

High-Purity Quartz: A Review of Global Resources, Beneficiation Chemistry, Underexplored Feedstocks, and Market Dynamics

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ABSTRACT

High-purity quartz (HPQ)—silica with absolute purity exceeding 99.99% SiO₂ (4N) and, for the most demanding grades, 99.999% SiO₂ (5N+)—is a foundational critical material for the semiconductor, photovoltaic, fibre-optic, and high-temperature optical industries. This review integrates two complementary bodies of work into a single account of the HPQ value chain: a detailed technical synthesis of beneficiation and chemical purification operations (comminution, sensor-based sorting, magnetic separation, flotation, thermal quenching, hydrometallurgical leaching, and chlorination roasting, including reaction kinetics and thermodynamic constraints), and a broader treatment of global feedstock geology, product specification, an underexplored regional feedstock opportunity in Madagascar and Mozambique, synthetic sol-gel alternatives, global and Indian demand-supply dynamics, and a scoping-level investment case for a synthetic ultra-high-purity silica plant in India. Together these strands connect the mineralogy and chemistry of HPQ production to the commercial and strategic questions that determine where, and how, new HPQ-grade capacity might realistically be built.

Keywords: High-Purity Quartz (HPQ); Mineral Beneficiation; Hydrometallurgical Leaching; Chlorination Roasting; Sol-Gel Synthesis; Critical Minerals; India; Madagascar

INTRODUCTION AND INDUSTRIAL SIGNIFICANCE

Silicon dioxide occupies a value pyramid that stretches from cheap, abundant commodity sand to some of the most tightly specified industrial materials in existence. At the base sit ordinary silica sands used in construction, glass, and foundry work. Higher up sit high-purity quartz (HPQ), the feedstock for semiconductor crucibles, solar photovoltaic (PV) glass, and precision optics. At the apex sit synthetic ultra-high-purity silicas, built molecule-by-molecule rather than mined, for the most demanding electronic and optical applications. In photovoltaic wafer synthesis, HPQ crucibles are required to hold molten electronic-grade silicon at temperatures exceeding 1,450 °C during Czochralski (CZ) crystal growth (Chowdhury et al., 2025), while semiconductor fabrication relies on high-purity fused silica tubing, quartz glassware, and optical lithography components capable of resisting extreme thermal and chemical environments without releasing metallic contaminants into silicon wafers (Jennings et al., 2024).

Natural quartz occurs abundantly in the Earth's crust, but deposits capable of yielding ultra-high-purity concentrates are extremely scarce (Jennings et al., 2024; Xia et al., 2024). The quality of raw quartz feedstock is governed by three categories of impurity, each requiring a different purification strategy:

- **Discrete intergranular gangue minerals** — associated minerals such as muscovite, biotite, feldspar, hematite, rutile, tourmaline, and zircon, present as individual liberated or intergrown mineral phases and removable by physical separation.
- **Intragranular inclusions** — microscopic mineral inclusions and liquid-gas fluid inclusions (H₂O, CO₂, NaCl brines) trapped within individual quartz grains during crystallisation, requiring thermal and chemical treatment to access.

- **Lattice-bound structural impurities** — atomic substitutions within the quartz crystal lattice where Si^{4+} is replaced by trivalent or tetravalent cations (Al^{3+} , Ti^{4+} , Fe^{3+} , B^{3+}), often charge-balanced by interstitial alkali cations (Li^+ , Na^+ , K^+) or protons (H^+). These are the most difficult impurities to remove and ultimately set the ceiling on achievable purity.

These three impurity classes map directly onto the beneficiation stages described in Sections 3–6: physical methods address discrete gangue, thermal pre-conditioning exposes intragranular inclusions for leaching, and only high-temperature chemical treatment (acid leaching and chlorination) reaches lattice-bound impurities.

HPQ literature mixes 3N–4N8 grade labels, lattice versus inclusion impurities, HF and Cl_2 flowsheets, and fused quartz versus Type I–III synthetic silica, often in the same paragraph. That vocabulary is correct for process metallurgists, but it is not a decision map. Non-specialists—investors, ESG reviewers, and policymakers—need a short, repeated spine: feedstock geology → physical beneficiation → acid or chlorine chemistry → melt → end-use specification. Each step should carry a ppm (or ppb) impurity table and explicit cost and hazard call-outs (HF handling, chlorine roasting, fluorine wastes, energy to melt), so grade, chemistry, and liability are visible without decoding the full mineralogical argument. Without that map, dense mineralogy and reagent chemistry serve the plant engineer and fail the feasibility and environmental reader. The review therefore opens with clear process logic and a specification table, then keeps later sections technically rigorous.

Global Resources of HPQ

Globally, high-purity quartz (HPQ)—defined by a SiO_2 concentration exceeding 99.995% and total impurity thresholds under 50 ppm—is an exceptionally scarce strategic material critical for semiconductor manufacturing, solar PV crucibles, and fibre optics. Despite silica’s vast abundance in the Earth’s crust, economically viable deposits of feedstock capable of being refined into ultra-high grades remain concentrated in very few locations. The Spruce Pine Mining District in North Carolina, USA, serves as the epicentre of the global supply, historically providing over 70% to 80% of the world’s raw high-grade feedstock from its unique granitic alaskite pegmatites (Jennings et al., 2024). Beyond the United States, China holds substantial reserves estimated in tens of millions of metric tons across regions such as Henan and Xinjiang, alongside major processing capacity, though it relies heavily on imported feedstock for top-tier semiconductor applications. Additional high-purity pegmatite and hydrothermal vein quartz resources are actively exploited or surveyed across Norway (Hamarøy), Australia, Brazil, Russia, Mauritania, and Madagascar, while growing demand has also spurred interest in synthetic hydrothermal quartz alternatives.

GLOBAL RESOURCES OF HIGH PURITY QUARTZ

High Purity Quartz (HPQ) is a critical industrial mineral essential for glass, ceramics, foundry, metallurgy, semiconductors, solar, and high-tech applications. Global resources are widespread but vary in grade¹ purity.

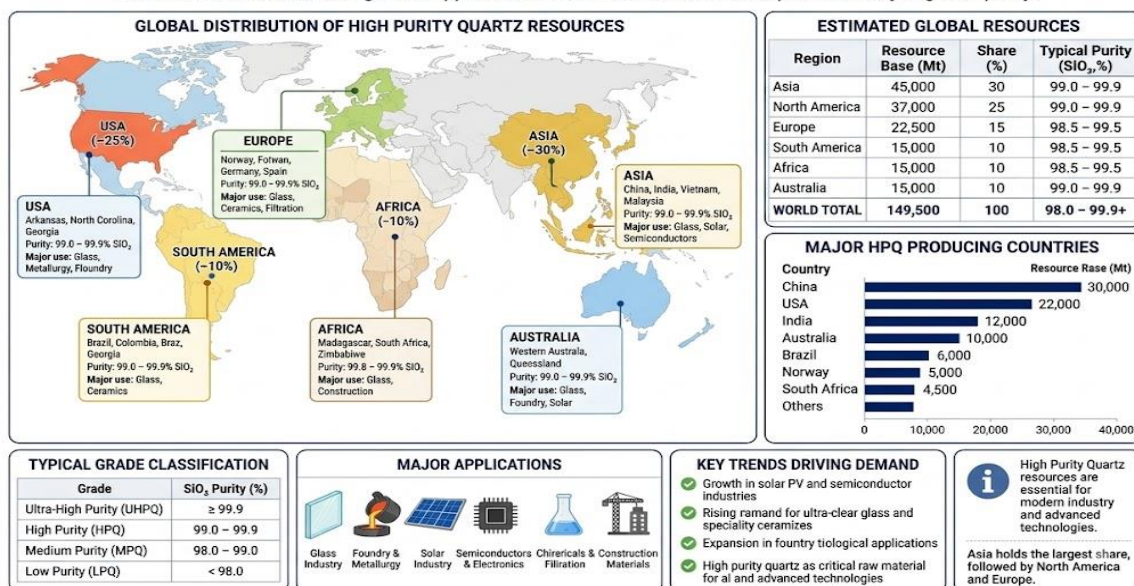


Figure 1. Global Resources of High Purity Quartz

Indian Resources of HPQ

India possesses extensive raw reserves and resources of high-grade quartz and quartzite hosted within granitic pegmatites, hydrothermal veins, and metamorphic rocks across its peninsular shield. The primary domestic supply corridor is concentrated in Andhra Pradesh and Telangana, where high-clarity vein quartz and pegmatitic lump deposits associated with the Eastern Ghats Mobile Belt and Dharwar Craton account for a major share of national output. Rajasthan forms another critical hub within the Aravalli-Delhi Fold Belt (notably in Ajmer, Bhilwara, and Tonk), alongside significant vein quartz reserves in Karnataka and Tamil Nadu, and metamorphic quartzites across Jharkhand and Odisha. While India's raw quartz resources routinely achieve SiO₂ purity levels between 99.5% and 99.9%, transitioning this material into true semiconductor- or solar-grade HPQ requires multi-stage thermal decrepitation, optical sorting, and advanced acid leaching. Driven by national mandates to expand domestic solar wafer and semiconductor fabrication facilities, Indian processors are increasingly focusing on chemical beneficiation to process local feedstock into refined HPQ rather than exporting raw lump quartz.

