

Research Article

Mineralogical and Geochemical Characterization of Silica Sand Deposits in Mugar, Oromia Region, Ethiopia

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Abstract

The industrialization of the Ethiopian economy necessitates the identification and characterization of high-purity mineral resources to support domestic manufacturing and reduce reliance on expensive imports. This research provides a comprehensive mineralogical and geochemical characterization of the silica sand deposits located in the Mugar area, Oromia Region, Ethiopia. The study focuses on the Koffe-Mute sector within the Mesozoic sedimentary architecture of the Abay (Blue Nile) Basin. Analytical techniques including X-ray Diffraction (XRD), X-ray Fluorescence (XRF) and granulometric sieving were utilized to evaluate the suitability of these sands for industrial applications, specifically glass and ceramic manufacturing. The results indicate that the Mugar silica sand is exceptionally pure, with quartz content ranging from 96% to 98% and silicon dioxide (SiO₂) concentrations averaging above 96%. Major impurities, primarily Fe₂O₃, range from 0.08% to 0.33%, falling within acceptable limits for sheet and container glass production. Mineralogical analysis reveals high crystallinity and high textural maturity, with sub-rounded to well-rounded grains. Physical property assessments show that over 75% of the grain size distribution falls within the 0.1 mm to 0.5 mm range, which is ideal for efficient melting in glass furnaces. The study concludes that the Mugar deposit represents a strategic resource for the national mineral development strategy, offering significant potential for import substitution in the burgeoning Ethiopian glass and construction sectors. Beneficiation strategies, particularly acid leaching, are recommended to further elevate the purity for specialized high-tech applications.

Keywords

Silica Sand, Mineralogy, Geochemistry, Beneficiation

1. Introduction

The strategic development of industrial minerals is a cornerstone of Ethiopia's broader economic transformation, as outlined in the national Growth and Transformation Plan (GTP II) and the Homegrown Economic Reform agenda. Silica sand, an essential raw material composed predominantly of quartz grains, serves as the primary component in glass manufacturing, foundry casting, and ceramic production [1].

Globally, the demand for high-purity silica sand is driven by the expansion of the construction, automotive and renewable energy industries, particularly the production of photovoltaic cells and specialized optical glass [2]. In Ethiopia, the demand for sheet glass and glass containers has surged alongside rapid urbanization, leading to significant imports of finished products and a drain on foreign currency reserves [3].

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The Oromia Region, characterized by its diverse geological formations, holds immense potential for the extraction of high-value industrial minerals. The Mugar Valley, located in the North Shoa Zone, is particularly significant due to its extensive Mesozoic sedimentary sequences, which host massive deposits of silica sand, limestone, and gypsum [3]. Despite the identified potential, prior characterization data for Ethiopian silica sands have been relatively limited, often restricted to reconnaissance-level surveys. This lack of detailed mineralogical and geochemical data has hindered the full-scale industrial utilization of these resources [3].

Characterizing the Mugar silica sand requires a multi-faceted analytical approach to determine its chemical purity, mineral phases, and physical properties. High-purity deposits, generally defined as those containing at least 95% SiO₂, are rare and require specific geological conditions for their formation, such as the intense chemical weathering of parent rocks and the subsequent sorting of resistant quartz grains through sedimentary processes [4]. The concentration of contaminants, most notably iron oxide (Fe₂O₃), is the primary determinant of the sand's suitability for clear versus colored glass products.

This research aims to bridge the data gap by detailing the mineralogical composition and geochemical signatures of the Mugar deposits. By evaluating these parameters against international standards, such as those published by the British Standards Institution (BS2975), the study provides a technical framework for domestic mineral development [2]. Furthermore, the investigation links the findings to Ethiopia's national mineral development strategies, emphasizing the role of institutions like the Ethiopian Mineral Industry Development Institute (MIDI) in fostering a self-sufficient industrial base [5]. The significance of this work lies in its potential to catalyze investment in local glass manufacturing, thereby promoting import substitution and enhancing the competitiveness of the Ethiopian industrial sector [6].

