolitic, dacitic, and basaltic lavas, pyroclastic flows, vitric tuffs, and volcanic ash [6, 16]. Tectonic extension created NNE-trending normal faults and asymmetric grabens that trapped thick volcano-sedimentary sequences [7, 8].

2.2. Depositional Environments and Hydrothermal Alteration

Ethiopian bentonites formed primarily through the diagenetic transformation and low-temperature alteration of glassy volcanic ash and tuff deposited in closed, alkaline lacustrine to fluvio-lacustrine environments [3, 7, 9]. In the Afar Depression and Main Ethiopian Rift, volcanic ash falling into alkaline, silica-saturated lake waters underwent glass hydrolysis and hydration reactions [8, 15]. The dissolution of volcanic glass released Si^{4+}, Al^{3+}, Na^+, K^+, Ca^{2+}, and Mg^{2+} into pore waters. Under alkaline conditions (pH 8.5–10) with restricted drainage and high Mg^{2+}/Ca^{2+} activity, smectite minerals (dioctahedral montmorillonite) precipitated rapidly as the primary stable phase [1, 3, 5]. Local low-temperature hydrothermal activity associated with active rift faulting further promoted smectite crystallization and pore-space alteration [7, 8].

3. Geological Characteristics and Deposit Distribution

Ethiopian bentonite deposits are primarily concentrated in two major rift provinces: the Afar Depression in northeastern

Ethiopia and the Main Ethiopian Rift (MER) in the south-central part of the country [7, 8]. In addition, recent geological reconnaissance has identified active commercial deposits in the Amhara Region, along with emerging prospects in Southern Ethiopia [11, 12], as illustrated in Table 1 and Figure 1.

3.1. Gewane Deposit

The Gewane deposit, located in the Afar Regional State, represents the largest single bentonite resource documented in Ethiopia [7, 9, 10]. Bentonite beds are exposed over an extensive area along the Ambule, Kalhaitu, Aburagarsa, and Tathamatu river valleys [7]. The Ambule River section displays the most prominent bentonite horizon, reaching thicknesses between 10 and 22 m [7, 9]. Historical reserve evaluations by UNIDO (1986) established a proven volume of 77.0346 million m^3 (~70 million tonnes), with an average bed thickness of 11.83 m covering a surface area of approximately 6.51 million m^2 [7, 10]. The overburden averages 14.35 million m^3 (14,354,313 m^3), consisting of stratovolcanics, gravel, and fluvio-lacustrine sediments [7]. Gewane bentonite exhibits a light grey to cream color and high silica content (61.93% SiO_2) [7, 14].

3.2. Warseiso Deposit

The Warseiso deposit is situated 1–3 km north of the Dessie–Assab highway between the Badona River and Warseiso in Afar [7]. The deposit occurs within a fluvio-lacustrine sedimentary sequence intercalated with rhyolite, basalt, volcanic ash, and gravel [7]. Five distinct bentonite blocks have been delineated, comprising grey to greenish-grey clay with low sand content [7, 15]. Total historical reserves are estimated at 7.00666 million m^3, with an average bed thickness of 5.58 m over a surface area of 1.26 million m^2, and 2.45 million m^3 of overburden [7, 10]. Raw Warseiso bentonite possesses an exceptionally high CEC of 82.1 meq/100g [15].

3.3. Ledi Deposit

The Ledi occurrence lies ~20 km south of the Dessie junction near the Ledi River in Afar [7]. Four main occurrences are recognized, consisting of grey-green compact clay to brownish saline bentonitic beds [7]. An outcrop on the northern bank reaches 8.5 m in thickness with zero overburden, while the Huana River exposure averages 7.5 m [7]. The overall reserve is evaluated at 1.784 million m^3, with an average bed thickness of 3.20 m and 1.20 million m^3 of overburden [7, 10]. Ledi bentonite contains elevated Na_2O (1.85%), reflecting a strong sodium-smectite tendency [7].

3.4. Hadar Basin Deposits (Kada Hadar & Ounda Hadar)

The Hadar bentonite deposit occurs along the Kada Hadar and Ounda Hadar river valleys in the Hadar sedimentary basin (famous for the 'Lucy' hominin discovery), approximately 7 km from the Dessie–Assab highway via Ascoma village [3, 7]. Bentonite beds (1.8–2.5 m thick, averaging 4.2 m) occur within Pliocene–Pleistocene lacustrine clays, silts, tuffs, and limestones [3, 7]. The combined proven reserve is 0.92545 million m^3 (925,450 m^3), with ~0.925 million m^3 of overburden [7, 10]. Hadar bentonite is characterized by Na_2O exceeding CaO (sodium bentonite tendency) and contains intermixed zeolites that enhance catalytic properties [3].