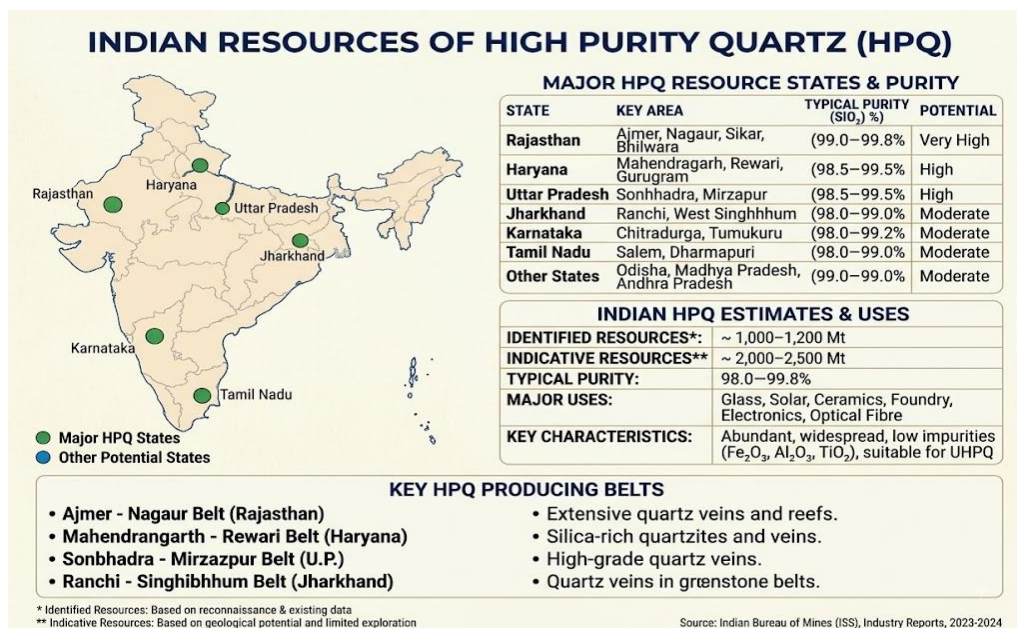


Figure 2. Indian resources of high purity quartz.

HPQ Purity Grade Classification

Industry and research usage of “high-purity quartz” spans a wide purity range, formalised into four broad grade tiers:

Table 1. HPQ Purity Grade Classification

Grade	SiO ₂ content	Total impurities	Typical use
3N (Standard Industrial)	≥ 99.9%	≤ 1,000 ppm	General industrial silica, ferrosilicon, standard glass
4N (High-Purity PV Grade)	≥ 99.99%	≤ 100 ppm (Al ≤ 20 ppm, Fe ≤ 10 ppm)	Solar PV crucibles and glass
5N (Ultra-High Semiconductor Grade)	≥ 99.999%	≤ 10 ppm (Al ≤ 5 ppm, Fe ≤ 1 ppm, alkalis ≤ 1 ppm)	Semiconductor crucibles and process components
5N+ (Optical Grade)	≥ 99.9995%	< 5 ppm	Precision optics, fibre preforms, laser components

Global Feedstock Geology and the Purity Hierarchy

Only a small fraction of the world’s quartz deposits are suitable for upgrading to HPQ. Suitable feedstock is generally drawn from pegmatites, hydrothermal veins, metamorphic quartzites, or well-sorted sedimentary sands, and the geological origin of a deposit directly determines which impurities are present and how difficult they are to remove (Mohanty et al., 2025). Pegmatite-hosted quartz—the source of the bulk of the world’s HPQ, including the Spruce Pine district—forms from highly fractionated, slowly cooled melts that yield large, well-developed crystals with comparatively few inclusions and limited intergrowth with feldspar and mica, allowing shorter, cleaner purification flowsheets (crushing/screening, magnetic/electrostatic sorting, limited flotation, and mild leaching) than hydrothermal or metamorphic sources (Mohanty et al., 2025). A 2024 case study of vein quartz purification in Pakistan similarly confirms that hydrothermal vein quartz, while abundant, typically carries higher intragranular fluid-inclusion loads and requires more intensive thermal and chemical treatment than premium pegmatite feedstock to reach 4N–5N specification (Xia et al., 2024).

Physical Beneficiation and Surface Pre-Treatment

Comminution and Non-Contaminating Size Reduction

The primary goal of comminution is to liberate associated gangue minerals and open grain boundaries while strictly avoiding secondary iron contamination. Conventional ball mills using steel grinding media introduce micro-abrasive iron particles that severely degrade raw quartz quality. Modern HPQ plants instead employ autogenous/semi-autogenous grinding (AG/SAG), high-pressure grinding rolls (HPGR), or ceramic-lined pebble mills charged with high-purity quartz lumps or high-density alumina media. Particle size classification is typically controlled within the 100–315 μm range, which maximises mineral liberation while minimising fine slimes ($< 45 \mu\text{m}$) that impair downstream flotation and leaching kinetics.

Sensor-Based Optical Sorting and High-Gradient Magnetic Separation

Prior to fine grinding, coarse lump quartz (10–50 mm) undergoes automated sensor-based sorting. Optical sorting using high-resolution RGB cameras, X-ray transmission (XRT), or ultraviolet (UV) fluorescence discriminates quartz from feldspar, iron-stained fragments, and surrounding wall-rock gangue. Following size reduction, slurry streams pass through multi-stage high-gradient magnetic separation (HGMS). Operating at flux densities of 1.2–2.1 Tesla with pulsating matrix structures, HGMS efficiently captures ferromagnetic minerals (magnetite, metallic wear iron) as well as weakly paramagnetic minerals (hematite, biotite, tourmaline, and iron-bearing micas).

Reverse Flotation Regimes

Flotation remains the core physical separation technique for removing silicate gangue minerals—chiefly feldspar and micas—from quartz. Because quartz typically constitutes over 95% of the feed mass, reverse flotation is universally deployed: gangue minerals are selectively floated into the froth phase while quartz is depressed and reports to the underflow.

Table 2. Summary of Flotation Systems for HPQ Gangue Removal

Target gangue	Reagents & conditioners	pH window	Mechanism / selectivity
Mica (muscovite/biotite)	Cationic primary amines (e.g., ether amine, DDA), H_2SO_4	2.5–3.5	Amine cations selectively adsorb onto negatively charged mica cleavage planes; quartz remains depressed near its point of zero charge ($\text{PZC} \approx 2.0$).

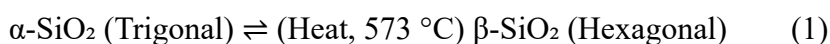
Feldspar (microcline/albite)	Hydrofluoric acid (HF) + cationic amine collectors	2.0–2.8	HF selectively complexes feldspar surfaces, forming fluoro-aluminate ions (AlF_6^{3-}) that enable amine attachment while the quartz surface remains unreactive.
Feldspar (fluorine-free)	$\text{H}_2\text{SO}_4/\text{HCl}$ activator + petroleum sulfonates + long-chain amines	1.8–2.2	Dual-collector synergistic adsorption avoiding hazardous HF discharge; requires higher reagent dosage and precise pulp-density control.

