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Geological Distribution and Downstream Product Potential of Silica Sand and Kaolin Resources in Sarawak, Malaysia

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Abstract

This study integrates statewide occurrence mapping with primary field and laboratory data from two Marudi silica sand samples (BKG01 and BKG02) and two Telagus kaolin samples (K001 and K005) to support downstream screening for planning purposes in Sarawak, Malaysia. Laboratory analysis included moisture and particle size testing, petrography, X-ray diffraction, loss on ignition, X-ray fluorescence, inductively coupled plasma mass spectrometry, and field emission scanning electron microscopy with energy dispersive X-ray spectroscopy. BKG01 and BKG02 contain 97.3026 and 98.2505 mass % SiO_2, respectively. Semiquantitative XRD estimates 92.6–95.9% quartz. BKG02 has lower LOI, zircon and total rare earth element content, but higher Al_2O_3, TiO_2 and Fe_2O_3. Bulk K001 and K005 are dominated by quartz at 82.1% and 55.9%, whereas their fractions below 63 µm contain 66.4% and 82.1% kaolinite. K005 has higher Al_2O_3 and kaolinite in the fine fraction, but also higher moisture, LOI and Fe_2O_3. Assessment using five gates assigns Potential to general industrial silica. Construction, container glass and filtration routes are Conditional. Silica routes with stricter specifications require further testing. General ceramics is Conditional for Telagus, while other kaolin routes require further testing. The results represent four samples and do not establish grade continuity across either deposit, beneficiation recovery, reserve status, product qualification or commercial feasibility.

Keywords: Silica Sand; Kaolin; Geological Distribution; Downstream Products; Industrial Minerals

1. Introduction

1.1 Background of Sarawak industrial minerals

Sarawak contains sedimentary basins, coastal plains, river systems, clay bearing sequences and sandstone units that support industrial mineral occurrence. These geological settings provide the basis for silica rich sediments and clay minerals. Regional studies show that Sarawak geology is shaped by basin development, sediment provenance, uplift, weathering and depositional change, all of which influence the distribution of silica sand and kaolin [1–5]. Industrial minerals are different from metallic minerals because their value depends not only on tonnage. Grade consistency, particle size, impurity control, processing response, logistics and customer specification are also critical. Sarawak has a broad industrial mineral base, especially in aggregates, clay, earth materials, sand and gravel. However, the producer base for silica sand and kaolin is much smaller, indicating a gap between occurrence, production and higher value downstream use [6–8]. National producer and establishment data are summarised in Tables 1 and 2.

Table 1. Number of industrial mineral producers in Malaysia by state, 2018 [6]

State	Johor	Kedah	Kelantan	WPKL	Melaka	N. Sembilan	Pahang	Perak	Perlis	Pulau Pinang	Putrajaya	Sabah	Sarawak	Selangor	Terengganu	TOTAL
COMMODITY																
Aggregates	57	20	11	0	10	18	30	58	7	15	0	54	62	27	15	384
Sand and gravel	120	120	83	0	10	21	101	103	0	1	0	79	23	96	48	805
Limestone for cement	0	1	0	0	0	1	1	5	1	0	0	0	1	1	0	11
Clay (include shale)	29	3	0	0	1	7	8	22	1	0	0	10	43	18	3	145
Earth Materials	171	93	86	14	121	72	85	129	7	1	13	15	112	100	177	1,196
Silica	7	1	0	0	0	0	1	18	0	0	0	0	2	1	2	32
Kaolin	7	0	0	0	0	0	1	13	0	0	0	0	0	0	1	22
Feldspar	0	0	2	0	0	1	1	0	0	0	0	0	0	0	0	4
Mica	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2
Dimension Stone	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	2
Total	391	238	183	14	142	120	228	350	16	17	13	158	243	243	247	2,603

Table 2. Silica sand and kaolin mineral based establishments 2023 in Malaysia by state [7]

Products Group	Product Component	Silica sand & Kaolin Mineral-Based Establishments 2023												
		Johor	Kedah	Kelantan	Melaka	N. Sembilan	Pahang	Perak	Perlis	Penang	Sabah	Sarawak	Selangor	Terengganu
Structural clay products	Clay brick	14	1	4	1	5	4	5		1	6	29	5	1
	Clay pipes/sewage pipes/drain tiles	1						2					1	
	Wall, Flooring, Mosaic & Terracota tiles	6				2							1	
	Clay roofing tiles	2		1								1		
	Refractory ceramic							3		1			2	
Household ceramic products	Ceramic tablewares	1	1					5					2	
	Sanitaryware	1						1				1	1	
Pottery products	Flower pot							24			2*	1		
	Cooking pot & stove							8*						
	Decorativeware			5		1		103			3	4	7	
	Others											4		
Advanced ceramic component	Electronic component products				1									
	Ceramic powder					1								
	Ceramic fiber/ceramic insulators	1												
	Clay powder							1						
	Formulated clay												1	
	Ceramic grinding stone												1	
Formers	Ceramic former					2							3	
Construction related glass products	Float/flat/tempered/laminated glass	1	1		1	2								
Advance & specialty glass products	Optical & pharmaceutical glass				1					1*				
Industrial glass products	Fibre glass * and fiberglass products							2		2			1	
	Cullet	1												
Household glass	Glass bottles & containers	1											1	
Activated clay	Bleaching earth	2						1			2		1	

Products Group	Product Component	Silica sand & Kaolin Mineral-Based Establishments 2023												
		Johor	Kedah	Kelantan	Melaka	N. Sembilan	Pahang	Perak	Perlis	Penang	Sabah	Sarawak	Selangor	Terengganu
	Total	31	3	10	4	13	4	147	0	4	11	40	27	1

Policy direction also supports a stronger downstream focus. The Post Covid-19 Development Strategy 2030 (PCDS 2030) promotes higher value development, infrastructure improvement and sustainable growth in Sarawak. The New Industrial Master Plan 2030 (NIMP 2030) places mineral based industries within Malaysia's wider industrial transformation agenda [9–10]. Silica sand and kaolin should therefore be assessed as potential industrial feedstock, not only as raw materials. The relevant policy direction is illustrated in Figure 1.

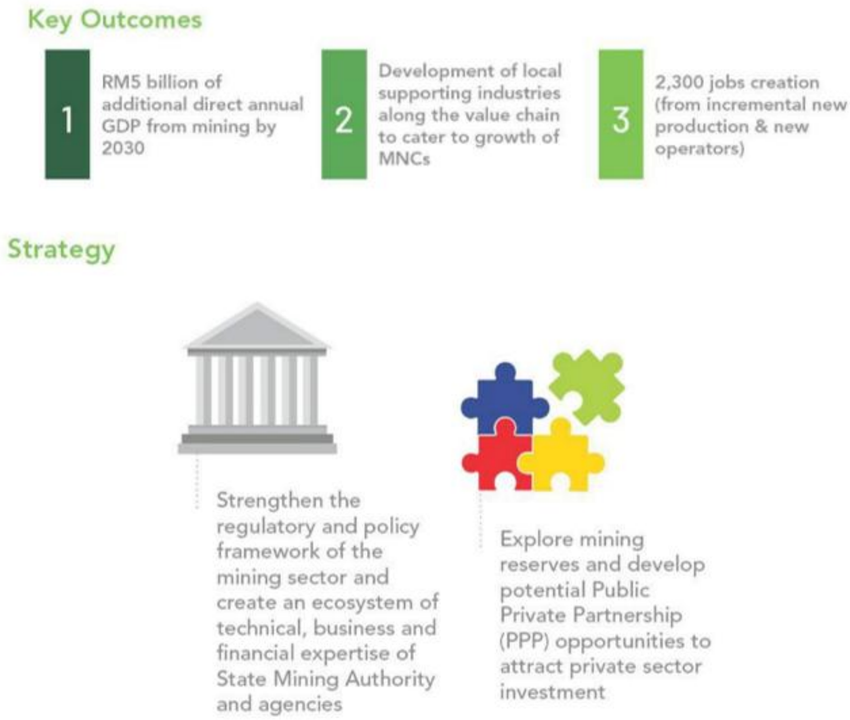

Figure 1. Sarawak long term strategy statement for mineral sector in PCDS 2030 [9]

1.2 Importance of silica sand and kaolin for downstream industries

Silica sand supplies silica for glass, foundry sand, ceramics, sodium silicate, silicon-based materials and higher purity silica applications. Downstream use is controlled by SiO_2 content, Fe_2O_3, Al_2O_3, TiO_2, alkalis, grain size, fines, clay coatings, heavy minerals and beneficiation response. Glass and higher purity pathways require strict impurity control because small amounts of iron, titanium or heavy minerals may affect colour, transparency and melting behaviour [11–14]. Kaolin supports ceramics, tiles, sanitaryware, paper coating, paper filler, paint, rubber, plastics, calcined kaolin, metakaolin, cementitious materials and adsorbent products. Its use depends on kaolinite content, brightness, whiteness, particle size, Fe_2O_3, TiO_2, quartz content, mica content, plasticity, firing behaviour, surface area and activation response. These properties control colour, rheology, shrinkage, abrasion, adsorption and product performance [15–19].

1.3 Problem statement

Sarawak has recognised silica sand and kaolin resource potential, but this potential remains weakly translated into systematic production, quality evaluation and higher value downstream product development. Recent government data show that silica sand is included within Sarawak's industrial mineral inventory, while kaolin is recorded as a national resource that includes Sarawak. However, production and industrial establishment data show that downstream activity remains concentrated mainly in bulk construction and clay-based products [7–8]. The production trend is shown in Figure 2 and Table 3.