3.5. Gidicho Island Deposit (Main Ethiopian Rift)

Located on Gidicho Island in Lake Abaya (Southern Main Ethiopian Rift), this deposit occurs within a Pleistocene lacustrine succession containing diatomite, silt, and diatomaceous earth [8, 17]. Proven reserves total 9.41236 million tonnes (3.46286 million m^3) [7, 8, 17]. The complex includes three major sub-deposits: Shigima (5.700712 Mt), Biaso (3.298368 Mt), and Arura (0.413280 Mt) [7, 8]. Gidicho bentonite is predominantly Ca-montmorillonite with a CEC of 77.0 meq/100g, a natural swelling index of 17.1 mL/2g, a bulk density of 1.64–1.67 g/cm^3, and specific gravity of 2.23–2.40 [8]. It represents the highest-grade raw drilling-mud clay in Ethiopia, competing closely with Russian commercial bentonite [7, 8].

3.6. Emerging Discoveries: Burji, Chacha, Degele Ruso, and Biaso

Recent mineral exploration has revealed major new bentonite occurrences across Ethiopia. In Chacha (Amhara Region), a high-grade montmorillonite deposit (SiO_2 63.03–78.4%, Na_2O/CaO ratio ~1.5) attracted commercial mining by Arerti Ceramics Manufacturing under an 870,000-tonne extraction concession [11]. In Burji Woreda (Southern Ethiopia), geological mapping delineated a significant calcium bentonite deposit of 5.22 million tonnes [7]. Reconnaissance surveys by the Geological Institute of Ethiopia (2025) identified lacustrine bentonites in Degele Ruso (Wolayta/Arba Minch) [13]. In the Mille area, historical bentonite beds serve as reference foundry material [7, 9].

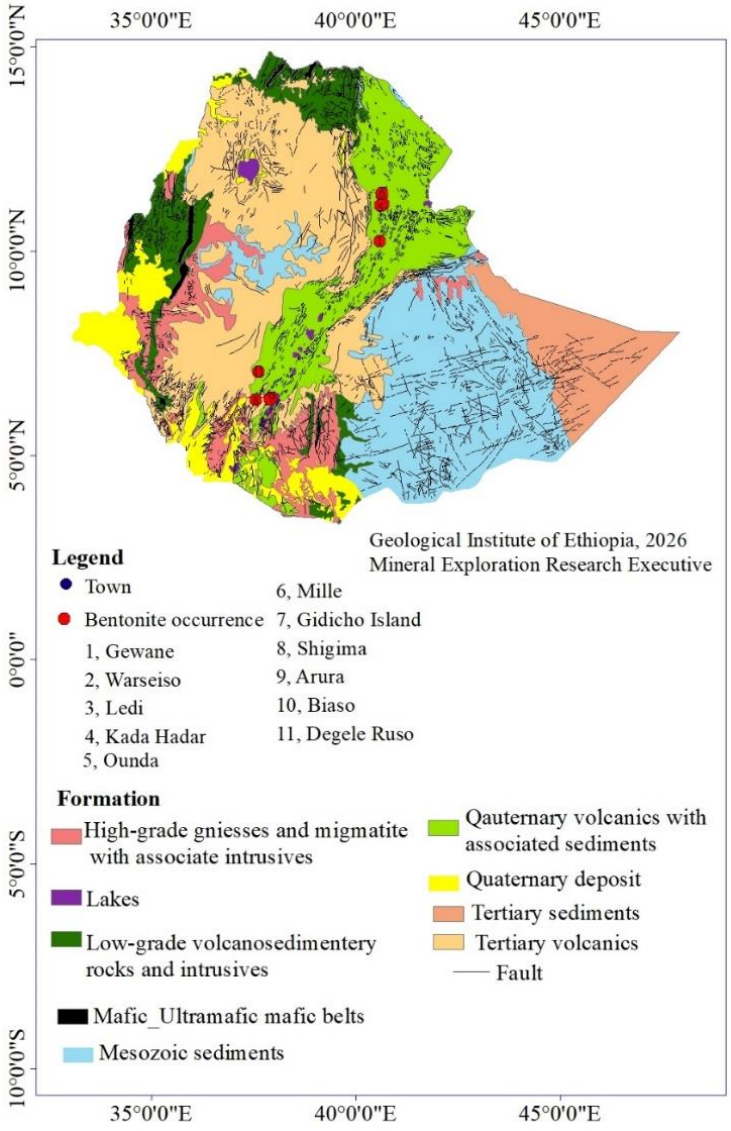


Figure 1. *Map of Ethiopian Bentonite Occurrences.*

Table 1. *Summary of Major Ethiopian Bentonite Deposits and Geological Characteristics.*

