

Mineral Processing of Silica Sand in Hanout Area/South of Jordan

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Abstract

White sandstone samples from Hanout area of Late Cambrian-Early Ordovician sandstone in south of Jordan were studied and assessed as a source of glass sand. Upgrading the sand included removing or reducing the content of the contaminant oxides and the heavy minerals. The aim of this research was to achieve this upgrading by examining the best-suited and cost-effective processing method(s) with sufficient product recovery. Following the initial sample characterisation at “bench scale”, a pilot study was performed. A high-grade Glass Sand product of 500 - 125 µm size fraction was produced by wet screening, attrition scrubbing and the separation of heavy minerals using spirals. The high quality Glass Sand product compared well with Grade-A of the British Standard for glass sand. Due to the relatively low level of impurities in the raw material, a substantial silica sand recovery was produced with a high silica grade. The silica sand product was capable to be used in the high quality glass industry and in many other applications where pure silica is required. The mass flowrate of the feeds and the products in the spiral was calculated for the bulk sample as well as the amount of water required operating the process.

Keywords

Glass Sand, Grade and Recovery, Mass Balance, Mineral Processing

1. Introduction

Sand or sandstone is normally found in huge quantities covering wide areas in arid and semi-arid countries such as Jordan. But, high quality white sand is found cropping out only in particular occurrences in south of Jordan. This research study was conducted to highlight this important source of silica sand for industrial applications. The objectives were to evaluate the quality of the silica

sand samples and to find out its possible industrial applications. It was also intended to examine the best-suited and cost-effective processing method for upgrading the material with sufficient product recovery.

1.1. Geology of the Deposit

The Disi Sandstone Formation forms beautiful landscape of large dome-like shapes outcrops where friable pale-grey and whitish sandstone can be recognized on the surface of the outcrops due to the weathering. The Formation consists mainly of massive bedded quartz arenite sandstone, greyish white to white, medium and coarse grained, rounded to sub-rounded with scattered granules and pebbles of quartz. It was determined that the age of this formation is Late Cambrian to Early Ordovician [1].

The white sandstones exposed in the south of Jordan have been described by many geologists in Jordan. References [1]-[7], and others had mentioned, mapped or reported these outcrops in their studies. Geological map at a scale of 1:50,000 covering most of the silica sand outcrops in Ras En-Naqb area was published by the Natural Resources Authority (NRA) and carried out by [8]. Ref. [9] carried out a feasibility study of the silica sand for a flat-glass plant. Ref. [10] and NRA staff conducted a laboratory investigation on different samples of the silica sand in south of Jordan. Ref. [11] studied silica sand samples of Disi Sandstone Formation from Ras En-Naqb area. Ref. [12] studied the silica sand samples from the middle part of the Formation as part of his PhD thesis and the data and the results from the study are used in this paper.

The lithology of the formation has been described and divided into three major parts; lower, middle, and upper part at Jabal Mi'zan (mountain name) 8 km south of the study area [8]. The studied sand samples are from the middle part of the Disi Sandstone Formation. The lithology of the middle part consists of white, fine to medium-grained sandstone, granules and scattered quartz pebbles with large scale trough cross-bedding. The study area is just a small part of huge sandstone outcrops, which extend over and occupy the floor of an area of more than 150 km². Exploration activities carried out by NRA in 1998 indicated that the thickness of the Disi Sandstone Formation is more than 300 m and the geological reserve of the Formation in Ras En-Naqb area was estimated of more than ten billions of tons [13].

The maturity of grains, sedimentary structure, and the palaeocurrent flows indicated that the depositional environment of the formation was high energy rivers for the lower part, reduced energy rivers for the middle part, and higher energy braided rivers, with interruptions of marine shallow water progression, for the upper part [5] [8].

1.2. Location and Description of Samples

The studied samples are from Dabat Hanout area of about 0.8 km², which is part of elongated and exposed mountain like outcrops of white massive sandstone.

Estimated reserve is at least 100 million tons. The Dabat Hanout area is located approximately 250 km south of Amman and just few hundreds of meters east of Amman-Aqaba Highway (**Figure 1**).

Three silica sand samples of more than 25 kg each were taken from a face of working quarry and the outcrop (channel samples) representing a thickness of 35 - 40 m of the sequence (**Figure 2**). The samples were friable sand of whitish to pale white, medium to fine, and partly coarse to very coarse-grained (**Table 1**). For the pilot study, a composite bulk sample (about 500 kg) represents the whole sequence was sampled and compiled from the same locations of the three samples.

2. Materials and Methods

The research study was intended to characterize, evaluate, upgrade and to beneficiate the raw material of the silica sand. The study consists of characterizations of the raw materials, which define the mineralogical, physical and chemical properties, upgrading (processing trials) of the mineral “the ore” to achieve quality and recovery, and then applying pilot study in order to design and model effective processing method.

2.1. Preparation

The studied samples were friable sand with small sandstone lumps, which were easily breakable with little energy. Therefore, the samples “as-mined” did not need any crushing or milling to liberate the particles. Riffing, coning, and quartering were used to divide and to obtain representative sub-samples.