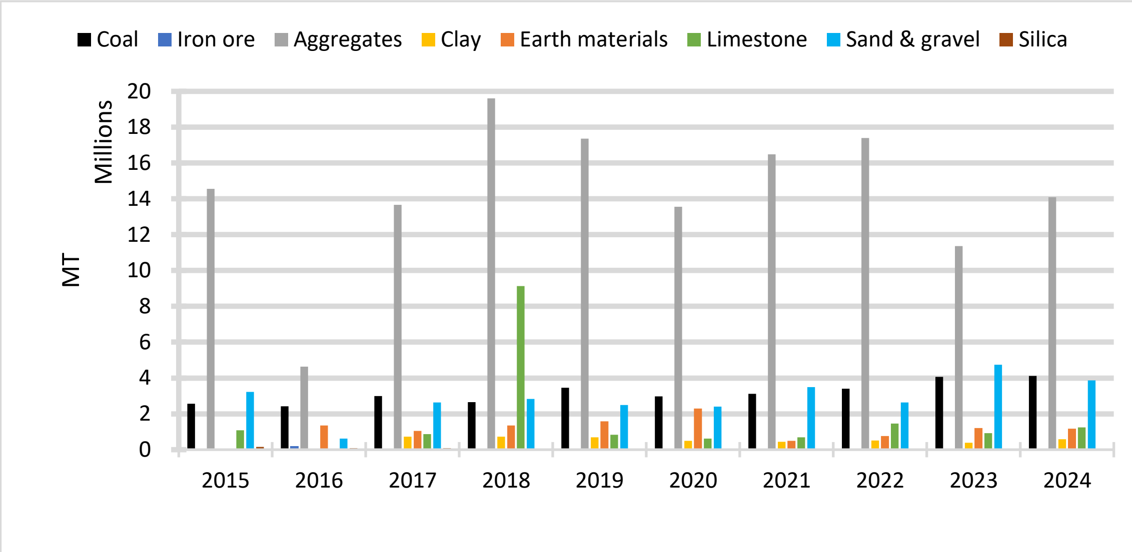

Figure 2. Chart of Sarawak mineral production, 2015–2024 [8]

Table 3. Sarawak mineral production, 2015–2024 [8]

Year / Minerals	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Coal	2,559,444	2,414,765	2,988,212	2,652,813	3,459,122	2,978,248	3,110,605	3,405,847	4,068,049	4,114,793
Gold (gram)		21,682								
Iron ore		193,608								
Aggregates	14,548,884	4,631,897	13,659,129	19,602,440	17,361,009	13,554,721	16,490,253	17,400,928	11,371,221	14,098,833
Clay	0	26,415	723,010	728,614	689,468	485,939	435,136	506,315	392,296	576,430
Earth materials	0	1,350,827	1,038,664	1,358,926	1,576,398	2,301,973	500,450	765,350	1,210,138	1,175,713
Limestone	1,076,881	0	869,748	9,137,979	838,123	625,960	692,791	1,454,075	922,074	1,248,627
Sand & gravel	3,219,156	622,757	2,637,751	2,830,907	2,500,636	2,408,857	3,495,736	2,628,780	4,734,451	3,861,587
Silica	158,293	82,153	88,875	17,892			68			
Kaolin										

The main problem is the limited integration between geological occurrence and industrial specification. Distribution maps can show where silica sand or kaolin may occur, but downstream planning requires chemical, physical, mineralogical, processing and logistics information. Without this link, a resource may be recognised geologically but remain disconnected from realistic product pathways. A second problem is the risk of overclaiming early-stage results. Field observations, mapping checks and results from four samples can support initial screening. They cannot replace systematic drilling, representative sampling, certified resource estimation, beneficiation trials, product testing or feasibility assessment. This study responds with a planning level framework that links distribution, material characteristics, specification interpretation and downstream product potential.

1.4 Scope and contribution of the study

The article focuses on silica sand and kaolin resources in Sarawak, Malaysia. Marudi silica sand and Telagus kaolin are the study areas used for planning level interpretation. Fieldwork provided primary location, observation, mapping and sampling data. Laboratory analyses characterise BKG01 and BKG02 from Marudi, plus K001 and K005 from Telagus. The results include physical properties, particle size distributions, mineralogy, chemistry, trace elements and selected microstructural observations. These four samples do not establish grade continuity across either deposit. The main contribution is an integrated framework that connects statewide occurrence context with field verification, laboratory results from four samples, industrial specifications, processing constraints and priorities for further testing. Earlier regional studies establish the geological setting, while commodity studies define beneficiation and final use requirements [5,12,20–21]. The study does not present a new occurrence inventory, a predictive GIS model, certified reserves, product qualification or commercial viability.

1.5 Research aim and objectives

The aim of this study is to develop a planning-level framework that integrates the geological distribution, mineral characteristics, industrial specification requirements, and downstream product potential of silica sand and kaolin resources in Sarawak, Malaysia. To achieve this aim, the study will compile and interpret the geological distribution of silica sand and kaolin resources for downstream planning, evaluate their physical, chemical, mineralogical, and industrial specification characteristics, and identify potential downstream product pathways based on the measured resource characteristics, processing requirements, and planning constraints.

2. Literature Review

2.1 Geological setting of Sarawak relevant to silica sand and kaolin

Regional geological studies agree that Sarawak's industrial mineral setting is controlled by long term tectonic assembly, basin development, uplift and changes in sediment supply, but they emphasise different parts of that history. Madon [1] provides a broad statewide framework. Metcalfe [22] places Sarawak within the wider tectonic evolution of Sundaland. Tongkul [2] relates Paleogene sedimentation in Central Sarawak to tectonic evolution, while Breitfeld et al. [4] define an older subduction margin between Sundaland and the Pacific in West Sarawak. Hennig-Breitfeld et al. [5] subsequently revise the stratigraphy and paleogeography from the upper Paleogene to the Neogene. These interpretations are complementary rather than mutually exclusive. The older tectonic framework explains contrasting source terrains, whereas the younger stratigraphic synthesis explains how those materials were redistributed among evolving basins [1–2], [4–5], [22].

Regional syntheses emphasise basin scale architecture and changes in sediment routing through time. Provenance and facies studies show how these controls are expressed locally. Breitfeld and Hall [23] use sediment provenance and depositional setting to distinguish relationships between sediment sources and sinks across the Kuching and Sibu zones. In contrast, Johansson [3] resolves depositional facies within the Plateau Sandstones at Bako. The findings differ because regional studies reconstruct sediment sources and basin evolution, while the deposit scale study evaluates local sorting, bedding and facies architecture. Both scales are needed for silica sand assessment. Regional models identify plausible systems rich in quartz, but local facies control

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grain size distribution, fines, cementation and impurity concentration [3,23]. Studies focused on clay provide a similar contrast of scale. Johansson [24] documents field prospecting for clay within the Belaga Formation, while Ibrahim et al. [25] confirm that fine clastic rocks in Central Sarawak contain kaolinite. These studies support the geological plausibility of clay and kaolin occurrence, but neither establishes product grade. Their limitation is the absence of brightness, particle size, impurity, plasticity and processing data for individual deposits. Regional geology and occurrence studies must consequently be followed by mineralogical and industrial evaluation specific to each site [24–25].

2.2 Silica sand occurrence and industrial specifications

Assessments based on occurrences identify where sand rich in quartz may be preserved, but chemical grade assessments define whether that sand can enter a specific industry. Burkowicz et al. [12] link the Polish glass sand resource base to demand from the glass industry. They show that manufacture depends on resource continuity and tightly controlled quality parameters. Their analysis distinguishes high silica content from glass grade qualification by considering colouring oxides and grain size distribution. This agrees with wider silica sand literature that identifies SiO_2 as necessary but not sufficient. Fe_2O_3, TiO_2, Al_2O_3, clay coatings, heavy minerals, fines and particle size consistency can determine whether a deposit is suitable for foundry sand, container glass, flat glass or applications requiring higher purity [12,26].

Beneficiation studies also agree that impurity removal depends on the process. Chammas et al. [11] compare magnetic separation, flotation and leaching with oxalic acid, indicating that different impurity forms require different treatment routes. Febriana et al. [14] test leaching in one and two steps, and report measurable upgrading based on mineralogical and chemical evaluation. These findings do not imply that every sand with high SiO_2 can be upgraded economically. Differences between raw grade studies and beneficiation studies reflect the starting materials, impurity hosts, reagent conditions and target products. Washing and classification may be sufficient for general uses. Solar, optical or other high purity routes may require attrition, magnetic separation, flotation or chemical leaching [11–12,14]. Accordingly, a reported value near 99% SiO_2 should be treated as an initial quality indicator rather than confirmation of glass grade or high purity silica. Qualification for glass and specialist products also requires representative impurity profiles, controlled grain size ranges, mineral liberation data and demonstrated beneficiation response. This distinction prevents occurrence information or a single major oxide result from being converted directly into an unsupported downstream product claim.

2.3 Kaolin occurrence and industrial specifications

Kaolin studies distinguish primary, secondary and mixed formation pathways. Dill [15] synthesises residual, hydrothermal and sedimentary kaolin systems, whereas Ece and Ercan [27] examine hydrothermal origin deposits and explicitly distinguish hypogene, supergene and mixed alteration processes. These studies agree that parent material, fluid chemistry, weathering, transport and post depositional alteration control the mineral assemblage and physical properties. Their different emphases are not conflicting models: the broader classification explains the full range of kaolin environments, while the hydrothermal review resolves processes and mineral associations within one important deposit family [15,27]. At the national and Sarawak scales, the literature shows substantial deposit variability. Baioumy and Ibrahim [16] compare Malaysian kaolin deposits and demonstrate that mineralogical composition cannot be generalised from one locality to another. Ibrahim et al. [25] identify kaolinite in Central Sarawak fine clastic rocks, but their study is mineralogical context rather than an industrial kaolin evaluation. Eki et al. [20], in contrast, directly examine beneficiation of Telaga Air and Telagus kaolin. The studies therefore address different levels of analysis: occurrence and mineral identification establish geological potential, whereas beneficiation testing evaluates whether impurities and brightness can be improved for industrial use [16,20,25].

Kaolinite occurrence alone does not establish filler, coating or ceramic grade. Quartz and mica can increase abrasion or alter forming behaviour; iron and titanium minerals can reduce brightness and firing whiteness; and particle size distribution affects dispersion, rheology and product consistency. Product reviews emphasise fine particle size, brightness and low grit for coating and filler uses, while ceramic routes additionally require plasticity and firing tests. Acid activation studies show that some clay materials may support adsorbent or bleaching earth pathways after modification, but activation response must be demonstrated experimentally [17–18]. Thus, beneficiation may improve a particular property without proving suitability for every downstream product.