Deposit / Occurrence	Region	Resource / Reserve Tonnage	Status	Geological Setting & Characteristics	Source
Gewane	Afar	77.0346 Mm^3 (~70 Mt)	Proven / Major Deposit	Lacustrine beds exposed along Ambule, Kalhaitu, Aburagarsa, Tathamatu. Avg thickness 11.83 m (10–22 m max); overburden 14.35 Mm^3.	[7, 9, 10, 14]
Warseiso	Afar	7.00666 Mm^3	Proven / Exploit-able	Fluvio-lacustrine beds between Badona River & Warseiso. 5 blocks; grey to green clay. Avg thickness 5.58 m; over-burden 2.45 Mm^3. Raw CEC 82.1 meq/100g.	[7, 15, 24]
Ledi	Afar	1.784 Mm^3	Proven Deposit	Lacustrine bentonitic clay near Ledi River. 4 occurrences; outcrop 8.5 m without overburden; Huana River avg 7.5 m. Avg thickness 3.2 m; overbur-den 1.2 Mm^3.	[6, 7, 14]

Deposit / Occurrence	Region	Resource / Reserve Tonnage	Status	Geological Setting & Characteristics	Source
Kada Hadar & Ounda Hadar	Afar	0.92545 Mm^3 (combined)	Proven Deposit	Pliocene–Pleistocene Hadar lacustrine sequence ('Lucy' site). Beds 1.8–2.5 m thick (avg 4.2 m). Zeolite present; Na_2O > CaO.	[3, 7, 14]
Gidicho Island	SNNPR (Main MER)	9.41236 Mt (3.46286 Mm^3)	Proven / Major Deposit	Pleistocene lacustrine bentonite with diatomite & silt in Lake Abaya. Sub-deposits: Shigima (5.70 Mt), Biaso (3.30 Mt), Arura (0.41 Mt). CEC 77 meq/100g, swelling 17.1 ml/2g.	[7, 8, 17, 26]
Mille	Afar	Not established	Reconnaissance	Lacustrine/volcaniclastic materials near Mille. Reference material in foundry binder testing.	[7, 25, 27]
Chacha	Amhara	870,000 t (mining agreement)	Active Mining License	Montmorillonite clay with Na_2O/CaO ~1.5; SiO_2 63.03–78.4%. Arerti Ceramics commercial mining concession.	[11]
Burji Woreda	Southern Ethiopia	5.22 Mt	Emerging Prospect	Calcium bentonite deposit delineated through regional geological and geochemical mapping.	[7]
Degele Ruso	SNNPR (Wolayta/Arba Minch)	Not quantified	Reconnaissance	Lacustrine bentonite identified during Wolayta–Arba Minch industrial mineral exploration.	[13]

4. Mineralogical, Chemical, and Physical Characteristics

4.1. Smectite Mineralogy and Structural Properties

Quantitative X-ray diffraction (XRD) combined with FTIR and SEM-EDS analysis confirms that Ethiopian bentonites are predominantly composed of dioctahedral calcium montmorillonite (Ca-montmorillonite) [3, 8, 15]. The montmorillonite crystal structure consists of 2:1 layer units (two tetrahedral silica sheets sandwiching an octahedral alumina sheet) [1, 5]. Isomorphous substitution of Mg^{2+} for Al^{3+} in the octahedral layer and minor Al^{3+} for Si^{4+} in the tetrahedral layer creates a net negative layer charge (~0.33 per formula unit), balanced by exchangeable interlayer Ca^{2+} and Na^{+} ions [1, 8]. Associated non-clay and secondary clay minerals include minor kaolinite, quartz, albite (plagioclase feldspar), and trace zeolites [3, 8].

Table 2. *XRD Mineralogical Composition and Phase Identification of Ethiopian Bentonites.*

Mineral Phase	Relative Abundance	Ideal Chemical Formula	Structural & Performance Role	Source
Ca-montmorillonite	Major (>75–85%)	$(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$	Primary smectite phase; governs CEC, interlayer hydration, and swelling behavior.	[3, 8]
Kaolinite	Minor (5–12%)	$Al_2Si_2O_5(OH)_4$	Non-swelling 1:1 layer clay impurity; slightly dilutes total expansion capacity.	[8]
Quartz	Minor (3–10%)	SiO_2	Crystalline free-silica contaminant; affects grit content and slurry abrasiveness.	[3, 8]
Albite (Feldspar)	Minor (2–8%)	$NaAlSi_3O_8$	Plagioclase feldspar remnant from primary volcanic ash precursor.	[3]