A critical review of mineralogy and processing routes for high-grade quartz confirms that flotation selectivity of this kind, applied after appropriate comminution, routinely removes 90–98% of liberated silicate gangue—but cannot touch impurities trapped inside individual quartz grains, which require the thermal and chemical steps described in Sections 4–6 (Lin et al., 2020).

Thermal Pre-Conditioning and Phase-Transformation Quenching

Physical beneficiation cannot eliminate fluid inclusions encapsulated inside quartz grains, nor impurities trapped deep along grain boundaries. To overcome this limitation, thermal calcination coupled with rapid water quenching is applied as a critical pre-conditioning step ahead of chemical leaching (Xia et al., 2024).

Quartz is heated in a rotary kiln or fluidised-bed furnace to 800–1,000 °C. During heating it undergoes a reversible structural phase transition from low-temperature alpha-quartz (trigonal) to high-temperature beta-quartz (hexagonal) at 573 °C, accompanied by a volumetric expansion of approximately 0.82%:



Upon reaching 850–950 °C, internal fluid inclusions decrepitate under high internal hydraulic pressure. The calcined quartz is then immediately dropped into cold deionised water or dilute acid solutions. The resulting thermal shock generates dense networks of intergranular and intragranular micro-cracks without destroying the crystal lattice—these micro-cracks expose previously isolated inclusions and interior grain surfaces directly to the leaching reagents described in Section 5. This decrepitation-and-quench step typically achieves 70–90% inclusion decrepitation ahead of leaching and is treated as a non-negotiable stage in essentially every modern HPQ flowsheet regardless of feedstock type (Lin et al., 2020).

Hydrometallurgical Chemical Purification (Acid Leaching)

Atmospheric Leaching Chemistry

Chemical leaching removes surface-stained metal oxides, fine mineral films along micro-cracks, and soluble lattice-adjacent impurities. Standard atmospheric leaching runs at 60–90 °C for 2–12 hours under vigorous agitation, using inorganic acid combinations:

- Hydrochloric acid (HCl) — highly effective for dissolving iron hydroxides, carbonates, and surface-bound metallic oxides via chloride complexation:



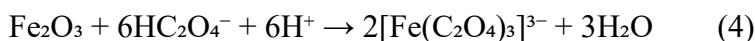
- Hydrofluoric acid (HF) — uniquely capable of slightly etching the silica matrix to expose subsurface inclusions and dissolve refractory aluminosilicate micro-inclusions:



- Nitric acid (HNO_3) — provides strong oxidising conditions to dissolve sulfide trace contaminants and residual organics.

Pressure Hydrothermal Leaching and Organic Alternatives

For stubborn, highly refractory ores, high-pressure hydrothermal leaching is conducted in Teflon-lined autoclaves at 150–220 °C and 0.5–2.5 MPa; the elevated thermal energy accelerates dissolution kinetics by three to five orders of magnitude relative to ambient leaching. In response to environmental regulations on toxic HF emissions, recent research emphasises organic chelating-acid systems—citric acid, oxalic acid, and malic acid—as lower-hazard alternatives (Pan et al., 2022). Oxalic acid acts as both a hydrogen-ion donor and a powerful ligand, forming stable soluble iron-oxalate complexes:



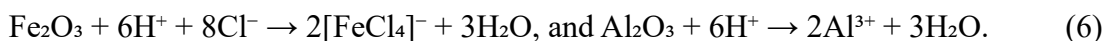
Dissolution Mechanisms: Matrix Etching and Metal Complexation

The hydrometallurgical purification of quartz sand using a mixed HF/HCl system relies on two distinct chemical actions operating simultaneously: surface-matrix dissolution/etching (HF) and metallic-cation complexation (HCl). Because pure silica is thermodynamically inert to most mineral acids, HF acts as the primary matrix-etching agent that exposes encapsulated subsurface micro-inclusions, while HCl prevents dissolved heavy metals from re-precipitating (Lin et al., 2018).

Matrix etching proceeds via a multi-step nucleophilic attack in which undissociated HF and hydrofluoride species (HF_2^-) coordinate with surface silicon atoms—fluoridation of surface silanols ($\equiv\text{Si}-\text{OH} + \text{HF} \rightarrow \equiv\text{Si}-\text{F} + \text{H}_2\text{O}$), cleavage of siloxane bridges ($\equiv\text{Si}-\text{O}-\text{Si}\equiv + \text{HF} \rightarrow \equiv\text{Si}-\text{F} + \text{HO}-\text{Si}\equiv$), and continuous fluoridation converting surface silicon into soluble hexafluorosilicic acid along the micro-cracks opened during thermal quenching:



In parallel, HCl supplies a high concentration of H^+ and Cl^- ions that rapidly dissolve insoluble iron oxides and aluminosilicate inclusions exposed along micro-fractures:



The resulting stable, soluble chloro-complexes such as tetrachloroferrate prevent iron from re-precipitating onto the quartz surface as hydroxides during cooling or washing.

Reaction Kinetics: The Shrinking Core Model and Arrhenius Behaviour

The overall dissolution process follows the Shrinking Core Model (SCM) for non-catalytic fluid-solid heterogeneous reactions, governed by three sequential steps: (1) boundary-layer film diffusion of HF/HCl through the liquid film to the quartz surface; (2) surface chemical reaction—cleavage of Si–O and Fe–O bonds at the solid-liquid interface; and (3) product diffusion of reaction products (H_2SiF_6 , $[\text{FeCl}_4]^-$) back out through the micro-cracks into the bulk solution.

If the surface reaction is slow relative to diffusion, the fraction of dissolved impurities/silica (x) over time (t) follows a chemical-reaction-control kinetic model:

$$1 - (1 - x)^{1/3} = k_r \cdot t \quad (k_r = \text{apparent chemical reaction rate constant}) \quad (7)$$

When reaction products struggle to diffuse out of narrow, thermally quenched micro-cracks, the process instead becomes diffusion-controlled:

$$1 - (2/3)x - (1 - x)^{2/3} = k_d \cdot t \quad (k_d = \text{diffusion rate constant}) \quad (8)$$

Temperature dependence of the rate constant (k) follows the Arrhenius equation:

$$k = A \cdot \exp(-E_a / R \cdot T) \quad (9)$$

For HF/HCl leaching of quartz, the activation energy (E_a) typically falls between 40–65 kJ/mol. An activation energy above 40 kJ/mol confirms the process is controlled by the surface chemical reaction rather than mass-transport diffusion (which would show E_a below roughly 20 kJ/mol); consequently, raising the leaching temperature from ambient to 80–90 °C significantly accelerates dissolution.

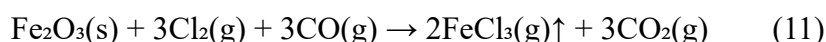
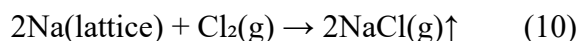
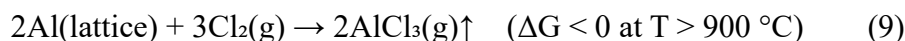
Key Process Variables

- **Acid ratio (HF : HCl)** — an optimal molar ratio, typically 1:2 to 1:4, is required; excess HF causes over-etching and mass-yield loss, while insufficient HF fails to unroof subsurface inclusions.
- **Particle size and micro-fracturing** — pre-calcination and water quenching (Section 4) increase specific surface area and create artificial micro-cracks, bypassing the diffusion resistance of dense, unfractured quartz grains.
- **Agitation dynamics** — stirring speeds above roughly 300 RPM reduce boundary-layer thickness, shifting the system into the chemical-reaction-controlled regime described above.

Thermal Chlorination Roasting for Lattice Purification

Acid leaching removes surface- and crack-exposed contaminants, but cannot remove elements incorporated directly into the crystalline quartz lattice—such as Al^{3+} substituting for Si^{4+} with compensating Li^+ , Na^+ , or K^+ . Deep purification to 5N/5N+ semiconductor grade requires high-temperature chlorination roasting.

In a quartz fluidised-bed or rotary furnace, acid-leached quartz sand is heated to 1,000–1,200 °C under a reactive gas atmosphere containing chlorine (Cl_2), hydrogen chloride (HCl), or carbon tetrachloride (CCl_4). At these temperatures, alkali metals and structural transition metals diffuse to the grain surface and react with chlorine gas to form volatile metallic chlorides that evaporate into the off-gas stream:



Because alkali chlorides are extremely volatile above 1,000 °C, chlorination roasting reduces sodium, potassium, and lithium concentrations to sub-ppm levels (< 0.1 ppm), closing the gap that neither physical beneficiation nor acid leaching alone can reach.