2.2. Experimental Methods and Analytical Techniques

2.2.1. Sieving Technique

About 2 kg sample for each test was used. A set of sieves of aperture ranging from 1180, 850, 600, 425, 300, 212, 150, 106, 75, 53 to 38 μm were used in order to determine a full particle size distribution analysis. Brass frame sieves were used for both dry and wet sieving in order to avoid iron contamination [14]. The dry sieving test was carried out using Fritsch Analysette sieving shaker mounted by 4 sieves. A time was set of 20 minutes for each run with moderate shaking power. Wet sieving was also carried out using the cascade shaker mounted by 6 sieves with a steady water flow for about 20 minutes for every each run.

2.2.2. X-Ray Diffraction (XRD) Technique

The XRD spectrometry system using Phillips machine with Hiltonbrooks (HBX) software and employing copper tube radiation (Cu $K\alpha$ radiation) was used to examine the samples. The bulk samples, most of the sieved size fractions, and the products of the processing trials were examined and their mineralogy was identified.

2.2.3. Scanning Electron Microscope (SEM) Technique

The dry and wet sieved fractions; in particular the “glass sand size fraction” were

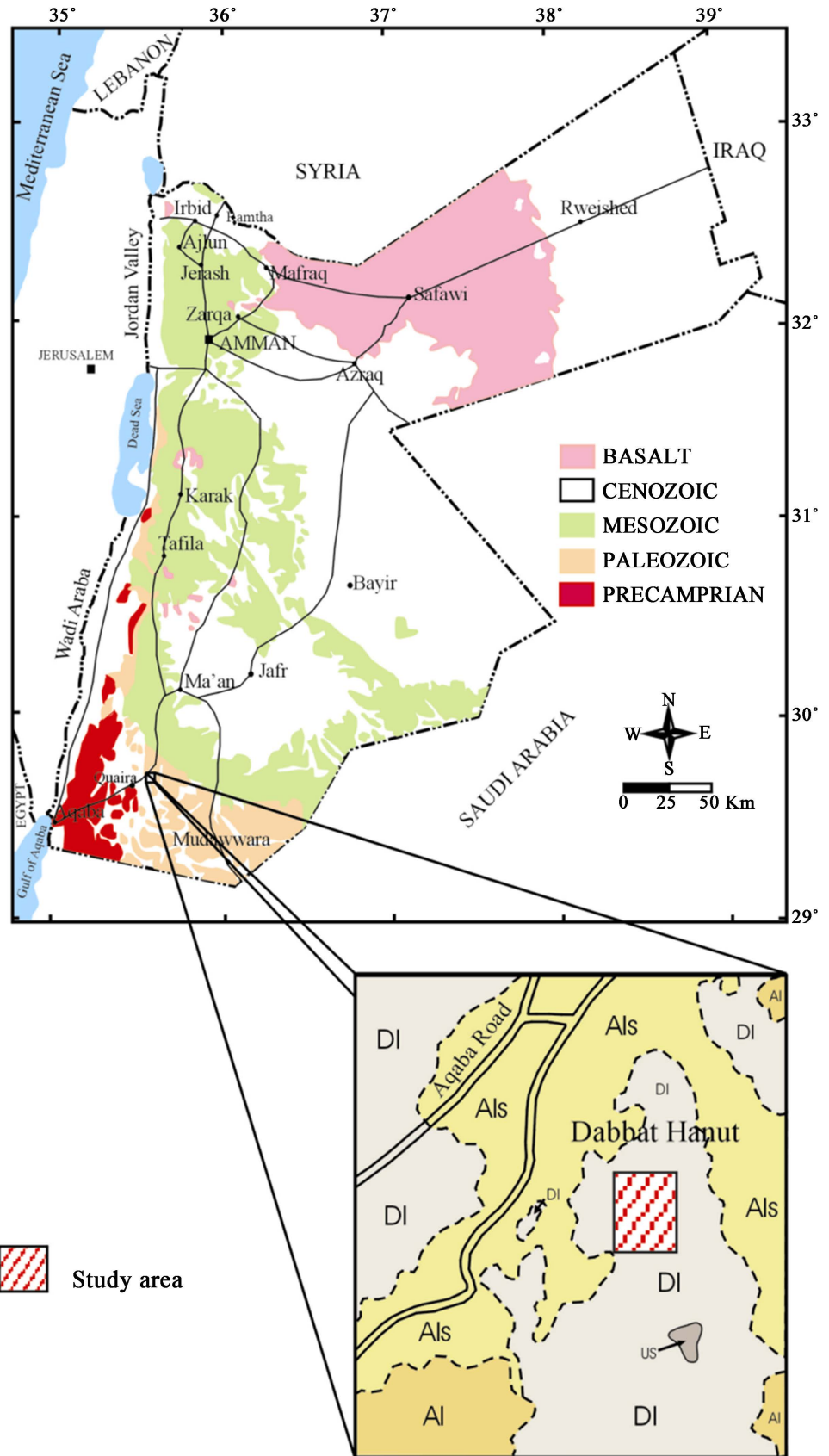


Figure 1. Location map of the study area.



Figure 2. Face of silica sand working quarry representing part of the outcrop.

Table 1. Description of the study samples from Dabat Hanout sandstone outcrop.

Sample	Description	Thickness (m)
SS1	Sandstone, massive to thick bands, friable, whitish, md. grained.	10 - 12
SS2	Sandstone, thick bands, slightly friable, whitish, fn. to md. grained, quartz pebbles.	10 - 15
SS3	Sandstone, slightly friable to compact, white to pale white, md. grained, thin bands of very coarse grains, quartz pebbles.	15 - 20
SS (bulk)	Sandstone, slightly friable, white to pale white, md. grained, slightly coarse grained, granules and quartz pebbles.	35 - 40

examined by SEM technique. On the other hand, the products produced from the scrubbing tests and the fine clay fractions were also examined.