2.4 Downstream product pathways for silica sand and kaolin

Downstream studies use different analytical starting points. Charles et al. [21] develop a resource abundance methodology for considering responsible use of mineral raw materials in downstream industries. Hamdani [28] focuses more directly on research design for mineral processing locations. Magno and Guzman [29] examine the role of energy in downstream integration using data from several countries. Barron et al. [30] show that local participation and institutional conditions influence who benefits from value addition. These studies agree that resource presence alone is insufficient, but they emphasise different constraints such as material availability, plant location, energy, institutional capability and participation.

Industrial mineral evaluation adds a technical gate that broad value chain studies may not resolve. Silica and kaolin product selection depends on specification compliance, consistency and processing response, not only on the existence of a downstream market. In contrast, development studies often begin with policy, infrastructure or market opportunity, and treat feedstock quality at a higher level. This difference in analytical scale explains why a region may appear attractive in a strategic value chain assessment while individual deposits remain unqualified for glass, coating, ceramic or activated clay production [12,17,21]. For Sarawak, the literature therefore supports a staged interpretation. Policy ambition, ports, energy and industrial clusters may improve development conditions, but they cannot substitute for representative sampling, beneficiation trials, quality assurance and customer qualification. Conversely, technically promising material may remain undeveloped where logistics, processing capability, governance or market access are weak. The apparent tension between downstream ambition and demonstrated product readiness reflects different levels of analysis rather than a direct contradiction [28–30].

2.5 Research gap

The literature consistently agrees on four points. First, Sarawak's tectonic and sedimentary evolution created spatially variable source rocks, basins and depositional environments. Second, occurrence does not establish industrial grade. Third, silica sand and kaolin pathways are controlled by product specific chemical, mineralogical and physical requirements. Fourth, downstream development requires both technically qualified feedstock and an enabling industrial system [5,12], [20–21]. Studies differ mainly because they operate at different scales and answer different questions. Regional geological work reconstructs tectonics, stratigraphy and provenance. Local studies describe facies, mineral occurrence or beneficiation response. Product studies define performance requirements, while downstream studies examine infrastructure, energy, governance and market organisation. Research using remote sensing in Sarawak also demonstrates that mineral features can be mapped for exploration targeting, but this does not establish industrial mineral

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quality or downstream readiness [31]. Consequently, high SiO_2 may coexist with unverified glass suitability. Kaolinite occurrence may coexist with insufficient brightness or excessive grit, while strong policy support may coexist with limited proof of product readiness. These apparent conflicts arise from differences in sampling scale, analytical parameters, target products and decision purpose rather than fundamental incompatibility between the studies.

The main Sarawak gap is the absence of a concise framework that links statewide occurrence, material data from specific sites, industrial specifications, processing constraints and the next verification step. This study addresses that gap by combining the mapped distribution with field and laboratory data from Marudi and Telagus. A transparent specification matching procedure without numerical weights is then applied. The output is not a certified resource or feasibility ranking. It is a planning level profile that identifies supported pathways, conditional pathways, and those requiring further sampling, beneficiation or product testing.

3. Materials and Methods

3.1 Study area and commodity scope

The study area is Sarawak, Malaysia. The commodity scope is limited to silica sand and kaolin. The study design combined three procedures: occurrence point mapping across Sarawak, field verification and sample collection at Marudi and Telagus, and specification matching without numerical weights. Silica sand was assessed for construction, foundry, glass, ceramic, silicon based and high purity routes. Kaolin was assessed for ceramic, filler, coating, calcined, metakaolin and adsorbent routes. Marudi silica sand is represented by the Bakong silica sand mine area in Marudi District, Miri Division. Telagus kaolin is represented by the Telagus area in Simunjan District, Serian Division. Field observations, mapping checks and laboratory results from these areas support downstream product screening for planning purposes. The Marudi field locations, mine exposures, sampling activities and inactive processing plant are documented in Map 3 and Figures 3–8.

3.2 Data sources and classification

Primary research data comprised field observations, coordinates, photographs, maps, sampling records and laboratory results from Marudi and Telagus. Government sources supplied statewide occurrence context, while published literature supplied mineral specifications and supporting interpretation. Laboratory methods, values, units and analytical qualifications were verified against the original analytical outputs. Derived checks were used only to confirm transcription and internal consistency. They did not replace measured results.

Statewide occurrence information came from government mineral sources, including the 2024 Malaysia Geospatial Mineral and Geoscience Information System and later JMG publications. The fieldwork in Marudi on 05 January 2026 recorded the BKG01, BKG02 and MRD01 locations, photographs, elevations and sampling details. The fieldwork in Telagus on 20 November 2025 recorded the K001–K006 locations, photographs, observations and sampling details. Samples BKG01, BKG02, K001 and K005 were submitted for laboratory analysis. Policy and industrial sources were excluded from technical quality scoring. Data preparation standardised commodity names, sample identifiers, coordinate fields, units and treatment of missing values. Sample identifiers were standardised to BKG01, BKG02, K001 and K005. Results reported as not detected remained ND. Undefined dashes remained distinct from zero. Bulk kaolin XRD was kept separate from the fraction below 63 µm. XRF, ICP-MS, petrography, XRD, FESEM and EDS were also kept as distinct analytical data types. Table 4 identifies the principal data sources and limitations.

Table 4. Data classification and use in the manuscript

Evidence or dataset	Records used	Analytical function	Verification and limitation
Statewide mineral occurrence	JMG MyGEMS 2024 and government occurrence records	Commodity, district/division and occurrence point mapping	Government source cross check; not a certified reserve inventory
Marudi primary research data	BKG01–MRD01 field records; BKG01 and BKG02 laboratory samples; field sampling: 05 Jan 2026	Field verification, sample comparison and silica pathway screening	Two laboratory samples only; no deposit wide grade or continuity
Telagus primary research data	K001–K006 field records; K001 and K005 laboratory samples; field sampling: 20 Nov 2025; broader Telagus planning data	Field verification, sample comparison and kaolin pathway screening	Two laboratory samples; broader planning results remain separate from the sample results
Imagery and map context	Global Mapper Pro 26.0.2 (64-bit; b121824); Google Earth Pro 7.3.7.1155 (64-bit); accessed 30 Jun 2026	Point plotting, figure preparation, coordinate and context checks	Marudi image 18 Mar 2016 (7 km); Telagus 03 Jan 2024 (5 km); overview 200 km; no polygon overlay
Port and logistics context	Six port coordinates, port type and reported draft	Contextual comparison of mapped occurrences and transport nodes	No network, buffer or distance analysis was performed
Specification literature	Cited silica sand and kaolin evaluation and processing studies	Product requirements, screening ranges and recommended tests	Planning ranges, not universal standards or product certification
Policy and industry context	JMG 2025–2026, PCDS 2030 and NIMP 2030	Production, establishment and strategic context	Context only; excluded from technical pathway classification
Laboratory characterisation of field samples	BKG01, BKG02, K001 and K005; physical, mineralogical, chemical, trace element and microstructural results	Measured results from four samples for specification and processing screens	Several method settings, raw replicates and batch QA/QC results are unavailable; qualified values remain qualified

3.3 Geological distribution mapping method

The mapping input comprised 12 statewide occurrence records: ten silica sand points and two kaolin points. The minimum attribute fields were commodity, district or area, division, latitude and longitude. All occurrence and field coordinates were standardised in geographic latitude and longitude using the World Geodetic System 1984 coordinate reference system (WGS 84; EPSG:4326) and stored as decimal degrees. Where a source coordinate was recorded in degrees, minutes and seconds, it was converted using $DD = D + M/60 + S/3600$, with north and east values treated as positive. Names were standardised, latitude and longitude ranges were checked for Sarawak, and each record was opened through its direct map link to identify transcription errors or obvious positional outliers.

The cleaned points were plotted as two commodity classes and labelled using the identifiers in Table 5. The statewide map and the port context map were descriptive point displays. Basemap and imagery were used to show geographic setting, while district/division fields supplied the administrative context. No interpolation, density surface, prospectivity modelling, buffer analysis, road network analysis, raster reclassification, weighted overlay or projected distance calculation was undertaken. Accordingly, road, river, land use, landform and environmental descriptions in Table 19 are desktop contextual interpretations rather than outputs from formal polygon overlay layers. Point plotting and figure preparation used Global Mapper Pro version 26.0.2 (64-bit; build b121824). Google Earth Pro version 7.3.7.1155 (64-bit) supported visual coordinate and imagery checks. The Marudi satellite image was dated 18 March 2016 and prepared with an approximate displayed extent of 7 km. The Telagus satellite image was dated 03 January 2024 and prepared with an approximate displayed extent of 5 km. The statewide overview map used an approximate displayed extent of 200 km. Basemap and imagery were accessed on 30 June 2026. These displayed extents describe the map views and are not formal representative fractions.