Integrated Processing Flowsheet and Impurity-Removal Efficiency

The stages described in Sections 3–6 are combined into a single, sequential flowsheet in every modern HPQ operation. The integrated circuit runs as follows:

- (1) comminution and size reduction to a 100–315 μm liberation target via non-contaminating AG/SAG or alumina-lined pebble milling;
- (2) pre-concentration via optical sorting and wet HGMS (1.2–2.1 T) targeting liberated iron and mica species;
- (3) reverse flotation at pH 2.0–2.8 with cationic amine collectors, separating mica and feldspar into froth concentrate while quartz reports to the underflow;
- (4) calcination and thermal-shock quenching (800–1,000 °C into cold deionised water), driving the α -to- β phase transition to decrepitate fluid inclusions and induce micro-fracturing;

(5) hot acid leaching (60–90 °C, HF/HCl blends) exploiting the micro-cracks generated during quenching to remove iron stains and leach exposed aluminosilicate inclusions; and

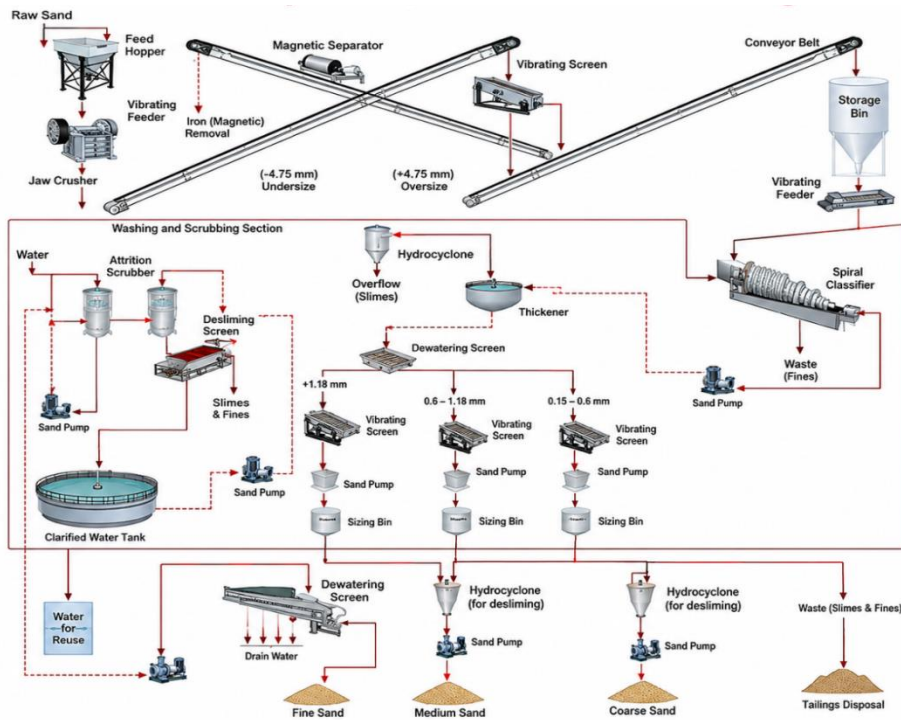


Figure 3. Principle of quartz sand physical processing: crushing, magnetic separation, classification, attrition scrubbing, and desliming ahead of thermal and chemical purification.

(6) high-temperature chlorination roasting (1,000–1,200 °C, Cl₂/HCl atmosphere), volatilising lattice-bound Li, Na, K, Al, Fe, and Ti as gas-phase metal chlorides to yield 5N/5N+ silica sand.

Table 3 summarises the impurity-removal efficiency and attainable product grade of each processing operation, from coarse physical sorting through to lattice-level chlorination roasting.

Table 3. Comparative Impurity-Removal Efficiency Across Processing Operations

Process operation	Target impurity types	Typical efficiency	removal	Product attainable	grade
Optical sorting & HGMS	Free iron oxides, biotite, tourmaline, staining	80–95%	of magnetic gangue	3N grade ($\geq 99.9\%$ SiO ₂)	
Reverse flotation	Feldspar, muscovite, structural silicates	90–98%	of silicate gangue	3N+ grade ($\geq 99.95\%$ SiO ₂)	
Calcination & water quenching	Fluid inclusions (H ₂ O, CO ₂), grain boundaries	70–90%	decrepitation of inclusions	Intermediate pre-treated feed	
Hot acid leaching (HF/HCl)	Surface Fe, micro-crack inclusions, interstitial Al	95–99%	of surface/crack impurities	4N grade ($\geq 99.99\%$ SiO ₂)	
Chlorination roasting	Lattice-bound Li, Na, K, Al, Fe, Ti	> 99%	of alkali & lattice Fe	5N–5N+ grade ($\geq 99.999\%$ SiO ₂)	

Certified Product Grades: Crucible and Solar PV Glass

Fused Silica Crucible Grade

This grade is engineered as feedstock for fused silica crucibles and ultra-high-purity silica ware in semiconductor and optical manufacturing, where micro-bubbles, fluid inclusions, and trace impurities must be minimised to avoid defects during melting and crystal growth.

Table 4. Trace impurities and their effects

Parameter	Typical limit	Notes
SiO ₂	≥ 99.998% (m/m)	Achieved via the integrated physical–chemical circuit of Sections 3–6
Fe ₂ O ₃ (total Fe)	≤ 1–2 ppm	Surface Fe removed by beneficiation and non-sulfate leach
Al ₂ O ₃	≤ 10 ppm	Controlled by feldspar/mica removal and leaching; residual is chlorination-sensitive
CaO / Na ₂ O / K ₂ O	≤ 10 / 2 / 2 ppm	Key devitrification drivers, monitored by ICP-MS/OES
Li, B	≤ 1 ppm each	Defining HPQ trace elements
TiO ₂	≤ 2–3 ppm	Ti phases minimised via SEM-EDS-guided beneficiation

Certification combines routine XRF plant control with ICP-MS/ICP-OES trace analysis, cathodoluminescence for lattice-bound element mapping, and quantitative fluid-inclusion (“bubble count”) analysis; lots that fail the crucible-grade bubble specification are downgraded to solar PV glass grade rather than rejected outright.

Solar PV Glass Grade

Solar PV glass grade uses the same core flowsheet but with operating targets tuned for glass-batch economics rather than crystal-growth optics: low iron for optical transmission and low coloration, with somewhat looser trace-element and inclusion tolerances than crucible grade.

Table 5. Impurities and their effects on solar PV and glass grade.

Parameter	Typical limit	Notes
SiO ₂	≥ 99.995% (4N5)	Premium lots reach ≥ 99.998%
Fe ₂ O ₃ (total Fe)	≤ 5 ppm	Main colorant for PV glass; driven down via pickling and full circuit
Al ₂ O ₃	≤ 20 ppm	Feldspar/mica removal through flotation and leaching
CaO	≤ 30 ppm	Reduced from native 0.13–0.14% via non-sulfate leach chemistry
Na ₂ O / K ₂ O	≤ 10 ppm each	Controlled for glass durability and devitrification resistance
Li, B, TiO ₂	≤ 2 / 2 / 5–10 ppm	HPQ-defining trace elements

Quality Assurance and Certification

Across both grades, certification layers routine plant XRF and wash-water monitoring with high-purity ICP-MS/OES digestion analysis, periodic laser-ablation ICP-MS mapping to distinguish lattice-bound from removable impurities, and optical/SEM-EDS microstructural review. This tiered QA regime allows a single beneficiation circuit—the one detailed in Sections 3–7—to serve both the semiconductor crucible market and the more cost-sensitive solar glass market from the same ore body.

Regional Feedstock Perspective: Madagascar and Mozambique

Global HPQ supply remains concentrated in a handful of pegmatite districts—Spruce Pine (USA), the Eyje-Ivland district (Norway), and a small number of Chinese and Brazilian sources—despite quartz-bearing pegmatites of broadly similar geological character occurring much more widely. Madagascar and Mozambique, both long-standing focus areas for exploration in gold, heavy mineral sands, and battery minerals, illustrate this gap between geological potential and confirmed HPQ supply.