2.2.4. X-Ray Fluorescence (XRF) Technique

The XRF technique was extensively used to determine the chemical composition of all raw materials and any sub-samples produced during the various stages of the experimental work and process steps. Samples for XRF analysis were prepared from finely powdered by pressuring them into fused glass discs (Fusion beads) or pressed pellets.

2.2.5. Heavy Liquid Separation

Heavy liquid separation was performed on the scrubbed sand. The samples were wet sieved, so the size fractions of 500 - 300, 300 - 212, 212 - 150 and 150 - 106 μm were produced. A non-toxic material, Sodium Polytungstate (SPT) of chemical composition $[\text{Na}_6(\text{H}_2\text{W}_{12}\text{O}_{40})\text{H}_2\text{O}]$ was used as heavy liquid media to separate the heavy minerals within the samples. The density was adjusted at 2.8

g/cm³ in order to float sand grains and clay mineral particles (if any) and to give chance for heavier specific gravity minerals to sink.

2.2.6. Attrition Scrubbing Technique

Attrition scrubbing is the most cost-effective way of removing iron staining and slimes coating the surface of sand grains. It is normally performed at high solids concentration by weight (70% solids or more) to give more chance for grain to grain contact. Effective removal of iron staining is more dependent on the grain shape and the structure.

Attrition scrubbing trials were carried out on the silica sand samples. Bench-scale tests were conducted using Wemco unit of one litre beaker capacity under conditions of 70% solids by weight, at 1000 rpm, 2, 4, 6, 8, 10, and 15 minutes scrubbing time, and using tap water. A pilot-scale Eimco attrition unit, of closed octagonal cell at a capacity of 30 litres was used under the same conditions but only at 8 minutes scrubbing time.

2.2.7. Spiral Separation Technique

The use of the spirals in the processing of silica sand is a reversal of their original role. The quartz grains in the spiral water stream move to the outer edge as concentrate and the heavy minerals move towards the inner edge as tailing [15]. The width of the product (silica sand) band and the tailing were controlled by adjustable splitters.

The scrubbed sand samples were subjected to the mineral spiral separator (spiral of 5¼ helical conduits) in the pilot study. The samples were mixed with water that a feed pulp of about 30% solids by weight was achieved. Two time-samples at low yield and high yield products were obtained.

3. Experiments and Results

3.1. Characterisation

Dry and wet sieve analyses were performed on the bulk silica sand sample (SS). The particle size distribution was determined. The weight retained on each sieve was measured and the weight percentage was calculated and listed in **Table 2**.

The cumulative undersize of the dry and the wet sieving of the (SS) sample showed that the median size (d_{50}) of the sample is about 280 µm, which indicates that the sample is mainly medium-grained size (**Figure 3**). The results indicated that the sand is fairly sorted and a substantial amount of the sand (about 87%) is between the grain size of 600 and 106 µm.

The mineralogical investigation of the (SS) sample indicated that major mineral constituent was quartz. Kaolinite-1A clay mineral was found as a trace mineral in the rock sample (**Figure 4**) and almost in all the dry sieved size fractions. Other subordinate minerals, such as calcite and mica/illite were detected in the coarse fractions (*i.e.* +1180 & +850 µm), while Anatase was detected in the -38 µm size fraction (**Table 3**).

SEM was used mainly to visualize the shape, size and morphology of the

Table 2. The weight retained in percent on each sieve of the wet and the dry sieving analyses of the silica sand (SS) sample.

Nominal aperture size (μm)	Silica sand (SS)	
	Dry wt%	Wet wt%
1180	1.31	1.17
850	1.25	1.23
600	4.89	5.01
425	16.73	14.91
300	30.55	34.65
212	24.16	25.34
150	13.03	9.65
106	3.93	2.92
75	1.41	1.43
53	1.22	0.78
38	0.87	0.59
<38	0.65	2.32
Total	100	100

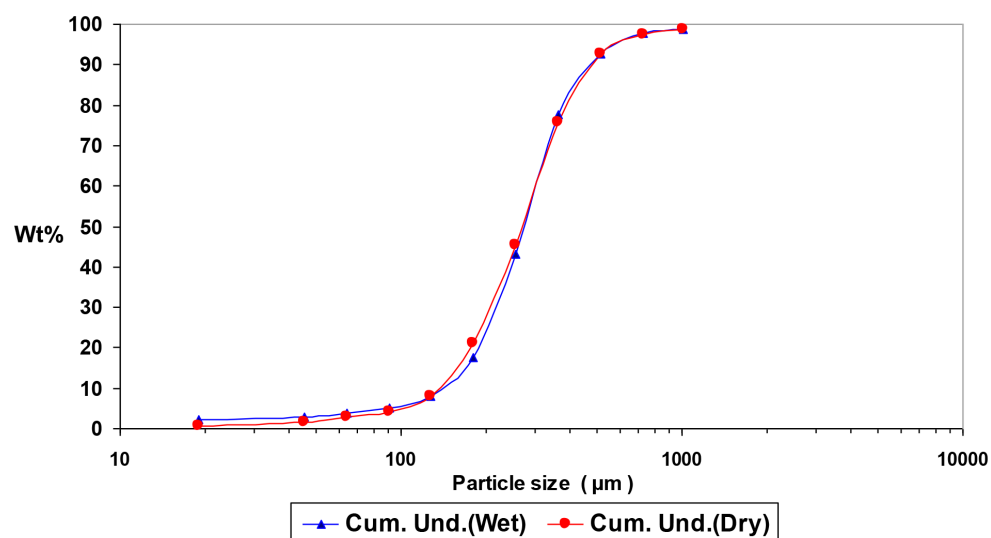


Figure 3. The cumulative undersize distribution of the dry and wet sieving of the (SS) sample.

particle's surfaces, and in particular to examine the difference between the dry and wet sieved fractions in terms of contaminants. The results showed that the sand grains are supermature quartz arenite of subhedral crystal shape, which indicate that they had been exposed to erosion and weathering conditions due to transportation.