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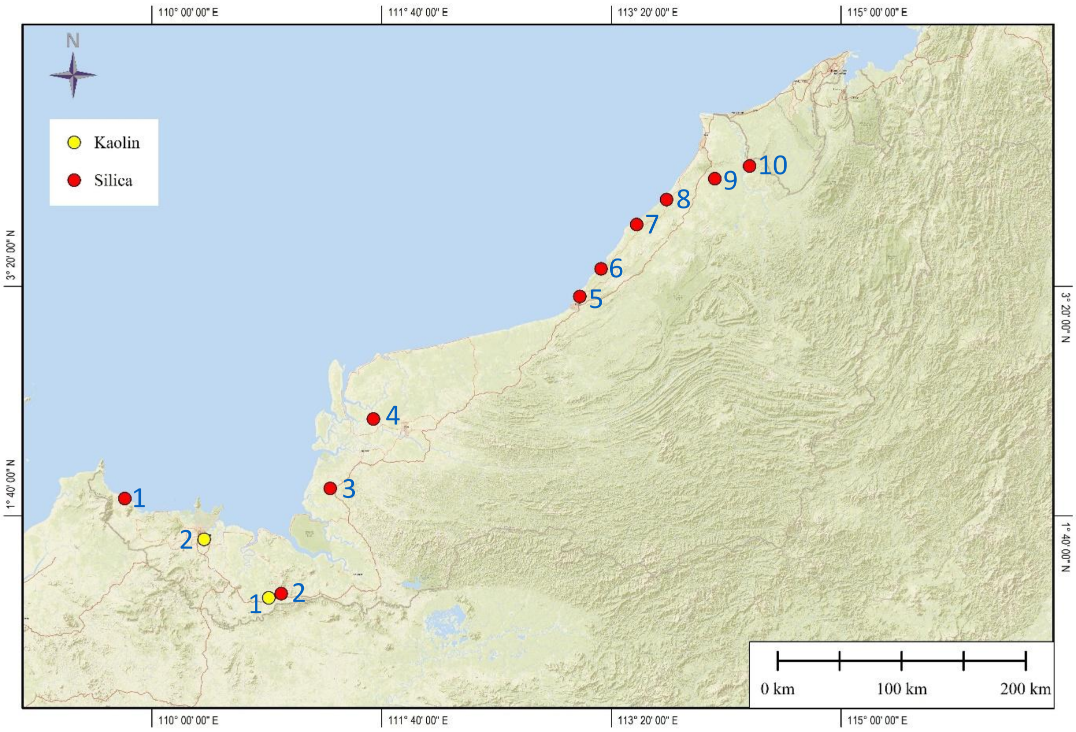
Table 5. Distribution coordinates of silica sand and kaolin occurrence areas in Sarawak

Map	Commodity	District or area	Division	Northing	Easting
1	Silica sand	Lundu	Kuching	1.791	109.804
2	Silica sand	Simunjan	Sri Aman	1.101	110.938
3	Silica sand	Roban	Betong	1.866	111.293
4	Silica sand	Daro	Mukah	2.37	111.607
5	Silica sand	Tg. Kidurong	Bintulu	3.26	113.104
6	Silica sand	Similajau	Bintulu	3.461	113.258
7	Silica sand	Niah	Miri	3.782	113.517
8	Silica sand	Niah	Miri	3.964	113.734
9	Silica sand	Kuala Nyabor	Miri	4.116	114.084
10	Silica sand	Marudi	Miri	4.208	114.336
1	Kaolin	Simunjan	Serian	1.071	110.848
2	Kaolin	Kuching	Kuching	1.496	110.379



Map 1. Distribution of silica sand and kaolin resources in Sarawak (WGS 84; approximate displayed extent 200 km; imagery accessed 30 June 2026)

3.4 Field verification and primary data treatment

Field verification used a Garmin GPSMAP 65S at three Marudi locations (BKG01, BKG02 and MRD01) on 05 January 2026 and six Telagus locations (K001–K006) on 20 November 2025. Laboratory samples BKG01 and BKG02 are linked to Marudi, while K001 and K005 are linked to Telagus. Field coordinates were standardised to WGS 84 (EPSG:4326). The recorded locations and surface conditions support planning level interpretation, but they do not define surveyed boundaries. The broader Telagus geology, mineral composition, exploration, processing and pilot test information was evaluated as primary research data. These data were analysed separately from the laboratory results for K001 and K005. The Marudi area, thickness and tonnage interpretations were also kept separate from the four laboratory samples. The positional accuracy specification for the Garmin GPSMAP 65S was not recorded. The field recording procedure also requires further method detail. This limitation affects final survey method reporting but does not alter the stated links between the samples and study areas.

Map 2. Fieldwork locations (Marudi fieldwork: 05 January 2026; Telagus fieldwork: 20 November 2025)

3.5 Laboratory and specification interpretation

Laboratory analyses characterised BKG01 and BKG02 as Marudi silica sand, plus K001 and K005 as Telagus kaolin. Sample preparation included visual inspection, oven drying, homogenisation and pulverisation as required by each method. A single general preparation sequence was not available, so conditions specific to each analysis were retained. LOI followed ASTM C114 principles with minor modifications. Approximately 1 g was heated at 1000°C for 1 h. Moisture followed ASTM D2216/D2216M using 20–50 g portions dried at 105 ± 5°C to constant mass. Reported means and standard deviations describe three replicates, but the wet and dry masses were not provided. Silica particle size followed ASTM C136/C136M principles. Dried material was shaken for 10–15 min through 2.00, 1.00, 0.50, 0.25, 0.125 and 0.063 mm sieves plus a pan. The exact starting masses were absent. The reported percentages retained total 99.47% for BKG01 and 99.51% for BKG02. Kaolin sedimentation followed ASTM D7928 principles with a 152H hydrometer, a 50 g portion dried in an oven and 40 g/L sodium hexametaphosphate. The suspension was soaked for 16–24 h and mixed for 1–2 min. Readings extended from 30 s to 24 h. Temperature, meniscus, blank, effective depth and particle diameter corrections were not reported. The sand, silt and clay fractions are therefore preliminary operational estimates.

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Silica petrography used thin sections approximately 30 µm thick that were impregnated with epoxy. A Leica DM750P polarising microscope was used. The observations are qualitative because no point count method was reported. XRD used a Bruker D8 Advance with Cu Kα radiation at I-CRIM, Universiti Kebangsaan Malaysia. Bulk silica powders were analysed, whereas the bulk kaolin and fraction below 63 µm were kept separate. XRD abundances are semiquantitative.

Major and minor oxides were measured by wavelength dispersive XRF using a Rigaku ZSX Primus IV at I-CRIM, Universiti Kebangsaan Malaysia. Fused glass beads were prepared with lithium tetraborate flux. Results are reported in mass %. Calibration details, certified reference materials, replicate results and uncertainties were not supplied. Trace elements and rare earth elements were measured with a PerkinElmer NexION 2000 quadrupole ICP-MS after microwave acid digestion at I-CRIM, Universiti Kebangsaan Malaysia. Silica values were screened by TotalQuant and are semiquantitative. The conversion from raw solution values in ppb to the reported solid values in mg/kg is not reproducible from the available analytical details. Kaolin concentrations in the main table were retained on the reported solid basis. The inconsistent K001 zirconium calculation example was not used. Kaolin morphology was examined with a Thermo Scientific Quattro S FESEM and UltraDry EDS. Image footers show 5.00 kV, low vacuum detector mode and a 5.0 mm working distance. FESEM observations describe selected fields. EDS values are localised spot measurements and are not equivalent to bulk XRF. Literature ranges in Tables 15 and 16 remained planning screens rather than test results. Table 6 summarises the analytical methods.

Table 6. Laboratory analytical programme, instruments and principal limitations

Method	Samples	Procedure or standard	Instrument / institution	Key conditions	Principal limitation
Preparation	All four	Laboratory procedure	Not specified	Visual check; drying; homogenisation; pulverisation as applicable	Exact conditions vary by analysis
LOI	All four	ASTM C114 principles; minor modifications	Muffle furnace; laboratory not specified	~1 g; 1000°C; 1 h	Modifications, replicates and CRM results absent
Moisture	All four	ASTM D2216/D2216M	Drying oven; laboratory not specified	20–50 g; 105 ± 5°C; constant mass	Raw replicate masses absent
Dry sieve	BKG01; BKG02	ASTM C136/C136M principles	Mechanical sieve shaker; laboratory not specified	2.00–0.063 mm plus pan; 10–15 min	Exact initial masses absent
Hydrometer	K001; K005	ASTM D7928 principles	152H hydrometer; laboratory not specified	50 g; 40 g/L dispersant; 30 s–24 h	Correction data absent; fractions preliminary
Petrography	BKG01; BKG02	Thin section petrography	Leica DM750P; laboratory not specified	~30 µm sections; PPL/XPL	Qualitative; no point count
XRF	All four	Laboratory WDXRF procedure	Rigaku ZSX Primus IV; I-CRIM, UKM	Lithium tetraborate fused beads	Calibration and uncertainty details incomplete
ICP-MS	All four	Microwave digestion; quadrupole ICP-MS	PerkinElmer NexION 2000; I-CRIM, UKM	Calibration at five points; TotalQuant for silica	Silica conversion and batch QA/QC incomplete
XRD	All four	Powder XRD; ICDD matching	Bruker D8 Advance; I-CRIM, UKM	Cu Kα; bulk plus <63 µm kaolin	Semiquantitative; scan settings incomplete
FESEM with EDS	K001; K005	High vacuum imaging with EDS	Thermo Scientific Quattro S / UltraDry	Material coated with gold on carbon tabs	Selected images; EDS localised only

3.6 Downstream product matching method

Downstream product matching used an assessment with five gates. The gates were occurrence identity, measured material results, product requirements, processing constraints and pathway status. Each pathway was assigned one permitted status: Potential, Conditional or Further testing required. Potential requires direct support for a route with less stringent requirements. Conditional identifies a plausible route that depends on stated processing or confirmation. Further testing required applies where essential product data are missing or inconsistent. Laboratory results were compared parameter by parameter. No numerical weights, aggregate score or favourable default was used. Quantitative XRF and moisture results were not combined with semiquantitative XRD, qualitative petrography, selected FESEM images or local EDS spots. Missing brightness, performance and beneficiation results remained explicit gaps. A separate location status rule remained applicable to the 12 mapped occurrences in Table 19. High, Medium and Low describe the strength of available data and visible planning sensitivity. They are not product pathway terms. Tables 8, 9, 12 and 13 present the product screens based on laboratory results.

3.7 Study limitations

The laboratory results represent two Marudi silica sand samples and two Telagus kaolin samples. They do not establish lateral or vertical continuity, grade across either deposit, mineable tonnage or reserve status. Moisture means cannot be independently reproduced because replicate wet and dry masses are absent. The silica sieve percentages sum to 99.47% and 99.51%. The stated recovery above 99.9% cannot be checked because the starting mass basis is unavailable. Kaolin hydrometer fractions are preliminary because essential corrections and particle diameter calculations are absent. XRD percentages are semiquantitative. Both bulk kaolin samples are dominated by quartz in the numerical results, despite a conflicting narrative interpretation. FESEM observations represent selected fields. EDS values are localised. Duplicate K001 EDS entries were not treated as independent measurements.