Spruce Pine remains the only deposit that, after processing, routinely yields semiconductor-grade quartz with metallic impurities <10 ppm; Sibelco (IOTA) and The Quartz Corp. supply most crucible-grade sand. Industry commentary often assigns Sibelco roughly 70–90% of semiconductor HPQ share; China still imports the bulk of its highest grades from this source even after recent domestic finds.

Madagascar and Mozambique sit on the Mozambique Belt of high-grade metamorphic rocks that host flake graphite, gem quartz and pegmatites, but NI 43-101 / JORC HPQ resource statements, recoveries, impurity deportment and PEA/PFS economics are not in the public record in the same way as Spruce Pine or Nordic or Australian prospects. Graphite and heavy-mineral-sand literature for those countries is quantitative; HPQ is not. Highlighting East Africa without tonnes, ppm Al/Fe/Ti, yield and capex therefore remains geological speculation rather than a bankable opportunity. Shanghai Metals Market prices cited in an Indian feasibility context (17 September 2025) put HPQ sand for mid-layer crucibles at **INR 294,170–359,542 t⁻¹** (~USD 3,350–4,100 t⁻¹ at 87.75 INR/USD)—orders of magnitude above industrial silica, and sensitive to grade and logistics that African projects have not published.

Pegmatite Geology and Historical Quartz Production

Madagascar's crystalline quartz is hosted principally in the country's rare-element (LCT-type) pegmatite fields, of which the Sahatany Valley pegmatite field near Antsirabe, in the Vakinankaratra region, is the most extensively documented. Detailed field mapping classifies these pegmatites into zoned structures—the largest, “Three-Zone Type” dykes reach 100–300 m in length and 20–40 m in thickness, with a central core characterised by giant crystals of quartz and perthite. Within the western part of this field, the Ambolo locality is specifically documented for large groups of rock crystal quartz occurring in cavities within hydrothermal veins hosted in quartzite. Immediately southeast of these same pegmatites, extensive outcrops of massive rose quartz occur within tourmalinised quartzite host rocks—a scale of occurrence more typical of a mineable deposit than a mineral-collector curiosity.

Colonial-era and mid-twentieth-century records document systematic exploitation of these same pegmatite fields for piezoelectric-grade quartz, alongside industrial kyanite, sillimanite, corundum, mica, and niobium-tantalum oxides, with the French Commissariat à l'Énergie Atomique conducting further research focused on uranium and beryllium in the 1940s–50s (Field Course on the Rare Element Pegmatites of Madagascar, 2026). Twenty-first-century USGS minerals reporting continues to list quartz among Madagascar's ongoing industrial mineral commodities, though at a small and inconsistently quantified scale relative to the country's dominant chromite, graphite, and ilmenite exports (U.S. Geological Survey, 2006).

Present-Day Extraction: Three Tiers of Operation

Field reporting on Madagascar's quartz and gemstone sector describes a structure with three distinct tiers:

- **Artisanal quarrying** — the largest tier by volume and employment, comprising informal, family- or small-group-operated open pits.
- **“Industrial” or formal small-scale quarrying** — a step above artisanal work, where a locally based operator leases the land, employs organised labour, and pays royalties/taxes to the state, but without processing infrastructure beyond basic sorting and block extraction.
- **Commercial mining companies** — a small number of registered operators with named, leased deposits and direct export relationships to Western collector and wholesale markets. Madagascar Minerals (Norcross Madagascar Group) is a documented example, operating a dedicated Rose Quartz Mine among its Madagascar mining properties and marketing output directly through international gem and mineral trade shows in Tucson and Denver (e.g., Madagascar Minerals / Norcross Madagascar Group).

Current Supply Chain and Major Buyers

essentially none of this existing extraction and export infrastructure is currently oriented toward semiconductor- or solar-glass-grade HPQ. The confirmed, large-volume buyer of Malagasy quartz today is the global **crystal and “healing stone” trade**, not the electronics or glass industry. Wholesale-sourcing guides for this market explicitly name Madagascar as a primary source specifically for rose quartz and labradorite, alongside Brazil (amethyst, citrine) and India (agate, moonstone, jasper) (Role of Wholesale Suppliers in the Crystal Industry, 2026). Gemstones and precious metals were Madagascar's fastest-growing export category as far back as 2017, rising 170% year-on-year to roughly US\$109 million, with more than 80% of crystal output estimated to originate from artisanal, largely unregulated mining (“Healing Crystals” with a Trail of Exploitation and Violence, 2020).

The dominant downstream processing and re-export hub for this material is China's Jiangsu Province, and specifically Donghai County — described in industry sourcing guides as China's primary centre for crystal cutting and trade, where vertically integrated operations import raw Madagascar-origin rough, then cut, polish, and re-export finished stones globally through Shanghai and Ningbo ports (Wholesale Crystals Suppliers: Top Global Sources for Healing Stones, 2026). A parallel, smaller channel runs directly from Malagasy commercial operators to Western specialty dealers and trade shows. The overall healing-crystal market that this supply chain feeds were estimated at roughly US\$112.3 million in 2025, with reporting noting that trade tensions, new EU sourcing-transparency rules, and instability in other crystal-producing regions are pushing some buyers to diversify toward African sources including Madagascar (2025 Healing Crystal Market Surpassing \$112.3 Million, 2025).

From Gem-Grade Feedstock to Electronic-Grade HPQ: The Assessment Gap

A 2024 review of the global HPQ landscape explicitly groups Madagascar with Cameroon, Mauritania, Angola, and Namibia as African countries known to host quartz resources with HPQ potential, alongside more established Asian suppliers such as India and Sri Lanka (Jennings et al., 2024). The pattern across most of these occurrences is one of under-reported historical exploration, opaque or absent modern trace-element characterisation, and an absence of the systematic mineral-systems mapping that has underpinned confirmed reserves at Spruce Pine or in Norway. Madagascar's specific advantage is that it already has functioning (if gem-market-oriented) extraction and export logistics.

What is missing is confirmation of electronic-grade purity. Converting known crystal occurrences into a certified HPQ resource base would require the same modern sampling and beneficiation test-work described in Sections 3–7—LA-ICP-MS trace-element and fluid-inclusion screening, followed by magnetic separation, flotation, thermal shock, and multi-stage acid leaching—applied specifically to representative Sahatany-type and Ambolo-type feedstock. Madagascar's January 2026 lifting of a 16-year moratorium on new mining-permit applications (gold excluded) creates a practical window to secure exploration ground over quartz-specific pegmatite zones.

Mozambique: An Adjacent, Less-Characterised Opportunity

Mozambique's pegmatite belts, concentrated in provinces such as Zambézia, Nampula, and Tete, are geologically continuous with the broader East African LCT pegmatite province that also hosts Madagascar's fields, and are already established sources of tantalum, lithium (spodumene), and gemstones. Publicly available data specific to HPQ-grade quartz within these pegmatites is even more limited than for Madagascar, and no confirmed HPQ operation has been reported to date. Geological reconnaissance for quartz-core zones within already-known Mozambican tantalum- and lithium-bearing pegmatites represents a logical, low-cost extension of existing exploration programmes rather than a standalone greenfield search.

Operators already active in both Madagascar and Mozambique alongside India, this regional picture suggests a practical sequencing: use existing in-country pegmatite knowledge and access to prioritise a small number of quartz-core zones for modern trace-element screening, before committing to the capital-intensive beneficiation infrastructure described in Sections 3–7. A positive result would diversify HPQ feedstock supply away from the small number of currently dominant Western and Asian sources; a negative result is inexpensive to obtain relative to the cost of committing a beneficiation plant to unproven ore.

Beyond Natural Quartz: Synthetic Ultra-High-Purity Silica

Why Synthesis: The Purity Ceiling of Natural Quartz

Even the best natural feedstock, subjected to the full physical-thermal-chemical circuit of Sections 3–7, is fundamentally limited by lattice-bound impurities inherited from the deposit's geological history. Natural HPQ can reach 4N or occasionally 5N purity with exceptional feedstock, but consistently reaching 6N–7N purity—the tier increasingly demanded by leading-edge semiconductor and optical applications—generally requires building the silica network from purified molecular precursors rather than upgrading a mined mineral. High costs and the geographic concentration of premium natural quartz deposits are accordingly driving continued development of synthetic quartz produced via hydrothermal growth or sol–gel processing of liquid silicates (Chowdhury et al., 2025), even though natural HPQ remains cost-superior for bulk crucible and photovoltaic applications at current scale.