Mineral Phase	Relative Abundance	Ideal Chemical Formula	Structural & Performance Role	Source
Zeolite	Trace to Minor (0–5%)	Variable aluminosilicate (e.g., Clinoptilolite)	Porous framework silicate phase in Hadar deposit; enhances catalytic/adsorptive surface area.	[3]
Calcite / Gypsum	Trace (< 2%)	$CaCO_3$ / $CaSO_4$ $2H_2O$	Impurities formed during volcanic ash alteration; Structurally, dilute active smectite content and impair functional properties like swelling and rheology, making mineral beneficiation or chemical activation necessary to meet industrial performance standards.	[17]

4.2. Complete Major Oxide Geochemistry

Whole-rock major oxide geochemistry (determined by X-ray fluorescence, XRF) demonstrates that Ethiopian bentonites are aluminum-rich silicates with systematic chemical variations between deposits [3, 7, 8]. Silica (SiO_2) ranges from 48.78% (Kada Hadar) to 61.93% (Gewane), while Al_2O_3 ranges from 10.90% (Gidicho Arura) to 16.40% (Gidicho Biaso) [7, 8]. The alkali and alkaline-earth oxide ratio (Na_2O/CaO) serves as a key geochemical indicator for distinguishing swelling (Na-dominant) from low-swelling (Ca-dominant) bentonites [1, 3, 7]. Afar deposits such as Hadar (Native) exhibit higher Na_2O (2.15%) relative to CaO (~1.52%), displaying a sodium bentonite tendency [3]. In contrast, Gidicho Island deposits contain higher CaO (1.05–2.00%) and MgO (0.90–2.00%), reflecting calcium-montmorillonite characteristics [8]. Gidicho Arura exhibits elevated Fe_2O_3 (13.50%), requiring magnetic or gravity separation [7, 8].

Table 3. *Complete Major Oxide Geochemistry (wt.% oxides) and Geochemical Classification of Ethiopian Bentonites.*

Deposit / Location	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	MnO	Source
Gewane (Afar)	61.93	11.06	6.76	1.06	1.03	2.56	1.68	1.27	0.10	[7]
Warseiso (Afar)	49.00	13.40	8.71	1.61	3.81	2.79	1.10	1.31	0.10	[7]
Kada Hadar (Afar)	48.78	13.42	8.78	1.50	4.12	2.80	1.32	1.40	1.10	[7]
Ounda Hadar (Afar)	54.23	12.90	9.10	1.40	1.90	2.50	1.76	1.10	0.10	[7]
Hadar Native (Afar)	58.18	14.28	6.24	—	<CaO	—	2.15	—	—	[3]
Ledi (Afar)	54.23	12.65	7.75	1.35	3.15	2.80	1.85	1.35	0.10	[7]
Gidicho Shigima (SNNPR)	56.40	14.40	8.30	1.05	2.00	1.60	3.00	1.60	0.19	[7]
Gidicho Arura (SNNPR)	60.80	10.90	13.50	1.09	0.90	1.30	2.20	1.10	0.16	[7]
Gidicho Biaso (SNNPR)	59.40	16.40	8.70	1.04	0.90	1.40	2.40	1.50	0.16	[7]
Chacha (Amhara)	63.03–78.4	10.9–16.4	6.0–9.0	—	0–3.75	0.98–2.89	Na_2O/CaO ~1.5	—	—	[11]

4.3. Cation Exchange Capacity, Swelling, and Physical Properties

Cation exchange capacity (CEC) measures the density of exchangeable cations that balance the negative layer charge, serving as a primary determinant of adsorption efficiency and chemical reactivity [1, 15]. Raw Ethiopian bentonites exhibit remarkably high CEC values, ranging from 77.0 meq/100g for Gidicho Island bentonite to 82.1 meq/100g for raw Warseiso

bentonite [8, 15]. These values match or exceed international commercial benchmarks for calcium bentonites (60–100 meq/100g) [1, 8]. Notably, [15] demonstrated that thermal activation at 300 ℃ for 6 hours reduces the CEC of Warseiso bentonite from 82.1 to 67.2 meq/100g, while simultaneously increasing its specific surface area from 57.6 m^2/g to 81.74 m^2/g [15]. In its raw form, Gidicho bentonite exhibits a natural swelling index of 17.1 mL/2g, an optimum moisture content of 30.1%, a bulk density of 1.64–1.67 g/cm^3, and a specific gravity of 2.23–2.40 [8], as illustrated in Table 4.