2. Geological Setting and Study Area

2.1. Regional Geology and Tectonics

The Mugar area is situated within the Abay (Blue Nile) Basin of Central Ethiopia, an intracratonic rift basin that represents a failed arm of the Karoo rift system associated with the early breakup of Gondwanaland during the Late Paleozoic to Mesozoic eras. The basin is filled with a thick succession of sedimentary rocks, reaching up to 2,600 meters in some sections, which unconformably overlie the Precambrian crystalline basement. This basement complex is composed of highly deformed and metamorphosed granites, gneisses, and schists, which provided the primary source material for the subsequent sedimentary cycles [7].

The Mesozoic sedimentary sequence in the Abay Basin is divided into several major formations reflecting changing depositional environments, from continental fluvial systems

to marine transgressions and subsequent regressions. The base of the sequence is the Adigrat Sandstone (Triassic to Early Jurassic), characterized by mature to sub-mature continental class [8]. This is followed by the Abbai beds, the Antalo Limestone (the result of a marine transgression), the Mugher Mudstone, and finally the Debre Libanos Sandstone, often referred to as the Upper Sandstone [7]. The silica sand deposits of interest in the Mugar Valley are primarily hosted within these Upper Sandstone units, which reflect a regressive, shallow-marine to fluvial environment [9].

2.2. Deposit Description and Stratigraphy

The study area, specifically the Koffe-Mute sector, is located approximately 55 km northwest of Addis Ababa and about 22 km northwest of Chancho. The topography of the Mugar region is marked by deep gorges and steep cliffs carved by the Mugar River drainage system, exposing the sedimentary layers for investigation and extraction [3]. The plateau surface typically exceeds 2,000 meters in elevation, while the valley floors drop to 1,500 meters, creating a distinct vertical relief that exposes the stratigraphy [3].

The Koffe-Mute silica sand deposit is characterized by horizontally to sub-horizontally bedded sandstone units that are part of the broader Mesozoic architecture. Field observations indicate that the sand is relatively loose or weakly cemented, facilitating disaggregation during the beneficiation process [4]. The formation history involved multiple cycles of reworking, which concentrated resistant quartz grains and removed less stable minerals through chemical weathering and mechanical sorting [8].

2.3. Sampling Strategy and Representativeness

A robust sampling strategy was employed to ensure the representativeness of the data across the deposit's lateral and vertical extent. A total of 4 primary samples were collected. The sampling points were strategically chosen based on variations in color, grain size, and composition observed during the mapping phase at a scale of 1:1,000. This high-density sampling allows for a statistically significant assessment of the geological reserves, which are estimated at 3,413,500 tons of indicated and inferred material. The inclusion of samples from different stratigraphic levels ensures that any variations in mineralogical or geochemical signatures due to depositional cycles are captured [3].

3. Materials and Methods

3.1. Sample Preparation and Granulometric Analysis

Following collection, the samples were transported to the

laboratory in contaminated-free canvas bags to maintain purity [2]. The initial preparation involved air-drying the materials at room temperature to achieve a constant weight, followed by gentle mechanical disaggregation of any weakly cemented fragments [10]. A primary stage of sample preparation involved the removal of weathered surface parts to ensure that the analysis reflected the fresh mineralogy of the deposit [11].

Approximately 1 kg of each representative sample was placed on a mechanical shaker and vibrated for 10 minutes to ensure complete separation of the grain size fractions. The mass retained on each sieve was weighed using an electronic balance to calculate the percentage distribution. This physical characterization is essential as grain size directly influences the melting capacity and permeability of the sand in industrial furnaces [10].