Heavy minerals were identified using binocular microscope, SEM, and XRD. Schorl (Fe-tourmaline) was the most abundant heavy mineral found (more than

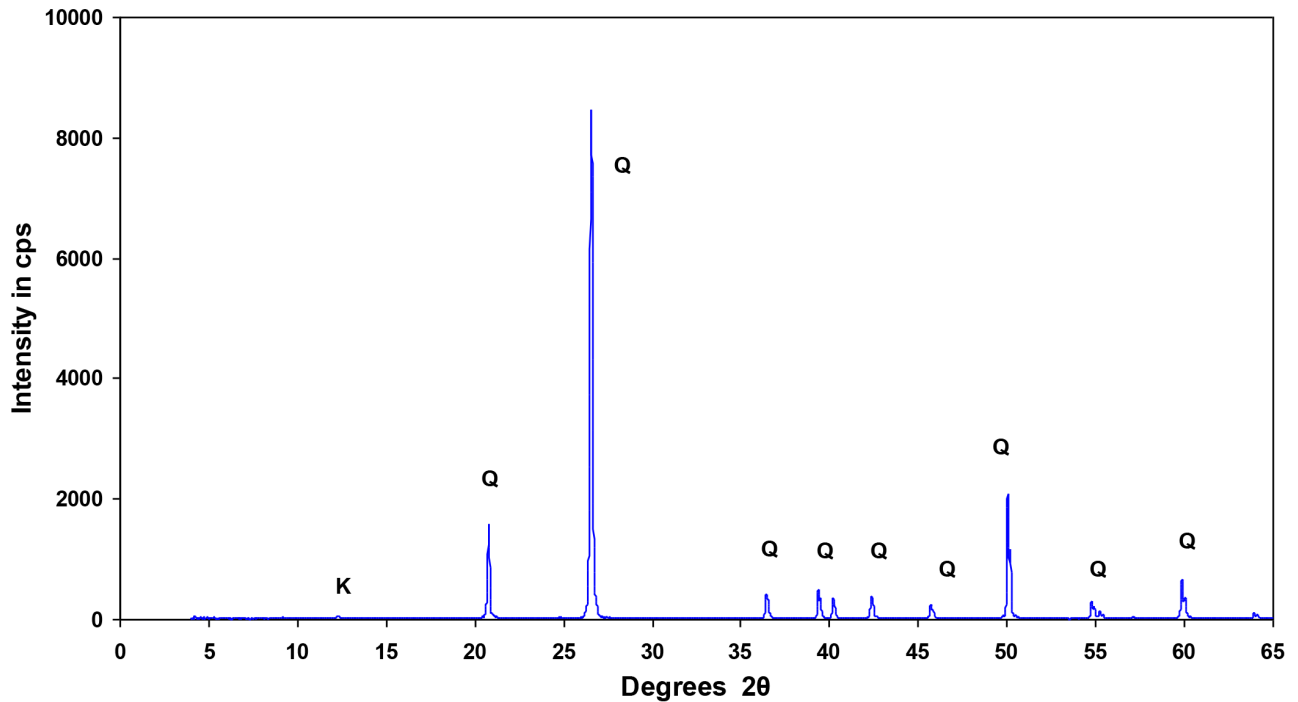


Figure 4. The XRD graph of the whole rock (SS) sample.

Table 3. The mineralogical results of the whole rock and the dry sieved fractions of the (SS) sample using XRD.

Sample code	Description (size in μm)	Minerals		
		Major	Minor	Trace
JMA1-06	Whole rock	Q	-	K
JMA6-04	+1180 & +850	Q	K	Ca, M/I
JMA5-04	+425 & +300	Q	-	K
JMA4-04	+212 & +150	Q	-	K
JMA1-04	-38	Q, K	-	An
JMA1-05	-38 (wet)	Q, K	-	An

Q: Quartz, K: Kaolinite, An: Anatase, Ca: Calcite, M/I: Mica/illite.

50% by weight of the heavy minerals). Other heavy minerals were rutile, anatase, zircon, ilmenite, monazite, fluorapatite, and iron oxides. The results showed that the weight percentage of the heavy minerals increases as the grain size decreases in the sample.

The samples of the silica sand deposit (Dabat Hanout area) were chemically analysed for their major standard oxides (Table 4). In addition, all the dry and wet sieved size fractions were also analysed (see in Annex-A).