Table 4. *Physical Properties, Swelling Index, and Surface Area Characteristics of Ethiopian Bentonites.*

Deposit / State	CEC (meq/100 g)	Swelling Index (mL/2g)	Specific Surface Area (m^2/g)	Optimum Moisture (%)	Bulk Density (g/cm^3)	Specific Gravity	Source
Gidicho Island (Raw)	77.0	17.1	N/A	30.1%	1.64 – 1.67	2.23 – 2.40	[8]
Warseiso (Raw)	82.1	6.5	57.6rface	28.5%	1.58 – 1.62	2.31 – 2.35	[15]
Warseiso (300 ℃ Activated)	67.2	8.0	81.74	22.0%	1.52 – 1.55	2.30	[15]
Ledi River (Raw)	78.5	11.0	SN/A Area (m^2/g)	29.0%	1.60	2.32	[14]
Gewane Deposit (Raw)	74.2	5.5	N/A	31.0%	1.65	2.38	[7]
Hadar Native Clay	79.0	12.5	Significantly Expanded Surface Area (m^2/g)	27.8%	1.59	2.34	[3]
Commercial Benchmark (Ca-Bentonite)	60–100	5–15	40–80	10–15%	0.80–1.20	2.00–2.40	[1]
Commercial Benchmark (Na-Bentonite / API)	80–120	≥ 24	60-120pecific Surface Area (m^2/g)	10–12%	0.70–1.10	2.20–2.60	[18]

5. Industrial Specifications, Beneficiation, and Upgrading Pathways

5.1. Evaluation against International Industrial Standards

To determine the commercial viability of Ethiopian bentonites, raw and activated clays must be evaluated against sector-specific international standards [1, 4, 18, 19].

For drilling fluid applications, the primary technical benchmarks are defined by API Specification 13A and ISO 13500, which require a viscometer dial reading at 600 rpm of at least 30, a yield point to plastic viscosity ratio of 3 or less, an API filtrate fluid loss of no more than 15.0 mL, and a wet residue retention (>75 µm) of ≤ 4.0%. Raw bentonite from Gidicho competes closely with international drilling mud benchmarks, whereas calcium bentonites from Gewane and Warseiso require sodium activation via the addition of 3–5 wt.% soda ash to achieve required API yield points [7, 8].

In bleaching earth production, suitability is evaluated against the UNIDO (1986) standard, which mandates a specific surface area of 250–300 m^2/g, a cation exchange capacity (CEC) of 50–55 meq/100g, a free acidity of ≤0.4 mg KOH/g, a pH of 3.4–3.5, and a filtered oil retention of 40–60%. Clays from Hadar and Warseiso meet or exceed these thresholds following acid activation with 0.8M HCl [3, 15].

Similarly, for foundry sand binders, standards including JB/T 9227-2013 and IS 12446 specify a green compression strength of ≥12.5 psi, a swelling index of 32–35 mL/2g, and fine grinding with ≥85% passing a 75 µm mesh [20, 21]. Unactivated Warseiso and Gewane clays demonstrate high performance as green sand binders under these foundry requirements.

For iron-ore pelletizing, industrial specifications require a methylene blue absorption of ≥350 mg/g, a plate water absorption of ≥600%, and a moisture content of ≤15% [1, 4]. Gewane and Ledi clays possess the high binding strength required to meet these pelletizing standards. Lastly, for civil engineering and environmental sorbent applications, the naturally high CEC of Ethiopian bentonites (77–82.1 meq/100g) provides effective sealing and contaminant retention for geosynthetic clay liners (GCLs), landfill capping, and heavy metal

wastewater adsorption [8, 15, 22], as illustrated in Table 5.

5.2. Beneficiation and Chemical Activation Pathways

Because the majority of Ethiopian bentonite deposits are calcium-dominated, appropriate industrial upgrading pathways are essential to optimize product quality and suit target commercial applications [3, 8, 15]. Primary processing begins with crushing run-of-mine clay, solar or rotary drying to achieve a moisture content of <15%, secondary pulverization, and air classification to obtain a fine powder passing a 75 μm (200 mesh) sieve [14, 15]. The choice between dry and wet beneficiation is governed by deposit purity and operational economics. Dry processing is recommended for clean, high-grade deposits such as those at Gewane, Warseiso, and the main Gidicho beds to minimize water usage and energy costs [7, 10]. Conversely, wet processing—comprising dispersion with 0.2 wt.% sodium hexametaphosphate, hydrocyclone desanding, sedimentation, and dewatering is required for impurity-rich beds, such as Gidicho Arura containing 13.5 wt.% Fe_2O_3, to remove gangue minerals and achieve the required purity [8].