The CVD / Flame-Hydrolysis Route

One established synthetic route oxidises or hydrolyses gaseous silicon tetrachloride (SiCl_4) in a hydrogen-oxygen flame, producing a fine silica “soot” that is deposited and consolidated into bulk fused silica or fibre-optic preforms. This chemical-vapour-deposition (CVD) approach can achieve very high purity and is the standard method for optical-fibre-grade fused silica, but it demands complex gas-handling systems and very high-temperature furnaces, and is optimised for monolithic or bulk components rather than powders (Fosco Connect, 2026).

The Silicon Alkoxide Sol–Gel Route

An alternative liquid-phase route uses silicon alkoxides—tetraethyl orthosilicate (TEOS) or tetramethyl orthosilicate (TMOS)—dissolved in ethanol or methanol as the silica precursor. Because purification happens at the molecular precursor stage rather than on a solid mineral, metallic and ionic impurities can be excluded before the silica network even forms, in principle enabling parts-per-billion metal control. The process proceeds through five sequential stages:

- **Hydrolysis** — TEOS/TMOS reacts with deionised water under acid or base catalysis; Si–OR (alkoxy) groups are progressively replaced by Si–OH (silanol) groups, releasing alcohol as a by-product.
- **Condensation** — silanol groups react with one another, eliminating water or alcohol and forming Si–O–Si bridges, with pH and temperature governing the balance between hydrolysis and condensation kinetics.

- **Gelation and aging** — as cross-linking proceeds, the system passes through a sharp viscosity increase (the gel point) to form a three-dimensional network; during aging, continued condensation strengthens the gel and refines its pore structure.
- **Drying** — solvent and water are removed from the wet gel under controlled vacuum or humidity conditions to form a mechanically stable xerogel without the cracking that uncontrolled capillary forces would otherwise cause.
- **Calcination / sintering (1,000–1,200 °C)** — residual organics and silanol groups are driven off, the network further densifies, and hydroxyl content is reduced to the low levels required for high-temperature and optical applications.

Compared with both natural-quartz beneficiation and the CVD route, the sol–gel process operates at comparatively low temperature up to the drying step, purifies at the precursor stage, and offers fine control over microstructure and particle size—characteristics that make it well suited to high-purity powders and shaped parts rather than bulk monolithic optics.

Product Specification and Target Markets

Sol–gel synthetic silica can be tuned across a purity range from 5N (99.999%) up to 7N (99.99999%) for select grades, with hydroxyl content, particle-size distribution, and porosity engineered to application: very low OH[−] for semiconductor and high-temperature optical uses; controlled sub-micron particle-size distributions for CMP slurries, coatings, and advanced ceramics. Target markets sit at the top of the silica value pyramid—semiconductor dielectric layers and CMP slurries, optics and photonics, advanced ceramics and refractories, and specialty coatings—where absolute tonnage is modest but unit value and margin are substantially higher than in commodity or even standard HPQ markets.

Process Chemistry versus Cost and Hazard

Purification typically dominates 50–60% of HPQ cash cost and relies on mixed-acid leaching (HF, HCl, H₂SO₄) plus high-temperature chlorination (>1,000 °C with Cl₂ or HCl) to strip lattice alkali metals for SiO₂ >99.995%. HF is the “last-resort” reagent because quartz resists other acids; it also dissolves silicates and can attack SiO₂ if overdosed. Plants need corrosion-resistant alloys, double containment, scrubbers and spent-acid regeneration, which raise both CAPEX and OPEX as Chinese and OECD rules tighten.

HF is systemically toxic (tissue penetration, hypocalcaemia, arrhythmia) even in dilute form; Cl₂ chlorination generates hazardous off-gas and waste acid. Recent work has therefore trialled CaCl₂ roasting as an HF-free substitute (Gao et al., 2025), and independent test work has shown that certain high-grade sands can reach Fe <0.5 ppm and Ti <1 ppm without HF—a material ESG and permitting advantage. A chemistry-only review that omits these cost, waste and permitting numbers cannot support an investment case.

Global Market Context, Demand, and Supply Gaps

Global Demand and Supply Trends

The semiconductor segment is consistently identified as the largest single application for high-purity quartz and silica, commanding over half of global HPQ market value, with solar PV as the fastest-growing segment. Asia-Pacific’s share of global HPQ value is estimated at roughly 59–63%, reflecting the region’s concentration of semiconductor fabrication and solar manufacturing capacity, with India’s targeted build-out of 280 GW of solar capacity by 2030 cited as a specific regional demand driver (Coherent Market Insights, 2026a, 2026b).

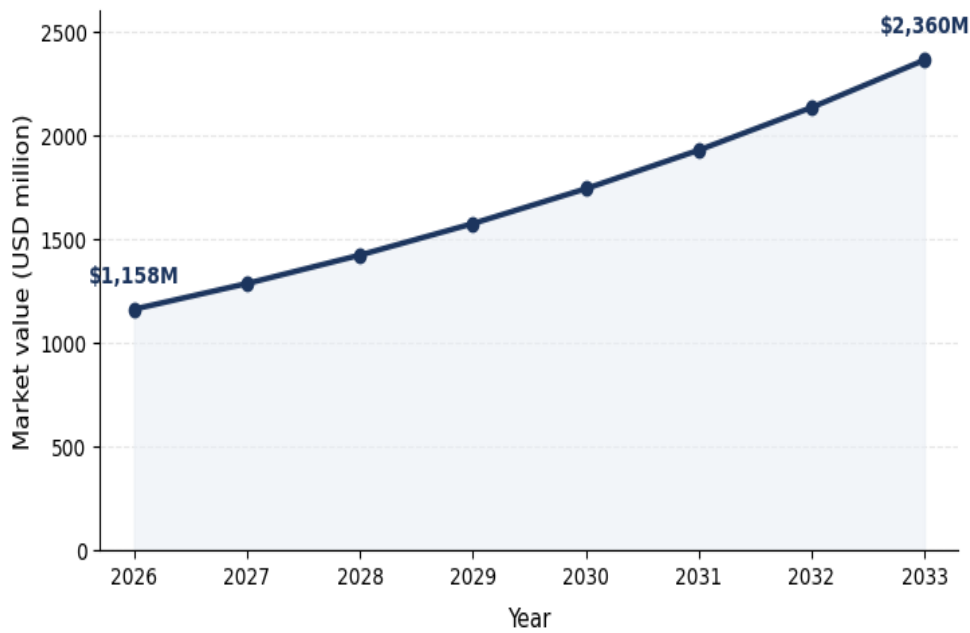


Figure 4. Global HPQ market value, 2026–2033, modeled from the stated CAGR (Coherent Market Insights, 2026b).

Expressed in physical volume, global HPQ demand is estimated at roughly 110–119 kilotons in 2025–2026, rising to nearly 175 kilotons by 2031—a compound annual growth rate near 8%, with semiconductor applications accounting for approximately 40–42% of volume and solar-grade demand growing fastest (Mordor Intelligence, 2026). Premium electronic-grade output remains concentrated in only a handful of operations, with Spruce Pine (USA) and Kyshtym (Russia) together estimated to account for the large majority of global high-end HPQ production. Industry analysts describe HPQ supply as having reached a genuine “tipping point” since 2021, as solar-driven demand growth collided with a resource base that is fundamentally scarce, slow to qualify, and concentrated among very few producers (Sibelco, The Quartz Corp, and Jiangsu Pacific Quartz chief among them). Independent revenue estimates cluster but do not fully agree (Table 6), itself a market-analysis gap.