The chemical composition of the raw samples showed that it consists mainly of silica (>98%) with little Al_2O_3 and very little constituents of other oxides. Furthermore, it was noticed from the chemical composition of all the dry and

wet sieved size fractions that the best results obtained were within the size fractions of -600 to $+106 \mu\text{m}$ in terms of higher silica content and lower content of other oxides *i.e.* Al_2O_3 , TiO_2 and Fe_2O_3 content. In addition, the SiO_2 content values have increased in wet sieving compared to the dry, while values of Al_2O_3 and TiO_2 and to some extent Fe_2O_3 contents have decreased in wet sieving compared to the dry within that range (**Figure 5** & **Figure 6**). Other oxides, such as MgO , MnO , and K_2O were found in very low contents in most of the size fractions and values were in the range of 0.03% - 0.01% . Therefore, a wet process route was adopted to carry on the detailed study.

Table 4. The chemical results of the bulk and silica sand samples using XRF.

Major Oxides (%)	Bulk sample SS	Silica sand samples		
		SS1	SS2	SS3
SiO_2	98.51	98.35	98.49	98.41
TiO_2	0.09	0.11	0.08	0.09
Al_2O_3	0.73	0.73	0.69	0.83
Fe_2O_3	0.02	0.03	0.02	0.04
MgO	0.00	0.01	0.00	0.01
CaO	0.08	0.12	0.09	0.06
Na_2O	0.01	0.02	0.01	0.02
K_2O	0.02	0.01	0.02	0.01
MnO	0.01	0.01	0.01	0.01
P_2O_5	0.01	0.01	0.01	0.01
LOI	0.50	0.41	0.47	0.61
Total	99.99	99.81	99.89	100.12

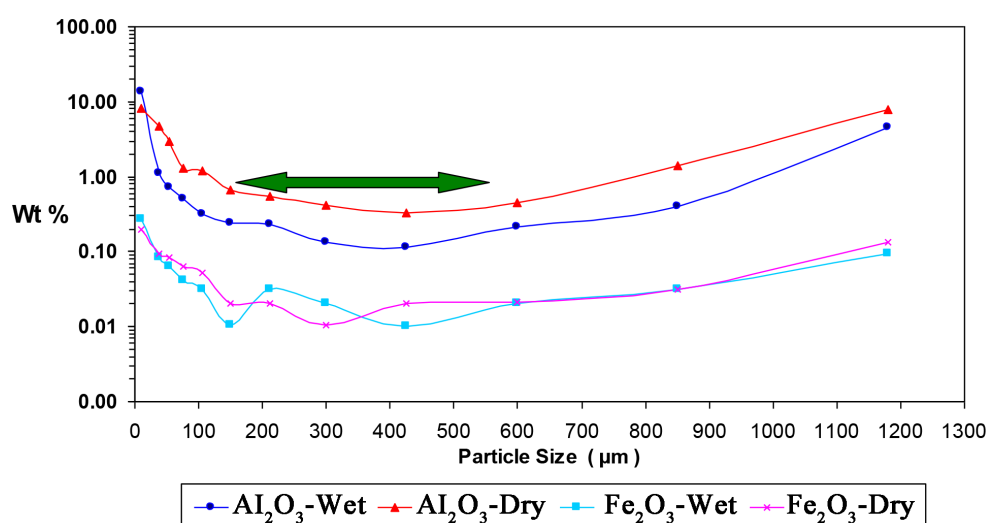


Figure 5. The variation of Al_2O_3 and Fe_2O_3 contents with the size fractions in the silica sand sample (Arrow refers to -600 to $+106 \mu\text{m}$).

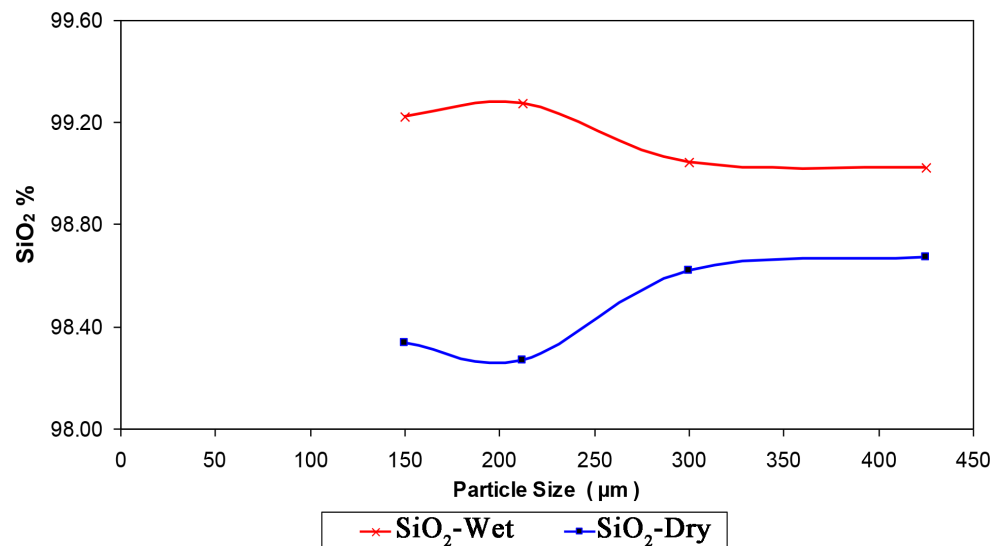


Figure 6. The variation of the SiO₂ content of the wet and dry sieved in the size fractions between -600 and +106 µm of the silica sand sample.