Chemical activation pathways provide the primary mechanism for upgrading low-swelling Ca-bentonites into high-value functional materials. Sodium activation (soda ash treatment) involves adding 3–5 wt.% sodium carbonate (Na_2CO_3) during extrusion or wet mixing to promote $Ca^{2+} \leftrightarrow Na^{+}$ ion exchange. This transformation converts calcium bentonite into a high-swelling sodium bentonite capable of meeting API specifications for drilling fluids [7, 8]. For adsorbent and catalytic applications, acid activation is employed by digesting the raw clay with 0.8M HCl or H_2SO_4 at 90–95 ℃ for 2–4 hours. This treatment selectively leaches octahedral cations (Al^{3+}, Fe^{3+}, and Mg^{2+}), opening micropores, expanding pore volume, and boosting the specific surface area to >250 m^2/g for edible oil bleaching and catalysis [3].

Thermal activation offers an alternative physical modification route. Controlled calcination at 300 ℃ for 6 hours increases the specific surface area from 57.6 to 81.74 m^2/g without destroying the underlying smectite layer structure, thereby enhancing adsorption performance for wastewater treatment and environmental remediation [28]. Together, these primary processing, beneficiation, and chemical activation strategies provide a complete technical framework for converting raw Ethiopian bentonite resources into commercial-grade products [15], as illustrated in Figure 2.

Table 5. *Industrial Application Suitability Summary of Ethiopian Bentonite Deposits.*

Deposit	Drilling Fluids (API 13A)	Foundry Sand	Iron-Ore Pelletizing	Bleaching Earth	Civil Eng. & Barrier	Agriculture (CEC ≥ 70)	Specialty / Catalysis	Activation & Beneficiation Pathway	Source
Gewane	High (with Na activation)	High	High	High (with acid activation)	High	High	Moderate	Na-activation for drilling; acid activation for bleaching earth	[7, 9]
Warseiso	High (with Na activation)	High	High	High (acid activated)	High	High (82.1 CEC)	High	Highest CEC (82.1); thermal or acid activation	[15, 24]
Ledi	High	High	High	High (with activation)	High	High	High	High natural Na_2O (1.85%); Na or acid activation	[6, 14]
Kada Hadar	High (Na-bentonite)	High	High	High (acid activated)	High	High	High	Zeolite presence enhances catalysis; acid activation	[3, 7]
Ounda Hadar	High	High	High	High (with activation)	High	High	Moderate	Na_2O > CaO; combined resource with Kada Hadar	[7, 14]
Gidicho Island	High (meets API)	High	High	High	High	High (77 CEC)	High	Best overall quality; natural swelling 17.1	[8, 17]

Deposit	Drilling Fluids (API 13A)	Foundry Sand	Iron-Ore Pelletizing	Bleaching Earth	Civil Eng. & Barrier	Agriculture (CEC ≥ 70)	Specialty / Catalysis	Activation & Beneficiation Pathway	Source
								ml/2g; Na-activation	
Shigima	High	High	High	High	High	High	Moderate	Part of Gidicho complex; CEC ~77 meq/100g; Na/acid activation	[7, 8]
Arura	High (beneficiated)	High (beneficiated)	High (beneficiated)	High (beneficiated)	High	High	Moderate	Highest Fe_2O_3 (13.50%); requires magnetic/gravity desanding	[7, 8]
Biaso	High (beneficiated)	High (beneficiated)	High (beneficiated)	High (beneficiated)	High	High	Moderate	Highest Al_2O_3 (16.40%); requires beneficiation	[7, 8]
Chacha	High (with activation)	High	High	High (with activation)	High	High	High	Na_2O/CaO ratio ~1.5; active commercial mining agreement	[11]
Burji Woreda	High (with activation)	High	High	High (with activation)	High	High	Moderate	Calcium bentonite (~5.22 Mt); requires systematic exploration	[7]



Figure 2. *Bentonite beneficiation flow sheet and processing pathways.*

6. Domestic Market Dynamics, Import Substitution, and Economic Potential

6.1. Domestic Industrial Demand and Growth Drivers

The domestic market for bentonite in Ethiopia is experiencing robust expansion, driven by rapid industrialization, infrastructure development, and agricultural modernization [7, 14, 23]. The national edible oil refining industry requires thousands of tonnes of activated bleaching earth annually for pigment decolorization and contaminant removal [10, 14]. Expanding geothermal, groundwater, and oil/gas exploration drilling generates steady demand for API-grade drilling bentonite [7, 18]. Additionally, local foundries, iron/steel manufacturing plants, civil construction projects, and agricultural soil reclamation programs represent growing domestic end-markets [4, 7, 15, 22]. Quantitative market projections indicate that domestic demand for bentonite will expand substantially, with annual compound growth rates accelerating from 12.43% in 2025 to 15.81% by 2029 [23].