3.2. Mineralogical Analysis Techniques

The mineralogical composition was determined through a combination of X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and petrographic microscopy. XRD analysis was performed to identify the crystalline phases and quantify the modal mineralogy. Samples were pulverized to less than 75 μm in an agate ball automatic milling machine to ensure homogeneity [11]. The diffractometer, typically operated at 40 kV and 30 mA, scanned from 3° to 80° of 2θ [12]. The resulting peaks were analyzed using data processing software like High Score to differentiate between quartz, feldspars, and clay minerals [10].

3.3. Geochemical Analysis Methods

Geochemical characterization focused on the quantification of major and trace elements. X-ray Fluorescence (XRF) spectrometry was used to determine the concentration of major oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , TiO_2 , CaO , MgO , Na_2O , and K_2O) [1]. This method is the industry standard for purity control in industrial minerals [13]. For trace elements and Rare Earth Elements (REE), more sensitive techniques like Inductively

Coupled Plasma Mass Spectrometry (ICP-MS) were employed where high precision was required for provenance analysis [14]. Loss on Ignition (LOI) was determined by heating the samples to 1000°C to measure the volatile content, which typically represents structural water in clay minerals or carbonate decomposition. [1] Quality control measures included the use of international standards and the determination of detection limits to ensure the accuracy and reliability of the geochemical data. Statistical methods, such as the calculation of mean concentrations and standard deviations, were used to evaluate the variability across the deposit [10].

4. Results

4.1. Mineralogical Composition and Textural Features

The Mugar silica sand deposit is predominantly composed of high-purity quartz, which accounts for approximately 96% to 98% of the mineral volume. The quartz grains are primarily monocrystalline, exhibiting high crystallinity as evidenced by sharp and intense XRD peaks. Accessory minerals include minor amounts of K-feldspar, muscovite, zircon, and sphene. Clay minerals, particularly kaolinite, are present in small percentages, often occurring as fine matrix or as thin coatings on the surface of the quartz grains.

Textural analysis reveals a high degree of maturity in the Mugar sediments. The majority of the sand grains exhibit sub-rounded to well-rounded morphologies, indicating extensive transport and reworking [1]. Microscopic observation shows that the grains have moderate to high sphericity, although a percentage of less spherical grains is common in these fluvial-deltaic sequences. The lack of strong cementation between the grains suggests that they can be easily liberated during mechanical processing, which is a favorable characteristic for industrial scaling.

Table 1. Mineralogical Composition of Silica Sand Samples.

Mineral Fraction	Percentage (%)	Characteristic
Quartz	97.0	High crystallinity, monocrystalline
Feldspar	1.75	Primarily K-feldspar, sub-rounded
Clay (Kaolinite)	0.98	Occurs as matrix or surface coating
Heavy Minerals	< 0.27	Trace zircon, muscovite, and sphene

4.2. Geochemical Characteristics and Purity Levels

Geochemical analysis via XRF confirms the exceptional purity of the Mugar silica sand. The concentration of SiO₂ remains consistently high, averaging over 96%, which classifies the material as a high-grade silica resource. The most significant impurities are alumina (Al₂O₃) and iron oxide (Fe₂O₃). Alumina content typically ranges from 0.72% to 1.35%,

largely reflecting the minor presence of feldspar and kaolinite. Iron oxide levels, which are critical for the optical quality of glass, were found to range between 0.08% and 0.33% in the Mugar samples. While slightly higher than the levels required for ultra-clear optical glass, these concentrations are well within the specifications for sheet glass and colored container glass. Other oxides such as TiO₂, CaO, MgO, and K₂O are present in trace amounts, generally below 0.2% individually.

Table 2. Geochemical Composition of Silica Sand Samples.