3.2. Upgrading and Beneficiation Trials

Based on the results of the characterisation stage, most of the impurities found in the size fractions of 106 to 600 µm were clay (kaolinite), iron oxides and heavy minerals. It was anticipated that the raw material of the samples could be upgraded to meet the required specification of the glass industry. In this regard, the bulk sample (SS) was selected to carry on the detailed study as represented sample for the whole sequence.

Basically, to upgrade the material to produce high quality glass sand, it would be necessary to remove the clays and iron oxides as well as the heavy minerals. The British Standard for glass manufacturing specifies that the required grain sizes of sand for glass manufacturing are in the range of 500 to 100 µm [16]. Accordingly, grain size fraction in the range of 500 to 106 µm of the sample was produced employing wet sieving to produce sub-samples of this range for the upgrading trials.

3.2.1. Attrition Scrubbing Trials

Attrition scrubbing trials were carried out in two main phases in attention to find out the optimum parameters in terms of behaviour, time and size fractions of the grains.

In **Phase-1**, Two attrition scrubbing trials, using a laboratory Wemco attrition unit were performed on the sample (SS) under conditions of 70% solids concentration (by weight) at 1000 rpm, 15 minutes scrubbing time and using tap water, with the objective being to assess the effectiveness of attrition scrubbing technique on the different size fractions.

In **Trial A**, the size fraction 500 to 106 µm was wet screened into subordinate size fractions (*i.e.*, 500 - 300, 300 - 212, 212 - 150, 150 - 106 µm) with each fraction being scrubbed individually, deslimed and then analysed (**Figure 7**). While

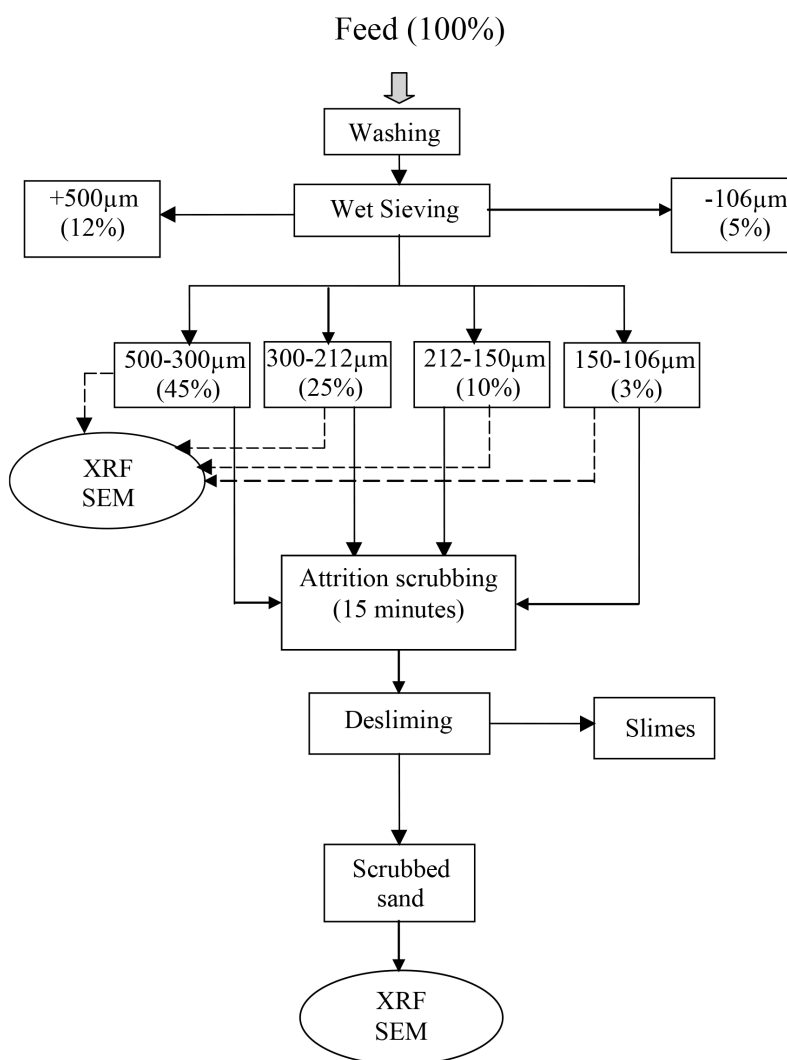


Figure 7. Trial-A Flowchart - silica sand (SS) sample. (%) by weight of material

in **Trial B**, the whole size fraction 500 to 106 μm was scrubbed, deslimed and then wet sieved into individual size fractions (*i.e.*, 500 - 300, 300 - 212, 212 - 150, 150 - 106 μm) (**Figure 8**).

In each case after scrubbing, the slurry was deslimed using the same sieves mounted on a cascade shaker. The products and slimes were recovered, oven-dried at temperature of 80°C, weighed and then representative sub-samples were prepared for XRF, XRD, and SEM analyses as well as for examination under the binocular microscope.

The results of the wet sieving showed that the total weight percentage of the 500 to 106 μm size fractions was 83% of the feed, whilst the +500 μm coarse fraction was found to represent 12% and the -106 μm fraction represented 5%.