Several chemical results require qualification. The reported silica SO_3 values fall below appendix detection limits. The BKG02 SeO_2 asterisk is undefined. Kaolin XRF dashes were not interpreted as zero or ND. The BKG02 Cu value of 46.60 mg/kg requires fully quantitative confirmation. The silica ICP-MS conversion basis is incomplete, and the K001 appendix zirconium example conflicts with the main result. Ce and Eu anomalies were not calculated because normalised values and equations were unavailable. Complete XRD scan settings, ICP-MS batch QA/QC results, method uncertainties, raw hydrometer worksheets and replicate analytical results were not supplied. Brightness, whiteness, beneficiation recovery, firing performance, rheology, product manufacturing and market acceptance were not tested. These analytical qualifications remain unresolved. The GIS component remains descriptive. No predictive prospectivity surface, weighted overlay, network analysis, buffer model or environmental suitability calculation was applied. The categorical uncertainty check therefore remains appropriate. If the results from the four samples are excluded, support for Marudi and Telagus is reduced to occurrence context.

4. Results and Discussion

4.1 Distribution of silica sand resources in Sarawak

Silica sand resources in Sarawak are distributed across several coastal, fluvial and sedimentary settings. The main occurrence areas include Lundu, Simunjan, Roban, Daro, Tanjung Kidurong, Similajau, Niah, Kuala Nyabor and Marudi. The distribution shows that silica sand is not restricted to one geological province. It follows environments where quartz rich sand may accumulate, be reworked or be preserved [1–3,32]. National resource records identify silica sand as one of Malaysia's industrial mineral resources, with Sarawak included among the listed states. However, recent production data show limited silica sand output from Sarawak compared with larger producing states. This indicates that the main issue is not only resource presence. Data completeness, processing capability, permitting, logistics and product grade confirmation also control development potential [7–8]. The distribution pattern has direct downstream implications. Areas near roads, ports, power supply, water sources or industrial clusters are more likely to support staged development. More remote occurrences may still be important, but they require stronger logistics justification and more detailed quality confirmation.

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4.2 Distribution of kaolin resources in Sarawak

Kaolin resources in Sarawak are more limited in publicly documented distribution than silica sand. The main known areas are Simunjan or Serian and Kuching. Telagus is the main kaolin study area. This distribution suggests that kaolin occurrence is controlled by local geological conditions rather than broad regional continuity [15,20,27]. Government records identify kaolin as part of Malaysia's industrial mineral base and include Sarawak in the national kaolin inventory. Recent production statistics show no regular kaolin production from Sarawak in the reported period. This does not mean kaolin is absent. It means that known kaolin occurrences have not yet been converted into consistent reported production [7–8]. Kaolin distribution must be interpreted cautiously because quality can vary strongly over short distances. Mineralogy, brightness, Fe_2O_3, TiO_2, quartz, mica, particle size, plasticity and firing behaviour must be assessed before product potential can be claimed.

4.3 Marudi silica sand results

Marudi silica sand is represented by the Bakong silica sand mine area. Fieldwork and sampling were completed on 05 January 2026. BKG01 and BKG02 are the two laboratory samples used here. Site coordinates were standardised to WGS 84 (EPSG:4326) and checked against imagery dated 18 March 2016. The field locations, mine exposures, sampling activities and inactive processing plant are documented in Map 3 and Figures 3–8. The mapped area is estimated at about 7,061,745 m², or approximately 706 ha. An interpreted thickness of about 10 m gives an indicative in situ volume near 70,617,450 m³. These planning estimates were derived from the Marudi field and mapping data rather than BKG01 or BKG02. They are not certified resources or reserves.

Table 7. Marudi fieldwork coordinates recorded on 05 January 2026

ID	Latitude	Longitude	Elevation
BKG01	4.256404	114.244663	106.79608
BKG02	4.257359	114.249656	42.537903
MRD01	4.184718	114.351744	18.029678

Map 3. Marudi fieldwork locations (BKG01, BKG02 and MRD01), satellite image dated 18 March 2016 and approximate displayed extent 7 km

Figure 3. Inactive silica sand mine (BKG01)

Figure 4. Inactive silica sand mine (BKG02)

Figure 5. Sampling work (BKG01)

Figure 6. Sampling work (BKG02)

Figure 7. Front view of inactive silica sand processing plant (MRD01)

Figure 8. Rear view of inactive silica sand processing plant (MRD01)

BKG01 is light cream to pale beige, fine to medium sand with moderate sorting and slight localised iron staining. BKG02 is very light grey to off white, finer, well sorted and predominantly subrounded. Mean moisture is 5.73 ± 0.37% for BKG01 and 5.49 ± 0.70% for BKG02. The reported D50 values are 0.276 mm and 0.231 mm, respectively. Both samples are concentrated between 0.125 and 0.500 mm. The percentages retained require the mass balance qualification stated in Section 3.7. Petrography shows grain supported sands rich in quartz. BKG01 contains minor feldspar, trace heavy minerals and rare opaque grains. BKG02 is more uniform and has fewer coatings. These are qualitative observations. Semiquantitative XRD estimates 92.6% quartz plus 7.4% metamict or partially metamict zircon in BKG01. BKG02 records 95.9% quartz plus 4.1% zircon phase.

XRF records 97.3026 mass % SiO_2 in BKG01 and 98.2505 mass % in BKG02. BKG02 has lower LOI at 0.9800 mass % and lower ZrO_2 at 0.0294 mass %. BKG01 records 1.9200 mass % LOI and 0.0693 mass % ZrO_2. However, BKG02 has higher Al_2O_3, TiO_2 and Fe_2O_3. It is therefore incorrect to describe every impurity as lower in BKG02. The reported total REE content is 13.00 mg/kg for BKG01 and 7.98 mg/kg for BKG02. These silica ICP-MS values are semiquantitative because the solid sample conversion is not reproducible from the available analytical details. The reported BKG02 Cu value of 46.60 mg/kg is anomalous and requires fully quantitative confirmation. The value is not used to support product qualification. The measured results support Potential for general industrial silica. Construction use, container glass and filtration media are Conditional. Foundry sand, ceramics, flat glass and routes with stricter specifications require further testing. Washing, attrition, sizing and magnetic separation should be evaluated before tests for specific products [11–12,14]. Tables 8 and 9 provide the main comparison.

Table 8. Physical, particle size, petrographic and XRD comparison of BKG01 and BKG02

Sample	Macroscopic character	Moisture (%)	D10 / D30 / D50 / D60 (mm)	Petrography (qualitative)	XRD (%, semiquantitative)
BKG01	Light cream to beige; fine to medium; moderate sorting; slight local staining	5.73 ± 0.37	0.142 / 0.202 / 0.276 / 0.313	Quartz >95% visual estimate; subangular to subrounded; minor feldspar and trace heavies	Quartz 92.6; zircon phase 7.4
BKG02	Very light grey to off white; fine; well sorted; no obvious staining	5.49 ± 0.70	0.139 / 0.179 / 0.231 / 0.266	Quartz >97% visual estimate; predominantly subrounded; very minor feldspar and trace heavies	Quartz 95.9; zircon phase 4.1

Note: Petrographic visual estimates are not modal analyses. XRD percentages are semiquantitative.

Table 9. Selected LOI, XRF, trace element and REE comparison of BKG01 and BKG02

Parameter	BKG01	BKG02	Comparison or qualification
SiO_2 (mass %)	97.3026	98.2505	BKG02 higher
LOI (mass %)	1.9200	0.9800	BKG02 lower
Al_2O_3 (mass %)	0.1353	0.1576	BKG02 higher
TiO_2 (mass %)	0.2874	0.3409	BKG02 higher
Fe_2O_3 (mass %)	0.0465	0.0747	BKG02 higher
ZrO_2 (mass %)	0.0693	0.0294	BKG02 lower
Total REE (mg/kg)	13.00	7.98	BKG02 lower; semiquantitative screening
Cu (mg/kg)	1.92	46.60	BKG02 requires fully quantitative confirmation

Note: Silica ICP-MS and REE values are semiquantitative. The SO_3 and SeO_2 qualifications are stated in Section 3.7.

4.4 Telagus kaolin results

Telagus kaolin occurs in Simunjan District, Serian Division. Fieldwork and sampling were completed on 20 November 2025. K001 and K005 are the two laboratory samples analysed here. Site coordinates were standardised to WGS 84 (EPSG:4326) and checked against imagery dated 03 January 2024. The area includes white, mottled and grey clay associated with weathered rocks that contain feldspar. Field locations, test trenches, planning areas and sampling activities are documented in Map 4 and Figures 9–16. Telagus mineral data record wide ranges of kaolinite, quartz and mica. These broader site data were analysed separately from the K001 and K005 laboratory results. The results for the two samples are presented by sample and analysed fraction.

Table 10. Telagus fieldwork coordinates recorded on 20 November 2025

ID	Latitude	Longitude	Elevation
K001	1.058977	110.87203	49.945431
K002	1.05493	110.874302	49.007523
K003	1.048999	110.858383	36.99472
K004	1.038656	110.825781	87.888832
K005	1.059919	110.856175	45.104866
K006	1.042115	110.836479	30.409927

Map 4. Telagus fieldwork locations (K001–K006), satellite image dated 03 January 2024 and approximate displayed extent 5 km

Figure 9. Excavated test trenches area (K001)

Figure 10. Excavated test trenches area (K001)

Figure 11. Kaolin reserve area (K003)

Figure 12. Kaolin reserve area (K004)

Figure 13. Kaolin reserve area (K005)

Figure 14. Kaolin reserve area (K006)

Figure 15. Sampling work (K002–K006)

Figure 16. Hand auger sampling work (K001)

Telagus resource and processing data provide broader feedstock context. They indicate approximately 25.368 Mt, a reported kaolin grade near 56%, water content near 28% and quartz near 35%. These planning values were derived independently of K001 and K005. Proposed processing concepts include classification, grit removal, flotation, filtration, drying, magnetic separation and fine grinding.