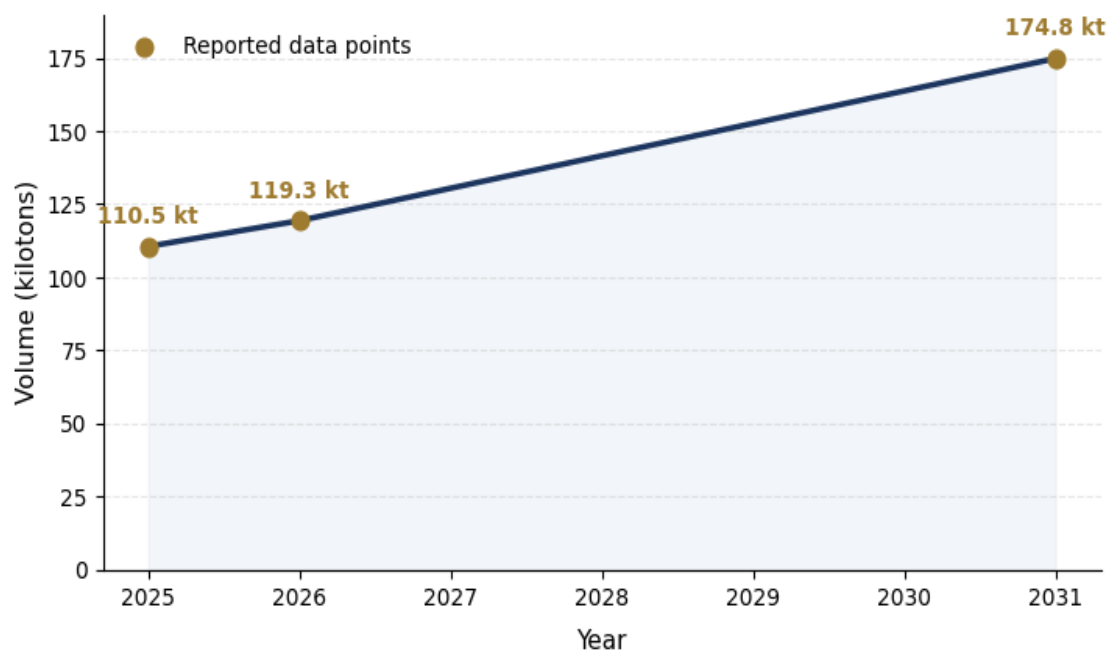


Figure 5. Global HPQ volume demand, 2025–2031 (Mordor Intelligence, 2026); intermediate years modeled from the reported CAGR.

Table 6. Selected Independent Revenue Estimates

Source	2024–2026 size	Outlook	CAGR
Grand View Research	USD 1.08 bn (2024); 1.11 bn (2025)	USD 1.53 bn by 2033	4.1% (2025–2033)
Fortune Business Insights	USD 1.15 bn (2025)	USD 1.65 bn by 2034	4.15%
Transparency Market Research	USD 1.1 bn (2025)	USD 2.1 bn by 2036	6.5%
Coherent Market Insights	USD 1,158.4 mn (2026)	USD 2,359.8 mn by 2033	10.7%
Mordor Intelligence (volume)	110–119 kt (2025–26)	174.8 kt by 2031	~7.95%

Asia Pacific held 59% of 2024 revenue; semiconductors 40.4%; 4N8 (~99.998% SiO₂) 38.5%. Asia Pacific HPQ alone is estimated at USD 522.4 mn in 2026, rising to USD 878.0 mn by 2033 (CAGR 7.7%). Competitive structure is oligopolistic (Sibelco/IOTA, The Quartz Corp., Jiangsu Pacific Quartz, Momentive, Russian Quartz, Imerys), which explains price rigidity and why new African tonnes without Spruce Pine-equivalent impurity control do not automatically capture 4N8 share.

India’s Quartz Demand-Supply Gap

India illustrates this global supply concentration problem at a national scale. India’s electronics and semiconductor sector alone was estimated to consume over 300,000 tonnes of high-purity quartz in 2025, driven by silicon-wafer production, solar photovoltaic manufacturing, and optical/frequency-control components. Against this, confirmed new dedicated HPQ-grade beneficiation capacity is far smaller: a notable recent addition is roughly 180,000 tonnes per year of new beneficiation capacity in Andhra Pradesh—a meaningful contribution, but on its own well short of estimated national demand. While India’s aggregate quartz production across all grades and states is considerably larger (on the order of two million tonnes annually), the overwhelming majority of that volume is low-purity material serving construction, foundry, and engineered-stone markets, not the sub-10-ppm electronic or solar-glass grades this review focuses on.

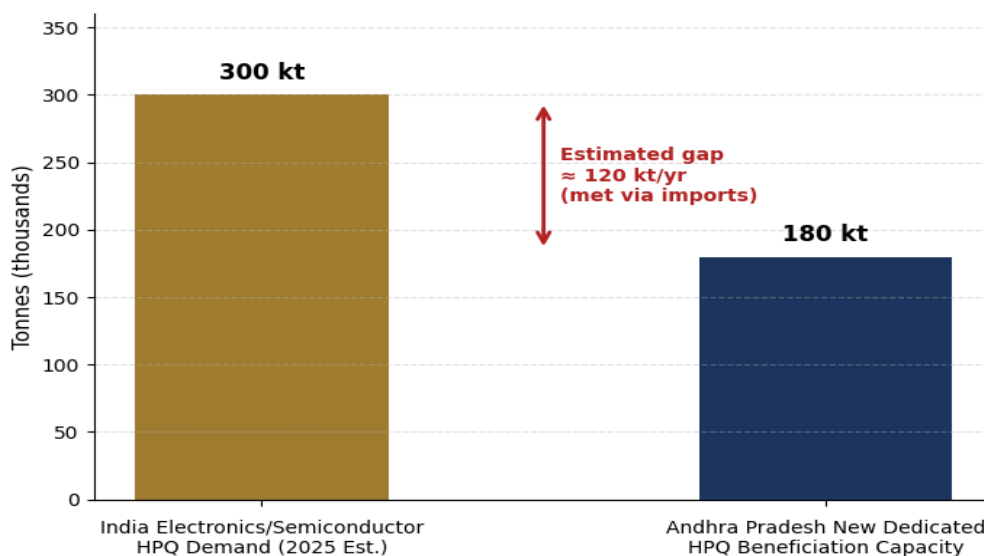


Figure 6. India: illustrative HPQ demand vs. confirmed new dedicated beneficiation capacity. Figures are directional estimates drawn from separate industry sources rather than a single reconciled national balance.

India therefore has real and growing HPQ-grade demand and meaningful, expanding beneficiation capability using the flowsheet described in Sections 3–7, but still falls back on imports of premium electronic-grade

material to bridge the difference—the same structural position occupied by China before its recent domestic discoveries, and the same gap that both the natural-quartz opportunities in Section 9 and the synthetic sol-gel investment case in Section 13 are intended to help close.

Strategic Positioning of Synthetic Silica

A synthetic sol-gel silica plant is best understood as occupying a distinct competitive tier from either commodity silica sand or standard mined HPQ. Three factors define this positioning: a high barrier to entry (organosilicon chemistry, precision process control, and rigorous contamination management); a correspondingly high QA/QC burden (ICP/OES, XRF, particle-size, and moisture/OH⁻ instrumentation); and a business logic built on smaller volumes at much higher unit value, rather than on maximising tonnage.

Challenges and Future Prospects

Despite major advances in HPQ beneficiation, several operational and environmental challenges persist. First, **lattice aluminum and titanium constraints**: substitution of Al³⁺ or Ti⁴⁺ into the quartz crystal lattice cannot be completely removed by hydrometallurgical leaching alone. The ultimate purity ceiling of any given quartz deposit is fundamentally dictated by its primary geological formation conditions and lattice-impurity budget (Jennings et al., 2024; Xia et al., 2024), which is precisely why the synthetic routes of Section 10 exist as a complement to, not simply a substitute for, natural-quartz beneficiation.

Second, **environmental and hazardous-effluent management**: the conventional flowsheet generates toxic hydrofluoric acid effluents and corrosive chlorine gas emissions. Research is rapidly shifting toward HF-free bio-leaching, ultrasonic-assisted organic leaching (building on the oxalic- and citric-acid chemistry introduced in Section 5.2), and closed-loop chlorine recycling systems intended to reduce the environmental footprint of chlorination roasting without sacrificing the sub-ppm lattice purification it delivers (Gao et al., 2025).

Third, the **high costs and geographic concentration of premium natural quartz deposits** are themselves driving continued development of synthetic quartz alternatives—both the CVD/flame-hydrolysis route and the silicon alkoxide sol-gel route. At present, however, natural HPQ remains cost-superior to any synthetic route for bulk crucible and photovoltaic applications at the scale required by the solar industry—meaning the practical path forward for most producers, including the regional opportunities discussed in Section 9 and the Indian investment case in Section 13, is improving and diversifying natural beneficiation capacity rather than a wholesale shift to synthesis.