Major Oxide	Concentration Range (wt%)	Significance for Industrial Use
SiO ₂	97.1	Main structural component; high purity
Al ₂ O ₃	1.34	Increases chemical resistance and viscosity
Fe ₂ O ₃	0.21	Critical for color control; acceptable for sheet glass
TiO ₂	0.11	Minor coloring agent
CaO	0.99	Acts as a stabilizer in glass batches
MgO	0.40	Enhances durability
Na ₂ O	0.03	Acts as a flux to lower melting point
K ₂ O	0.29	Minor fluxing agent
LOI	0.30	Represents volatile and organic content

Trace element analysis shows enrichment in immobile elements such as Zr, Nb, and Hf, which is typical for recycled and matured continental sediments derived from crystalline basements. Rare Earth Element (REE) patterns show a minor enrichment in light rare earth elements (LREE) relative to heavy rare earth elements (HREE), with a negligible negative europium (Eu) anomaly, suggesting a provenance consistent with the average upper continental crust.

4.3. Physical Properties and Granulometry

The physical properties of the Mugar silica sand further validate its industrial potential. Granulometric studies indicate a

narrow and uniform grain size distribution, which is a desirable property for ensuring consistent melting and avoiding "stone" defects in glass [1]. Approximately 76.97% of the sand grains fall within the optimal range of 0.1 mm to 0.5 mm, which is the industry standard for glassmaking.

The gravel and mud fractions are minimal, with sand-sized grains making up over 96% of the total mass [1]. The inclusive graphic standard deviation suggests that the sands are moderately to well-sorted. Bulk density measurements range from 1.5 to 1.7 g/cm³, and the whiteness index of the washed sand is favorable for applications in ceramics and high-grade fillers [11].

Table 3. Grain Size Distribution and Industrial Suitability of Silica Sand.

Grain Size Range (mm)	Average Retention (%)	Industrial Suitability
> 1.18	< 4.0	Oversize; typically discarded
0.6 - 1.18	16.5	Coarse; suitable for specific abrasives
0.15 - 0.6	75.15	Ideal range for glass and foundry
0.075 - 0.15	3.5	Fine; used in ceramics and fillers
< 0.075 (Mud)	0.85	Silt/Clay fraction; removed via washing

5. Discussion

5.1. Interpretation of Purity Against International Standards

The suitability of silica sand for the glass industry is primarily determined by its SiO₂ content and the strict control of coloring oxides, especially Fe₂O₃ and TiO₂. The Mugar silica sand, with its high SiO₂ content (>96%) and relatively low iron (0.08-0.33%), satisfies the requirements for several industrial categories. According to the BS2975 standard, Grade C sand, suitable for colorless glass containers, requires a maximum Fe₂O₃ content of 0.035%, while window (sheet) glass can tolerate between 0.1% and 0.5% iron oxide.

Comparing the Mugar results with other prominent Ethiopian deposits like Lemi (96.13% SiO₂, 0.96% Fe₂O₃) and Fetra (96.65% SiO₂, 0.85% Fe₂O₃), the Mugar deposit exhibits a lower initial iron concentration, positioning it as a superior candidate for high-transparency sheet glass. The presence of high-crystallinity quartz is also advantageous, as it ensures high thermal stability and predictable phase transitions during the heating process [12].

5.2. Geochemical Insights: Weathering and Provenance

The high mineralogical and geochemical maturity of the Mugar sand is the result of intense chemical weathering and multi-cyclic sedimentary reworking. The Chemical Index of Alteration (CIA) values reported for similar sandstones in the Blue Nile Basin range from 71% to nearly 100%, indicating moderate to intense weathering of the source rocks [13]. Under these conditions, labile minerals like feldspars and micas are chemically decomposed into clay minerals and leached away, leaving behind a residue enriched in resistant quartz grains [15].

The REE patterns and trace element distributions suggest that the primary source rocks were mafic to intermediate crystalline basement rocks [7]. The high SiO₂/Al₂O₃ and K₂O/Na₂O ratios further confirm that the sediments are highly reworked and matured, representing a passive margin tectonic setting. This geological history is fundamental to the formation of high-purity silica deposits, as it provides the mechanism for natural purification over millions of years.

5.3. Industrial Viability and Beneficiation Recommendations

While the Mugar silica sand is high-quality in its raw state, certain premium applications such as optical glass or solar panels require SiO₂ levels above 99% and Fe₂O₃ below 0.01%. To achieve these benchmarks, the application of beneficiation techniques is necessary.