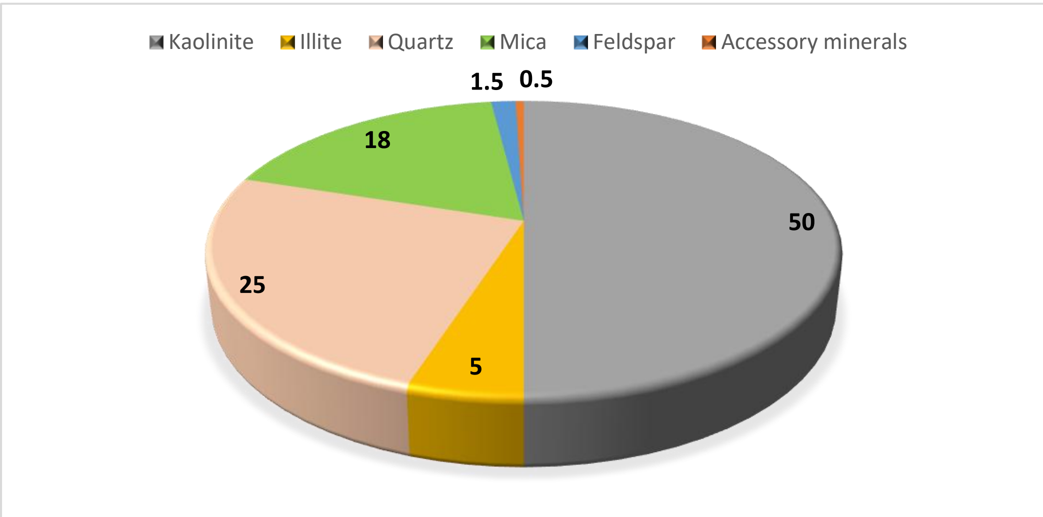

Figure 17. Pie chart for the average mineral composition (%) of Telagus crude clay

Table 11. Average mineral composition of Telagus crude clay

Mineral composition	Percentage (%)
Kaolinite	20–70
Illite	0–10
Quartz	19–68
Mica	3–47
Feldspar	Traces
Accessory minerals	Pyrite, chalcopyrite, cassiterite, zircon

K001 is a light grey to pale beige, compact and slightly plastic material. K005 is white to creamy, friable and powdery. Mean moisture is 28.90 ± 1.73% for K001 and 35.44 ± 0.72% for

K005. Preliminary hydrometer fractions are 10% sand, 44% silt and 46% clay for K001. K005 records 14% sand, 36% silt and 50% clay. These fractions retain the limitation caused by missing correction data stated in Section 3.7.

The bulk XRD results are dominated by quartz. K001 contains 82.1% quartz, 6.9% kaolinite, 3.2% halloysite, 3.6% illite and 4.2% muscovite. K005 contains 55.9% quartz, 17.7% kaolinite, 12.9% halloysite, 4.6% illite and 8.8% muscovite. Size separation changes the assemblage. The K001 fraction below 63 µm contains 66.4% kaolinite plus 33.6% montmorillonite/chlorite. The K005 fraction below 63 µm contains 82.1% kaolinite plus 17.9% sanidine. Percentages for the bulk and fine fractions are not combined.

FESEM shows platy and stacked lamellar particles in both samples. K005 includes well-formed platelet aggregates and a bright accessory grain in one field. No consistently tubular halloysite morphology was reported. EDS confirms local areas rich in Al, Si and O, together with selected accessory element spots. The spot results do not represent bulk composition. Duplicate K001 entries were excluded as independent measurements.

XRF records 63.210 mass % SiO_2, 23.776 mass % Al_2O_3, 1.253 mass % Fe_2O_3, 1.409 mass % TiO_2, 1.547 mass % K_2O and 7.920 mass % LOI in K001. K005 records 50.684 mass % SiO_2, 34.683 mass % Al_2O_3, 1.456 mass % Fe_2O_3, 1.197 mass % TiO_2, 1.597 mass % K_2O and 9.800 mass % LOI. The XRF dashes remain undefined and are not treated as zero or ND.

Reported total REE is 146.682 mg/kg for K001 and 82.626 mg/kg for K005. The corresponding LREE/HREE ratios are 11.83 and 21.41. Ce and Eu anomalies are not calculated. K005 has lower bulk quartz, more kaolinite in the fine fraction and higher Al_2O_3. It also has lower TiO_2 and total REE. Its moisture, LOI, Fe_2O_3, bulk muscovite and bulk halloysite are higher.

General ceramics is Conditional. Tiles, sanitaryware, porcelain, paper filler, paper coating, paint, rubber filler, polymer filler, calcined kaolin, metakaolin, cementitious materials, adsorbents and bleaching earth require further testing. Wet classification and grit removal should be tested first. Brightness, rheology, firing and functional performance remain essential [15,17,19–20]. Tables 12 and 13 provide the main comparison.

Table 12. Physical, particle size, XRD and FESEM comparison of K001 and K005

Sample	Macroscopic character and moisture	Preliminary sand / silt / clay (%)	Bulk XRD (%, semiquantitative)	<63 µm XRD (%, semiquantitative)	FESEM / EDS boundary
K001	Compact, cohesive, light grey to beige; 28.90 ± 1.73% moisture	10 / 44 / 46	Quartz 82.1; kaolinite 6.9; halloysite 3.2; illite 3.6; muscovite 4.2	Kaolinite 66.4; montmorillonite/chlorite 33.6	Platy/booklet aggregates; local EDS only
K005	Friable, white to creamy; 35.44 ± 0.72% moisture	14 / 36 / 50	Quartz 55.9; kaolinite 17.7; halloysite 12.9; illite 4.6; muscovite 8.8	Kaolinite 82.1; sanidine 17.9	Platy/lamellar aggregates; local EDS only

Note: Hydrometer fractions are preliminary operational estimates. Bulk and <63 µm XRD results are separate analytical fractions.

Table 13. Selected LOI, XRF, trace element and REE comparison of K001 and K005

Parameter	K001	K005	Comparison or qualification
SiO_2 (mass %)	63.210	50.684	K005 lower
Al_2O_3 (mass %)	23.776	34.683	K005 higher
K_2O (mass %)	1.547	1.597	K005 slightly higher
Fe_2O_3 (mass %)	1.253	1.456	K005 higher
TiO_2 (mass %)	1.409	1.197	K005 lower
LOI (mass %)	7.920	9.800	K005 higher
Total REE (mg/kg)	146.682	82.626	K005 lower
LREE/HREE	11.83	21.41	K005 higher ratio; no Ce/Eu anomaly calculated

Note: XRF values are bulk results. ICP-MS and REE values retain the reported solid basis and the limitation caused by incomplete batch QA/QC results.

4.5 Specification based downstream potential of silica sand

Marudi downstream screening uses measured purity, impurities, LOI, particle size, petrography, XRD and trace element results. General industrial silica is Potential. Construction use, container glass and filtration media are Conditional. Foundry sand, ceramics, flat glass, solar glass, optical glass, pharmaceutical glass, engineered stone, silica filler and high purity silica require further testing. Table 14 reports the status groups. Table 15 retains screening ranges from the literature as planning references [11–14]. BKG02 has higher SiO_2 and quartz estimated by XRD, plus lower LOI, zircon, total REE and median particle size. It also has higher Al_2O_3, TiO_2 and Fe_2O_3. Neither sample is qualified for foundry, glass, filtration or high purity use. Required work includes representative variability sampling, washing and attrition trials, magnetic separation, acid leaching where justified, AFS testing, filter media testing, melt trials and quantitative confirmation of anomalous trace results.

4.6 Specification based downstream potential of kaolin

Telagus downstream screening uses measured mineralogy from the bulk and fine fractions, moisture, preliminary particle fractions, FESEM observations, local EDS spots, bulk chemistry and trace element data. General ceramics is Conditional. Every other screened kaolin route requires further testing. Table 14 reports the status groups, while Table 16 retains planning ranges from the literature. K005 has more kaolinite in the fine fraction and higher Al_2O_3, but it also has higher moisture, LOI and Fe_2O_3. K001 has more bulk quartz, higher TiO_2 and higher total REE. Neither sample has brightness, whiteness, <2 μm fraction, grit, rheology, plasticity, fired colour, shrinkage, strength, surface area, pozzolanic activity or adsorption data. Paper filler and paper coating therefore require further testing [17–19,33].

Table 14. Downstream product pathway classification based on stated rules

Material	Potential	Conditional	Further testing required	Priority verification
Silica sand	General industrial silica	Construction use; container glass; filtration media	Foundry sand; ceramics; flat, solar, optical and pharmaceutical glass; engineered stone; silica filler; high purity silica	Variability sampling; beneficiation; product PSD; AFS, filter or melt tests; quantitative trace confirmation
Kaolin	None	General ceramics	Tiles; sanitaryware; porcelain; paper filler/coating; paint; rubber/polymer filler; calcined kaolin; metakaolin; cementitious materials; adsorbents; bleaching earth	Wet classification; brightness; rheology; firing; calcination; pozzolanic, activation and product tests

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Table 15. Silica sand screening ranges and recommended verification tests