6.2. Import Reliance and Import Substitution Analysis

Despite hosting vast natural resources estimated at 141.5 million tonnes, Ethiopia remains heavily reliant on foreign imports to fulfill its refined bentonite requirements. Official trade statistics reveal that in 2023, Ethiopia imported 1,871,870 kg (1,872 tonnes) of processed bentonite with a cumulative value of $710,100 USD [7, 23]. India represents the overwhelming primary foreign supplier, contributing 1,825,650 kg valued at $683,970 USD, supplemented by minor imports from Italy (26,274 kg; $17,040 USD), China (19,200 kg; $6,410 USD), France (661 kg; $2,480 USD), and the United Arab Emirates (84 kg; $200 USD) [7, 23]. Establishing domestic beneficiation facilities for drying, grinding, and chemical activation (sodium and acid treatment) presents an immediate opportunity for full import substitution, curbing foreign exchange expenditure while enhancing national supply-chain security.

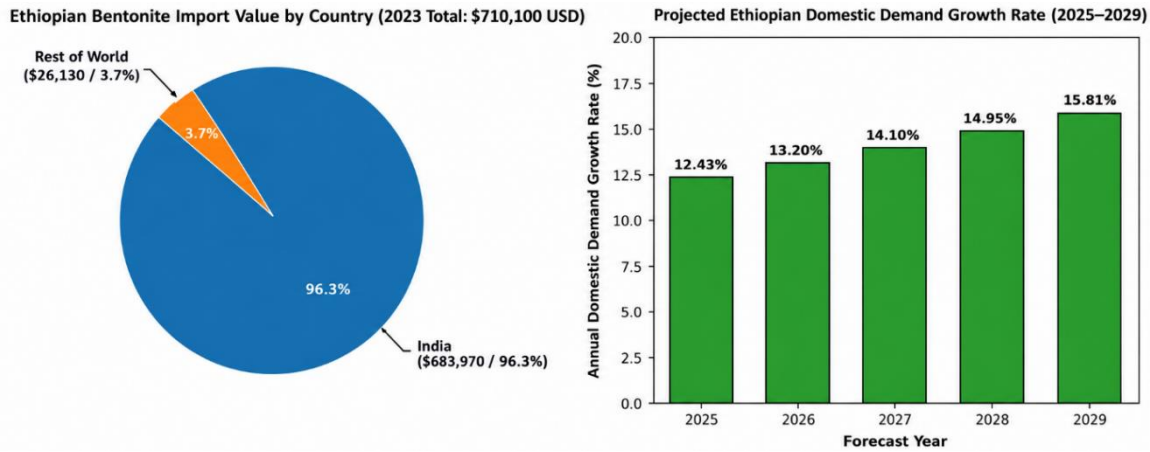


Figure 3. *Ethiopian industrial bentonite market breakdown and projected growth trajectory [23, 29].*

6.3. Value Addition, Employment, and Commercial Investments

Transitioning from raw clay extraction to domestic value-added processing yields significantly higher economic margins and socio-economic benefits [10]. Downstream processing pathways including sodium activation for API-grade drilling muds, acid activation for edible oil bleaching earth, thermal calcination for environmental sorbents, and organo-modification for specialty applications create strong domestic industrial linkages [10, 15]. Commercial investment in domestic deposits is already under way; notably, Arerti Ceramics Manufacturing signed a 10-year mining agreement with the Ministry of Mines to invest 41 million ETB in extracting 870,000 tonnes of bentonite at the Chacha deposit, a venture projected to create approximately 3,000 jobs upon full operation [11]. Nevertheless, economic viability requires balancing processing overheads such as transportation, energy, chemical additives, packaging, and quality testing against landed foreign import prices.

6.4. Regional Export Prospects and Strategic Investment Roadmap

Beyond domestic import substitution, Ethiopia's geographical location positions it strategically to serve expanding regional markets across East Africa and the Middle East. Value-added bentonite products specifically drilling-grade sodium bentonite, activated bleaching earth, and foundry sand binders

possess competitive regional export potential, supported by lower transport costs relative to intercontinental suppliers despite Ethiopia's landlocked logistics [7, 8, 14]. To capture this economic potential, strategic development priorities must focus on: (1) detailed reserve delineation of priority deposits (Gewane, Gidicho, Warseiso, Hadar), (2) establishment of commercial beneficiation and activation processing plants, (3) development of accredited national quality control laboratories, (4) implementation of supportive import substitution policies and tariff incentives, and (5) integration of Environmental, Social, and Governance (ESG) frameworks into mining operations.