Trial-A showed that the total weight recovery of scrubbed sand of size fractions from 500 μm to 106 μm is 76.6% for the (SS) sample. In Trial-B, the whole fraction (500 - 106 μm) was scrubbed as one size fraction then wet sieved. The results showed that the weight recovery of scrubbed sand, as a whole fraction

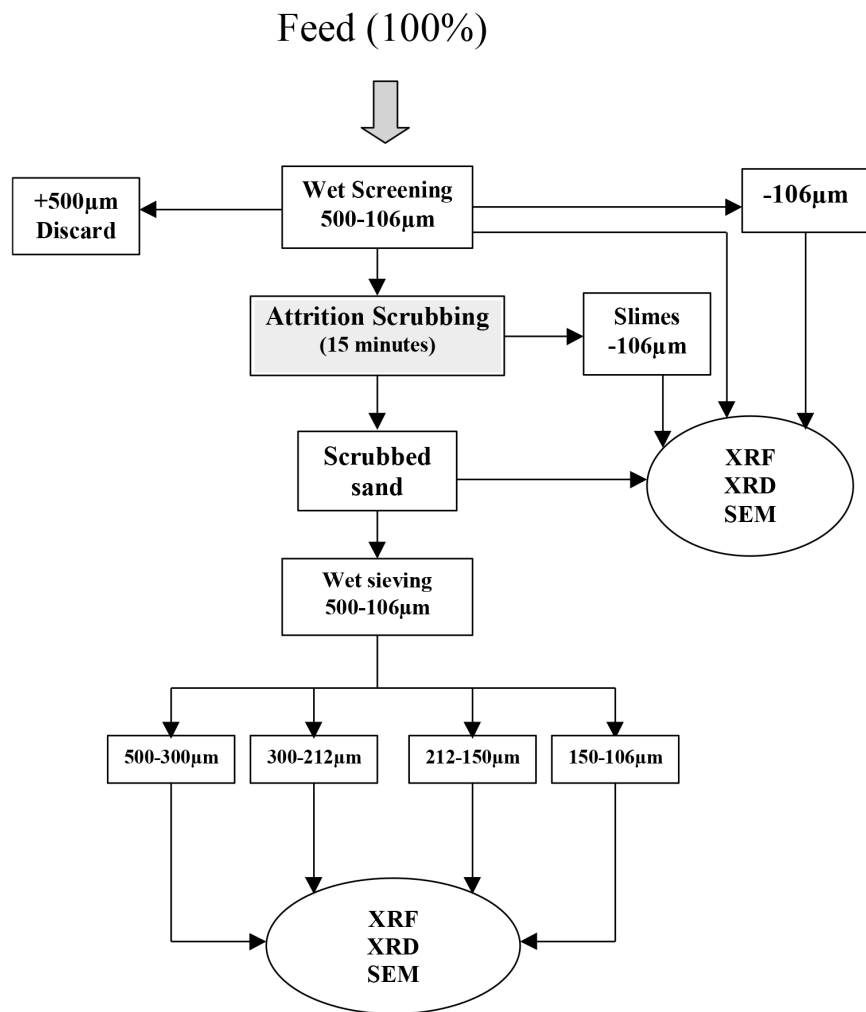


Figure 8. Trial-B Flowchart for SS sample.

(500 - 106 µm) is 80.1% (Table 5).

It was found that the weight recovery of scrubbed sand in Trial-B (80.1%) is more than that in Trial-A (76.6%) for the sample. On the other hand, the weight percentage of the slime was found in Trial-A more than that in Trial-B. The results indicated that more broken sand grains were produced in the individual size fractions of Trial-A which could be explained due to the narrow size distribution (sorted) of grains in the individual sieved fractions.

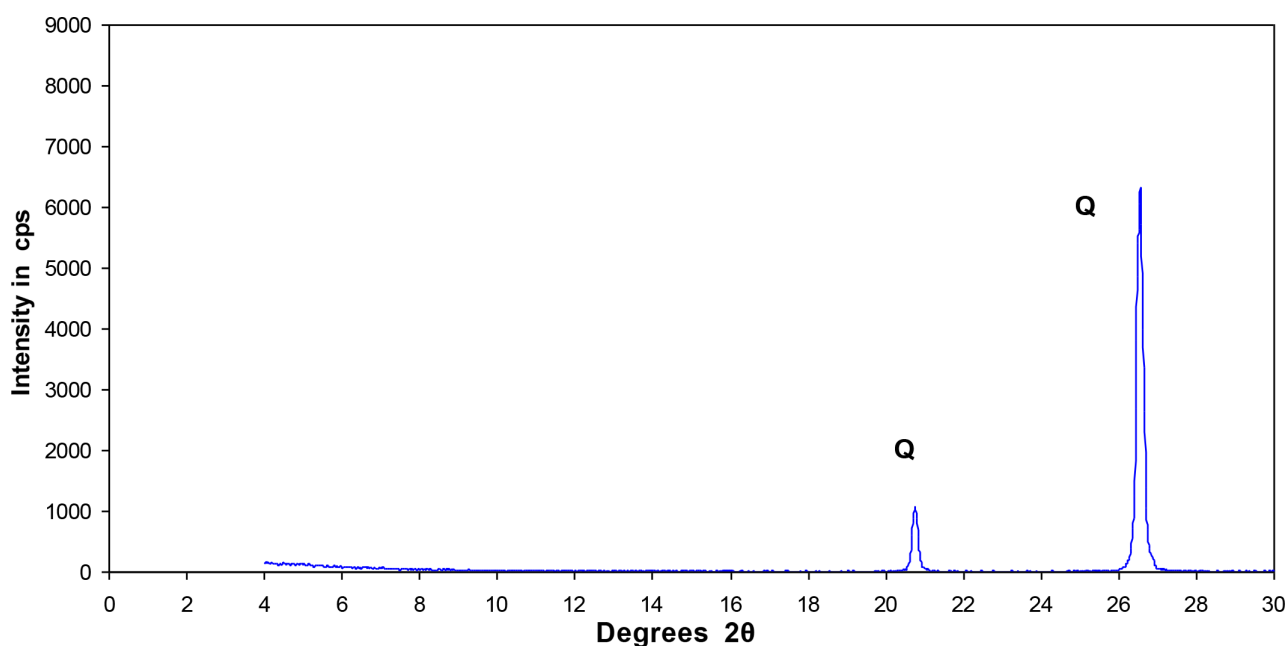
From the results of Trials A and B, it was found that attrition scrubbing of the whole size fraction 500 - 106 µm provided better results than that of scrubbing individual and separated fractions.