Mechanical Scrubbing and Desliming: This is the most

cost-effective initial step, utilizing mechanical collision to remove surface coatings of iron oxide and clay minerals [16]. **Magnetic Separation:** Wet high-intensity magnetic separation (WHIMS) can effectively remove paramagnetic impurities like hematite and limonite, which are often found as discrete grains in the sand. **Acid Leaching:** For the removal of deeply embedded iron inclusions or thin-film coatings that resist physical separation, acid leaching is highly effective. The use of organic acids like oxalic acid is increasingly favored over harsh mineral acids (sulfuric or hydrochloric) due to its lower environmental impact and its ability to form soluble complexes with iron. **Flotation:** This process can separate minor feldspar and mica fractions from the quartz, further elevating the SiO₂ percentage.

5.4. Environmental and Economic Considerations

The extraction of silica sand in the Mugar Valley, while generally having a low environmental impact compared to metallic mining, requires careful management of land degradation and water use [17]. National policies increasingly focus on sustainable development, requiring that mining areas be redeveloped and protected [18]. Implementing community-based monitoring and cleaner technologies, such as recycling process water, is essential for maintaining the long-term viability of the sector.

Economically, the development of the Mugar deposit has the potential to transform the local industry. With a projected annual consumption of 30,000 tons for a sheet glass factory, the estimated reserves could support operations for over 40 years [3]. This stability would encourage further investment in the glass and ceramics sectors, creating jobs and fostering technological innovation in Central Ethiopia [19].

5.5. Limitations and Future Work

The current study is based on extensive field and laboratory data, yet certain limitations exist. While the characterization confirms industrial suitability, pilot-scale processing is required to determine the actual recovery rates and the economic feasibility of various beneficiation circuits. Future work should also involve detailed studies on trace metal mobility to ensure that any by-products from beneficiation (e.g., leaching residues) are managed according to environmental standards [18]. Additionally, the expansion of characterizing other silica polymorphs like agate or jasper in the surrounding formations could unlock additional value for the gemstone and decorative stone industries [11].

6. Conclusions

The characterization of silica sand deposits in the Mugar area of the Oromia Region confirms that this resource is of

exceptional quality and holds significant potential for Ethiopia's industrial development. The research establishes that:

The Mugar silica sand is mineralogically pure, consisting of 96% to 98% quartz with high crystallinity and textural maturity. Geochemically, the sand is characterized by SiO₂ concentrations above 96% and iron oxide levels between 0.08% and 0.33%, making it suitable for standard sheet and container glass manufacturing. The physical properties, including a narrow grain size distribution and favorable density, align with international industrial standards for glass melting and foundry use. Beneficiation techniques, particularly mechanical scrubbing and acid leaching with oxalic acid, are recommended to produce ultra-high-purity silica for specialized high-tech applications.

These findings support the national strategy for mineral-based industrialization and import substitution. The Mugar deposit, with its substantial reserves and proximity to industrial hubs, represents a strategic asset for the Ethiopian mining sector. Policymakers should prioritize the establishment of integrated mining and processing facilities in the Mugar region to maximize the economic and social benefits for the Oromia Region and the nation as a whole.

Abbreviations

AAS	Atomic Absorption Spectrometry
EARS	East African Rift System
G-IRMS	Gas Source Isotope Ratio Mass Spectrometry
GIS	Geographic Information System
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
JORC	Joint Ore Reserves Committee
LCA	Life Cycle Assessment
LOI	Loss on Ignition
SEM-EDS	Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy
SIMS	Secondary Ion Mass Spectrometry
VCDT	Vienna Canyon Diablo Troilite (Sulphur Isotope Standard)
VMS	Volcanogenic Massive Sulphides
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

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Author Contributions

Wakjira Tesfaye is the sole author. The author read and approved the final manuscript.

Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest.

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