Parameter (unit)	**Literature derived screening ranges (Baseline / Glass / Foundry)**	**Why it matters**	**Recommended verification test**
SiO_2 (%)	B ≥90 | G ≥95–99+ | F ≥95–99	Primary purity driver	XRF (bulk); confirm quartz by XRD
Fe_2O_3 (%)	B ≤1.0 | G ≤0.05–0.15 | F	Colour (glass) + refractoriness	ICP/XRF; magnetic fraction check
Al_2O_3 (%)	B ≤5 | G ≤0.5–2.0 | F ≤1.0–2.5	Clay/feldspar proxy; melt/thermal impact	XRF + XRD; LOI + fines check
TiO_2 (%)	B ≤1.0 | G ≤0.05–0.2 | F ≤0.2–0.5	Glass colour; heavy mineral indicator	XRF; heavy mineral screening
CaO+MgO (%)	B ≤5 | G ≤0.1–1.0 | F ≤0.5–2.0	Carbonates affect melt/sintering	XRF; HCl fizz screen (field)
Na_2O+K_2O (%)	B ≤3 | G ≤0.2–1.5 | F ≤0.5–2.0	Alkalis affect glass chemistry (feldspar)	XRF; petrography (optional)
LOI (%)	B ≤3–5 | G ≤0.2–1.0 | F ≤0.5–2.0	Coatings/organics; gas defects	LOI at 950–1000°C
Fines <63/75 μm (%)	B ≤10–15 | G ≤0.5–2.0 | F ≤1–3	Turbidity; binder demand; defects	Wet sieving (+ hydrometer/laser if available)
PSD / grading (mm)	B broad | G tight/controlled | F controlled AFS range	Packing, melt consistency, permeability	Sieve analysis (ASTM/ISO equivalent)
AFS GFN (GFN)	B n/a | G n/a | F ~40–70 (product)	Foundry sizing standard	Sieve set + AFS GFN calculation
Clay lumps & friables (%)	B ≤3–10 | G ≤0.1–0.5 | F ≤0.5–2.0	Casting defects; higher binder demand	ASTM clay lumps; visual + wash loss
Heavy minerals (qual/%)	B monitor | G very low | F low/controlled	Fe/Ti heavies affect colour/refractoriness	Panning screen; magnetic fraction; Frantz (optional)
Moisture (%)	B specific to the project | G low/controlled | F controlled	Handling + screening + binder behaviour	Moisture content by oven drying
Grain shape / angularity (qual)	B any | G rounded to subrounded | F subangular to rounded	Flowability (glass) vs strength/permeability (foundry)	Microscope + roundness chart (image optional)
Colour / staining (qual)	B any | G low staining | F low staining	Quick proxy for Fe/organics coatings	Visual + dilute acid wash check
Acid solubility / carbonate reaction (qual/%)	Optional (all)	Carbonates/soluble impurities indicator	Simple HCl test; lab acid solubility if needed
Radioactivity / NORM (screen)	Not typical | If export/customer requires | If export/customer requires	Market compliance risk screen	Gamma survey (where required)
Planning level pathway decision	B Construction material | G Potential glass feed (after cleaning/upgrading) | F Potential foundry sand (after sizing/cleaning)	Suitability statement without overclaiming	Apply rule

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Table 16. Kaolin screening ranges and recommended verification tests

Parameter (unit)	Literature derived screening ranges (Baseline / Functional / Activated)	Why it matters	Recommended verification test
Brightness (ISO, %)	B ≥75–85 | F ≥85–92+ | A not primary	Key value driver for paper, paint, fillers, and premium ceramics	ISO brightness (reflectance)
Whiteness / L* (CIELAB)	B moderate to high | F high + consistent | A not primary	Colour consistency controls premium product acceptance	Colorimetry (L*a*b*)
Fe_2O_3 (%)	B ≤1.0–2.0 | F ≤0.5–1.0 | A ≤2.0 (dependent on route and final use)	Iron lowers brightness and signals impurity minerals	XRF/ICP + XRD check
TiO_2 (%)	B ≤0.5–1.5 | F ≤0.3–0.8 | A ≤1.5 (process dependent)	Ti phases reduce brightness and can be difficult to remove	XRF + XRD (rutile/anatase)
Al_2O_3 (%)	B high/moderate (proxy) | F high + consistent | A not primary	Proxy for kaolinite content and feed consistency	XRF + XRD (phase estimate)
SiO_2 (free quartz, %)	B low to moderate tolerated | F low (minimise) | A low to moderate (depends processing)	Quartz increases abrasion and affects rheology and firing	XRD (semiquantitative) + wet sieving (sand fraction)
Kaolinite content (%/qual)	B moderate to high | F high (preferred) | A moderate (if activation works)	Main functional phase controlling performance in the final use	XRD (semiquantitative); thermal (optional)
Accessory minerals (qual)	B controlled | F low | A acceptable (route dependent)	Affects plasticity, shrinkage, rheology, and product quality	XRD; Atterberg (if needed)
Particle size (d50 / <2 μm, μm/%)	B moderate PSD; moderate <2 μm | F high <2 μm; fine + narrow | A fine powder supports activation (not alone sufficient)	Controls opacity, dispersion, rheology, and surface behaviour	Laser PSD / hydrometer; wet classification
Residue on 325 mesh (45 μm, %)	B ≤1–5 | F ≤0.5–1.0 | A ≤1–3	Coarse grit causes abrasion and defects	Sieve residue (45 μm)
Moisture (%)	B controlled | F controlled (tight) | A controlled	Handling, storage, and activation consistency	Oven moisture
LOI (%)	B ~10–15 (confirm) | F consistent range (tight) | A route dependent; monitor pre/post	Proxy for kaolinite + bound water and consistency	LOI at specified T
pH (slurry, pH)	B project specific | F project specific | A low pH for acid activation; monitor response	Dispersion, processing behaviour, and activation chemistry	pH meter (slurry)
Cation exchange capacity (CEC, meq/100g)	B low to moderate | F low (preferred) | A higher activity post activation (if successful)	Relates to adsorption and bleaching performance	CEC test (activation focused, optional)
Specific surface area (BET, m²/g)	B optional | F optional | A high (preferred)	Correlates with adsorption capacity and bleaching efficiency	BET (activation focused)
Oil absorption / adsorption index (dimensionless)	B optional | F optional | A high (preferred)	Practical proxy for adsorbent and bleaching earth performance	Simple oil adsorption test (if available)
Plasticity (Atterberg, PI)	B optional | F controlled + consistent | A not primary	Controls forming behaviour for ceramics	Atterberg limits (ceramics focus)
Firing behavior (shrinkage/whitenes s after firing, %/qual)	B project specific | F better + consistent | A not primary	Indicates ceramic suitability and product consistency	Simple firing tests (proposal optional)
Contaminants (organic matter, staining, grit, qual)	B low | F very low | A low (pre activation)	Affects brightness, processing stability, and final performance	Visual + LOI + residue
Planning level pathway decision	B ceramics/fillers feed | F functional filler potential (after beneficiation) | A activated clay potential (after activation + performance tests)	Communicates fit for purpose screening rule	Apply classification rule

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4.7 Integrated downstream product pathway framework

The assessment using five gates produces conservative outcomes for the four samples. General industrial silica is Potential. Three silica pathways are Conditional, while the remaining silica routes require further testing. General ceramics is Conditional for the Telagus samples. The other kaolin pathways require further testing. These statuses describe the current level of verification, not market rank. The location rule remains separate. Marudi silica sand and Telagus kaolin retain High indicative location status because field observations and material results are available. Nine occurrences remain Medium. One Niah occurrence in a conservation sensitive area remains Low. These location classes do not certify mineability or product quality. The comparison shows why results for individual samples matter. BKG02 has higher SiO_2, but Fe_2O_3 and TiO_2 are also higher. K005 contains more kaolinite in the fine fraction, but moisture, LOI and Fe_2O_3 are higher. Table 17 links measured support, constraints, processing options and the next tests.

Table 17. Integrated sample results, constraints, pathway status and next verification work

Sample	Commodity	Measured support	Measured constraint	Provisional status	Processing and next tests
BKG01	Silica	97.3026% SiO_2; D50 0.276 mm; XRD quartz 92.6%	LOI 1.9200%; coatings and accessory phases; product tests absent	Potential: general industrial silica; Conditional: selected routes with less stringent requirements	Wash/attrition and magnetic trials; product PSD, AFS, filter and melt tests
BKG02	Silica	98.2505% SiO_2; D50 0.231 mm; XRD quartz 95.9%	Higher Al_2O_3, TiO_2 and Fe_2O_3; Cu 46.60 mg/kg requires confirmation	Potential: general industrial silica; Conditional: selected routes with less stringent requirements	Quantitative trace confirmation; beneficiation and product trials
K001	Kaolin	Bulk quartz 82.1%; <63 µm kaolinite 66.4%; Al_2O_3 23.776%	Quartz rich bulk; TiO_2 1.409%; brightness, firing and rheology absent	Conditional: general ceramics	Wet classification/grit removal; brightness, rheology and firing tests
K005	Kaolin	Bulk quartz 55.9%; <63 µm kaolinite 82.1%; Al_2O_3 34.683%	Moisture 35.44%; LOI 9.800%; Fe_2O_3 1.456%; functional tests absent	Conditional: general ceramics	Classification plus brightness, firing, filler and activation tests

Note: Statuses are for planning purposes and apply to the four samples. They do not establish grade across either deposit, product qualification or commercial feasibility.