7. Conclusions and Recommendations

7.1. Conclusions

Ethiopia hosts extensive bentonite reserves exceeding 141.5 million tonnes across the Main Ethiopian Rift and Afar Depression, predominantly composed of calcium montmorillonite derived from the weathering, devitrification, and diagenetic alteration of volcanic ash and tuff in alkaline lacustrine settings. The resource base is dominated by the Gewane deposit (~70 million tonnes), supplemented by substantial reserves at Warseiso (7.01 million m^3), Gidicho Island (>9.4 million tonnes), Ledi (1.78 million m^3), Kada Hadar (0.93 million m^3), Burji (5.22 million tonnes), and the commercial Chacha deposit (870,000 tonnes). Geochemically, these bentonites exhibit high cation exchange capacities (77–82.1 meq/100g), matching or surpassing global commercial benchmarks.

Although raw Ethiopian bentonites naturally display low to moderate swelling capacity due to their Ca-dominant interlayer chemistry, targeted chemical and thermal activation pathways successfully unlock high industrial utility. Sodium activation via soda ash treatment (3–5 wt.% Na_2CO_3) exchanges interlayer Ca^{2+} for Na^+, elevating rheological performance and swelling capacity to meet API Specification 13A / ISO 13500 drilling fluid standards. Acid activation using 0.8M HCl leaches octahedral cations, expanding micropores and increasing specific surface area to >250 m^2/g, thereby fulfilling UNIDO activated bleaching earth thresholds for edible oil refining. Thermal calcination at 300 ℃ increases surface area from 57.6 to 81.74 m^2/g for environmental wastewater remediation, while unactivated raw clays from Gewane and Warseiso demonstrate high binding performance as foundry sand binders and iron-ore pelletizing agents.

Realizing domestic beneficiation and activation presents an immediate import substitution pathway eliminating significant foreign currency outlays such as the $710,100 USD spent importing 1,871,870 kg of processed bentonite in 2023 (primarily from India at $683,970 USD for 1,825,650 kg)—while unlocking high-margin export potential across East Africa.

7.2. Recommendations

To transition Ethiopia's bentonite sector from raw geological potential into a sustainable industrial driver, the following policy and strategic measures are recommended. First, systematic core drilling and resource validation should be undertaken to upgrade historical reconnaissance data to international reporting standards (such as JORC or NI 43-101) through systematic core drilling, trenching, 3D block modeling, and detailed geochemical mapping across priority deposits (Gewane, Gidicho, Warseiso, Hadar, Burji, and Chacha). Second, integrated beneficiation and activation facilities should be established by directing capital investment toward modern commercial processing plants equipped for primary crushing, solar or rotary drying (<15% moisture), fine grinding to 75 μm (200 mesh), extrusion-based sodium activation, acid digestion, and thermal calcination to supply uniform, certified industrial grades. Third, accredited quality control testing infrastructure should be developed by establishing accredited national testing laboratories and mandatory technical standards for drilling muds, bleaching earths, and foundry sand binders, ensuring strict batch-to-batch quality assurance and user confidence among domestic industrial consumers. Fourth, supportive import substitution and tariff policies should be enacted through fiscal incentives and protective trade measures, including targeted import tariffs on foreign processed clays, tax relief for local mining operations, and local-content mandates compelling domestic edible oil refiners and drilling contractors to utilize certified Ethiopian bentonite products. Finally, environmental, social, and governance (ESG) frameworks should be implemented through rigorous environmental protection standards requiring progressive mine land rehabilitation, waste management protocols, and equitable community benefit-sharing to guarantee socio-economically sustainable resource extraction.

Abbreviations

API	American Petroleum Institute
CEC	Cation Exchange Capacity
EARS	East African Rift System
GSE	Geological Survey of Ethiopia
ISO	International Organization for Standardization
MER	Main Ethiopian Rift
UNIDO	United Nations Industrial Development Organization
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

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Author Contributions

Kisa Workineh: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing

Getnet Belachew: Data curation, Formal Analysis, Investigation, Writing – review & editing

Abinet Markos: Data curation, Formal Analysis, Investigation, Writing – review & editing

Data Availability Statement

The data supporting the findings of this research have been compiled from published and unpublished reports of the Geological Survey of Ethiopia, Ministry of Mines, and academic literature. The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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