An Indian Investment Case: Proposed Sol-Gel Ultra-High-Purity Silica Plant

Strategic Rationale for India

India presents a structurally attractive location for a silicon alkoxide sol-gel plant. The country has a mature, diversified chemical-manufacturing base with extensive experience handling solvents, acids, and organosilicon intermediates, concentrated in industrial belts across Gujarat, Maharashtra, Tamil Nadu, Andhra Pradesh, and Telangana. State industrial development authorities in these regions—including the Gujarat Industrial Development Corporation (GIDC), which has established over 180 dedicated industrial estates including chemical-specific zones at Vapi, Ankleshwar, Panoli, and Nandesari, alongside comparable bodies such as Maharashtra's MIDC and Tamil Nadu's SIPCOT—provide established permitting pathways, shared effluent-treatment infrastructure, and logistics support that reduce both risk and time-to-market for solvent-intensive facilities (Gujarat Industrial Development Corporation, 2026).

Rising domestic demand for advanced materials—driven by electronics manufacturing, solar energy targets, and advanced ceramics—creates a dual opportunity: import substitution, reducing reliance on imported high-purity silica and TEOS/TMOS-derived intermediates, and an export-oriented platform integrated into global semiconductor and optics supply chains, reinforced by industrial policy support under initiatives such as Make in India.

Proposed Plant and Phased Capacity Strategy

The proposed facility targets ultra-high-purity synthetic silica at three candidate capacities—50, 100, and 200 tonnes per day (tpd) of saleable product—to assess how capital intensity, operating cost, and cash generation scale with size. All financial figures below are scoping-level, expressed in Indian rupees (INR crore), and derived from indicative assumptions on premium pricing, capacity utilisation, tax, and working capital (Table 7, Fig. 7 and 8).

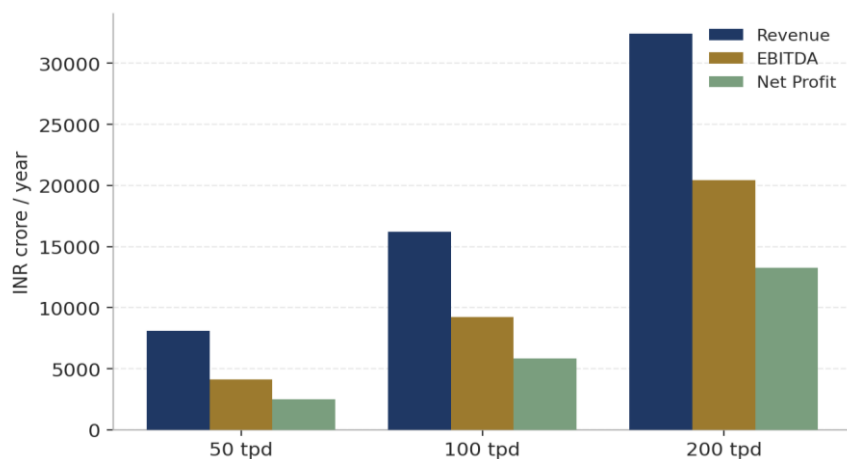
Table 7. Financial figures for scoping levels expressed in Indian Rupees

Plant size	CAPEX (INR cr)	Revenue (INR cr/yr)	EBITDA (INR cr/yr)	Net profit (INR cr/yr)	Simple payback (yrs)
50 tpd	5,460	8,108	4,116	2,499	1.49
100 tpd	8,820	16,216	9,231	5,844	1.06
200 tpd	15,120	32,432	20,457	13,262	0.82



Source: Project scoping-level estimates (this report).

Figure 7. Proposed plant: CAPEX by candidate capacity (scoping-level estimates, this review).



Source: Project scoping-level estimates (this report), based on indicative premium-pricing and utilization assumptions.

Figure 8. Proposed plant: annual revenue, EBITDA, and net profit by candidate capacity (scoping-level estimates, this review).

The 50 tpd option offers the lowest-risk technical and commercial entry point but suffers weaker fixed-cost absorption; the 200 tpd option maximises cash generation and shortens payback but assumes early maturity of TEOS/TMOS supply chains and customer qualification. The 100 tpd configuration is put forward as the most balanced base case: large enough to capture meaningful economies of scale, yet manageable enough to de-risk as a first full-scale plant, with land requirements of roughly 88 acres and CAPEX allocated across process reactors and gelation/wash/filtration systems (20–25%), solvent storage and recovery (10–15%), drying (10–12%), and calcination furnaces (10%), among other blocks.

Risk Landscape and Mitigation

- **Process and technical risk** — drying and calcination are the most defect-prone steps (cracking, residual OH⁻); mitigated through pilot-scale process optimisation before full-scale deployment and tight process control with robust QC testing.
- **Market and pricing risk** — viability depends on sustained access to premium high-purity pricing tiers; mitigated through early customer qualification, phased capacity deployment, and a diversified customer portfolio.
- **Raw material and supply risk** — TEOS/TMOS and key solvents are supplied by a limited number of global producers; mitigated through long-term framework contracts and, in the medium term, potential backward integration into organosilicon intermediates.
- **Environmental and regulatory risk** — flammable-solvent and acid handling requires robust effluent-treatment and emission-control systems, with proactive engagement with pollution-control authorities.
- **Financial and execution risk** — high CAPEX and technical complexity amplify the cost of schedule delays; mitigated through a phased CAPEX strategy and conservative contingency allowances.

Recommended Development Pathway

A three-stage pathway is recommended: (1) a 50 tpd demonstration/pilot stage to validate the sol-gel process at semi-commercial scale under Indian operating conditions, optimise drying and calcination schemes, and generate product for customer qualification; (2) a 100 tpd base commercial plant, designed from the outset for modular expansion, once pilot data and initial customer feedback are positive; and (3) an optional expansion to 200 tpd, undertaken only after stable operation at 100 tpd, validated long-term offtake agreements, and a robust TEOS/TMOS supply chain are all in place. This staged approach aligns with established practice for high-value, high-purity chemical projects: de-risk at small scale, establish a solid commercial base, and expand only when justified by empirical performance and market pull.

CONCLUSION

The production of high-purity quartz requires a tightly coupled, multi-stage processing circuit tailored to the mineralogical state of raw quartz impurities: physical methods (comminution, HGMS, reverse flotation) eliminate liberated silicate and magnetic gangue; thermal calcination and water quenching break open internal fluid inclusions and expose grain boundaries; and chemical purification via acid leaching and high-temperature chlorination roasting removes surface films and lattice-bound cations, yielding 4N to 5N+ ultra-pure silica sand essential for modern semiconductor and green-energy technologies. Where natural feedstock cannot reach the purity ceiling this circuit allows, synthetic routes—CVD flame hydrolysis for bulk optical components or silicon alkoxide sol-gel chemistry for high-purity powders—extend the value chain further, at higher cost but with parts-per-billion control unavailable to any mineral-processing route.

Beyond the chemistry, where HPQ capacity gets built is now as strategically important as how it is purified. Natural quartz beneficiation remains the dominant and most cost-effective route to certified HPQ for both semiconductor crucible and solar PV glass applications, and will likely remain so for the bulk of global demand—but that supply base is dangerously concentrated, with a small number of districts accounting for the

large majority of premium output against a demand curve growing faster than qualified capacity. Madagascar and Mozambique illustrate a real, under-assessed regional opportunity to diversify that supply base using existing pegmatite knowledge and export logistics, even though today's buyer for their quartz is the gemstone trade rather than a crucible manufacturer. India illustrates the demand side of the same problem: substantial and growing HPQ-grade consumption, meaningful but still-insufficient domestic beneficiation capacity, and a resulting reliance on imports that a synthetic sol–gel investment—sized, phased, and risk-managed as set out in Section 13—could begin to close. For India specifically, participating meaningfully in this value chain, whether through continued strength in natural HPQ processing, new exploration in Madagascar and Mozambique, or investment in synthetic sol–gel capacity, aligns with both import-substitution objectives and the country's stated ambitions in semiconductors and renewable energy.

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