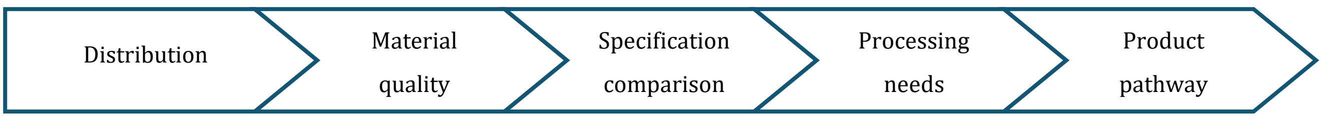


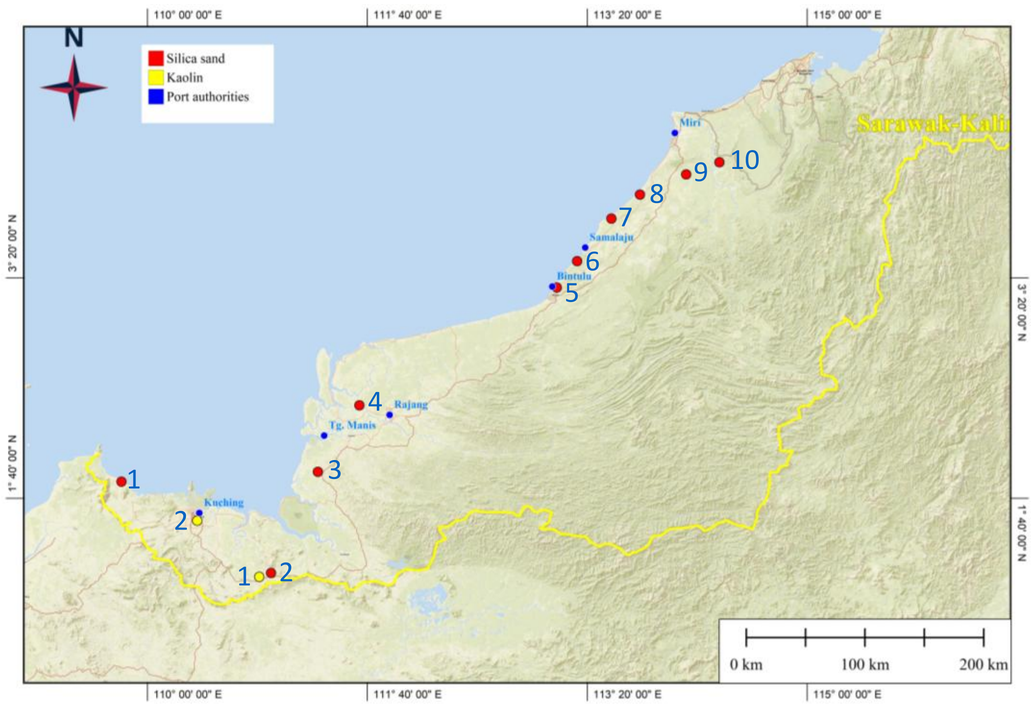
Figure 18. Framework linking distribution to downstream product potential

4.8 Planning implications for Sarawak mineral development

The revised framework converts laboratory gaps into a staged work programme. First, additional systematic sampling and drilling should test lateral and vertical variability. Second, silica trials should examine washing, attrition, sizing, magnetic separation and selective leaching. Kaolin trials should examine wet classification, grit removal, delamination, magnetic separation and controlled blending. Third, qualified feeds should proceed to laboratory and pilot tests for each product. The spatial component remains conservative. Occurrence and port points, imagery, land use descriptions and landform context do not constitute a road network, buffer, weighted overlay or environmental suitability model. The location status reflects the strength of available data and visible planning sensitivity rather than a quantitative GIS score. Infrastructure alignment remains necessary because potential projects require access, power, water, processing sites and customers. Policy alignment does not establish product suitability. Decisions require representative quality data, beneficiation performance, environmental assessment and market validation [9–10], [21,28,30,34].

Table 18. Six major ports along the Sarawak coast

Port Authority	Northing	Easting	Type	Draft
Kuching	1.554998	110.3946	Riverine	7.5
Tg. Manis	2.157549	111.3391	Riverine	11
Rajang	2.290073	111.8232	Riverine	4.6–8.5
Bintulu	3.254234	113.0711	Sea	15
Samalaju	3.562689	113.3191	Sea	13.5
Miri	4.42934	113.9981	Riverine	7.1–9.1



Map 5. Distribution of the study commodities and port authorities in Sarawak [32]

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Table 19. Land use, landform and indicative downstream potential status for all mapped occurrences

Map	Commodity	Land use	Landform	Potential
1	Silica sand	Rural agriculture, forest fringe, settlement, tourism and coastal land use	Coastal foothill and alluvial lowland near Lundu coastal belt	Medium
2	Silica sand	Rural agriculture, paddy, coconut, plantation, settlement and river corridor use	Lowland riverine and swampy alluvial plain	Medium
3	Silica sand	Agriculture, oil palm, smallholder farming, settlement and secondary vegetation	Peat swamp and lowland alluvial plain	Medium
4	Silica sand	Sago, agriculture, plantation, fishing settlement and river transport land use	Coastal deltaic lowland, peat and riverine plain	Medium
5	Silica sand	Industrial, port related, oil and gas, logistics, settlement and disturbed land	Coastal industrial plain near Bintulu port and industrial corridor	Medium
6	Silica sand	Industrial, port related, plantation, forest fringe and coastal land use	Coastal plain near Samalaju and Similajau industrial corridor	Medium
7	Silica sand	Forest, conservation sensitive area, agriculture, settlement and tourism related land use	Karst influenced lowland with limestone hills and forested terrain	Low
8	Silica sand	Plantation, secondary forest, rural settlement and road corridor land use	Undulating lowland to inland terrace between Miri and Bintulu	Medium
9	Silica sand	Plantation, agriculture, rural settlement, secondary forest and river corridor use	Riverine and coastal lowland near northern Sarawak corridor	Medium
10	Silica sand	Rural settlement, agriculture, forest fringe, plantation and access corridor use	Riverine alluvial lowland and terrace near Baram basin	High
1	Kaolin	Rural agriculture, forest fringe, plantation, settlement and project area land use	Clay bearing lowland to gently undulating sedimentary terrain at Telagus	High
2	Kaolin	Settlement, peri urban development, agriculture, road corridor and industrial market access	Lowland to gently undulating urban fringe and sedimentary terrain	Medium

5. Conclusions

This study links statewide occurrence context with primary field data and laboratory results from four silica sand and kaolin samples in Sarawak. BKG01 and BKG02 contain 97.3026 and 98.2505 mass % SiO_2. BKG02 has more quartz estimated by XRD, lower LOI, less zircon and lower total REE. However, it also has higher Al_2O_3, TiO_2 and Fe_2O_3. Bulk K001 and K005 are dominated by quartz. Their fractions below 63 µm contain 66.4% and 82.1% kaolinite, respectively. K005 has higher Al_2O_3 and more kaolinite in the fine fraction, but also higher moisture, LOI and Fe_2O_3. Assessment using five gates assigns Potential to general industrial silica. Construction, container glass and filtration routes are Conditional, while other silica routes require further testing. General ceramics is Conditional for Telagus, while other kaolin routes require further testing. The results support systematic sampling, beneficiation trials and prioritisation of product tests. They do not establish grade across either deposit, reserve status, beneficiation recovery, product qualification or commercial feasibility.

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Conflict of Interest

The authors declare no conflicts of interest.

Generative AI Declarations

During the preparation of this work, the author used ChatGPT for drafting support. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Author Contributions

Mohamad Fiqry Mohd Latif: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft. Dayang Zulaika Abang Hasbollah: Project administration, Supervision, Validation, Writing - review and editing. Nurul Syafida Abu Bakar: Validation, Data curation, Methodology. Bakhtiar Affandy Othman: Methodology. Vynotdni Rathinasamy: Methodology.

Availability of Data and Materials

The data supporting the reported results are available from the corresponding author on reasonable request.

Abbreviations

The following abbreviations are used in this manuscript:

AFS	American Foundry Society
AI	Artificial intelligence
ASTM	ASTM International; formerly the American Society for Testing and Materials (official terminology)
BET	Brunauer–Emmett–Teller method
CEC	Cation exchange capacity
CIELAB	Commission Internationale de l'Éclairage L*a*b* colour space
CRM	Certified reference material
DD	Decimal degrees; in the conversion equation, D = degrees, M = minutes and S = seconds
D10, D30, D50, D60	Particle diameters at which 10%, 30%, 50% and 60% of the cumulative sample are finer, respectively
EDS	Energy-dispersive X-ray spectroscopy
EPSG:4326	EPSG Geodetic Parameter Dataset code 4326, identifying the WGS 84 geographic coordinate reference system (IOGP explanation)
FESEM	Field-emission scanning electron microscopy
GFN	Grain fineness number
GIS	Geographic information system
ICDD	International Centre for Diffraction Data (official name)
ICP	Inductively coupled plasma
ICP-MS	Inductively coupled plasma mass spectrometry
ID	Identifier

i-CRIM	i-CRIM Centralised Laboratory, Universiti Kebangsaan Malaysia; associated with the Centre for Research and Instrumentation Management (UKM profile)
ISO	International Organization for Standardization; ISO is its official short name, not an acronym (ISO explanation)
JMG	Jabatan Mineral dan Geosains Malaysia
LOI	Loss on ignition
LREE/HREE	Light rare earth elements/heavy rare earth elements
MITI	Ministry of Investment, Trade and Industry
MyGEMS	Malaysia Geospatial Mineral and Geoscience Information System
N. Sembilan	Negeri Sembilan
n/a	Not applicable
ND	Not detected
NIMP 2030	New Industrial Master Plan 2030
NORM	Naturally occurring radioactive material
NRES	Ministry of Natural Resources and Environmental Sustainability
PCDS 2030	Post COVID-19 Development Strategy 2030
PI	Plasticity index
PPL/XPL	Plane-polarised light/cross-polarised light
ppb	Parts per billion
PSD	Particle size distribution
QA/QC	Quality assurance/quality control
qual.	Qualitative
REE	Rare earth elements
Tg.	Tanjung
UKM	Universiti Kebangsaan Malaysia
UTM	Universiti Teknologi Malaysia
WDXRF	Wavelength-dispersive X-ray fluorescence
WGS 84	World Geodetic System 1984
WPKL	Wilayah Persekutuan Kuala Lumpur
XRD	X-ray diffraction
XRF	X-ray fluorescence

Table specific shorthand:

Table context	**Shorthand**
Silica screening	B = Baseline; G = Glass; F = Foundry
Kaolin screening	B = Baseline; F = Functional; A = Activated

Chemical and scientific notation:

Al_2O_3	Aluminium oxide
CaO	Calcium oxide
Fe_2O_3	Iron (III) oxide
HCl	Hydrochloric acid
K_2O	Potassium oxide
MgO	Magnesium oxide
Na_2O	Sodium oxide
SeO_2	Selenium dioxide
SiO_2	Silicon dioxide
SO_3	Sulfur trioxide
TiO_2	Titanium dioxide
ZrO_2	Zirconium dioxide
Ce, Cu, Eu, Fe, Ti	Cerium, copper, europium, iron and titanium
Cu Kα	Copper K-alpha X-ray radiation
L*, a*, b*	CIELAB lightness, green–red and blue–yellow coordinates
pH	Measure of acidity or alkalinity

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