The mineralogy, using XRD of the scrubbed size fractions (500 - 106 µm) and its associated slimes' was determined to verify the changes, which took place to the other constituents (e.g. clays). The results showed that quartz was the only mineral found in the main size fraction (500 - 106 µm) (Figure 9).

Light microscopy was used to examine and visualize the surface and structure of the sand (quartz) grains. This revealed that there were few heavy mineral

Table 5. Results of the attrition scrubbing tests -Trials A & B for the (SS) sample.

Trials	Size Fractions (μm)	Feed (SS) (wt%)	Scrubbed Sand (wt%)	Slime (wt%)
A	500 - 300	45	39.76	5.24
	300 - 212	25	24.19	0.81
	212 - 150	10	9.75	0.25
	150 - 106	3	2.90	0.10
	Total	83	76.60	6.4
B	(500 - 106)	83	80.10	2.90

**Figure 9.** XRD graph of the scrubbed (500 - 106 μm) size fraction of the silica sand (SS) sample.

grains found as inclusions inside the quartz grain as well as iron oxides stains inside or at the fissures between quartz crystals (**Figure 10**).

The SEM photomicrographs showed the traces of clay and fine particles are still existed on the surface of quartz grains of the wet sieved (500 - 106 μm) fraction while clean quartz grains can be seen in the scrubbed sand of the same fraction (**Figure 11**).

The chemical results of attrition scrubbing in Trial-B were compared with the results of the attrition scrubbing in Trial-A. To observe the variations, the results of the main contaminant oxides (*i.e.*, Al_2O_3 , TiO_2 , CaO , and Fe_2O_3) were taken into consideration and illustrated in **Figure 12**.

The results of the chemical analysis of the wet sieved, scrubbed and the slime of the size fraction (500 - 106 μm) were plotted against the results of the feed sample in **Figure 13**. The results showed that attrition scrubbing was successful in cleaning the sand grains from most of the clay and fine particles, which were moved into the slime.

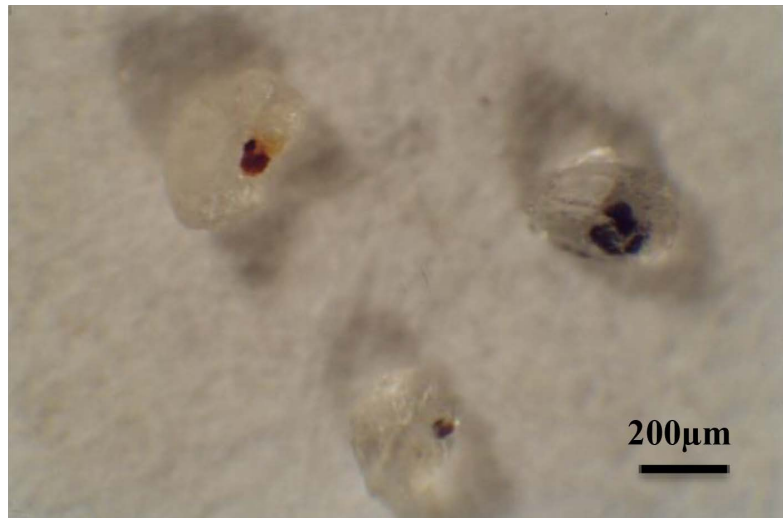
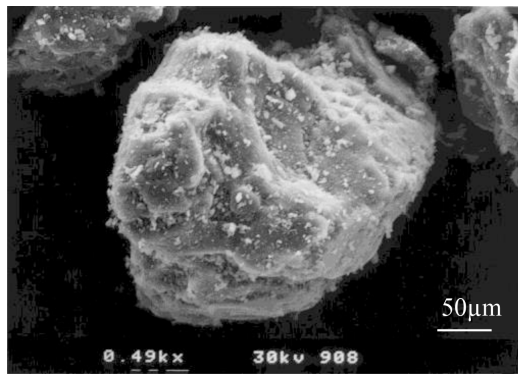
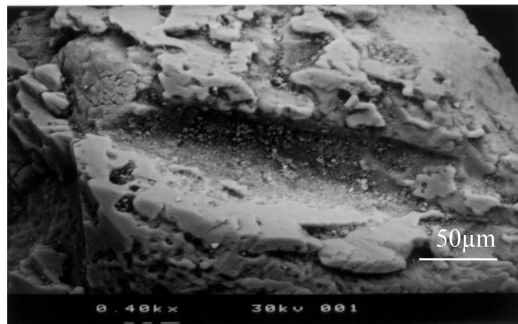


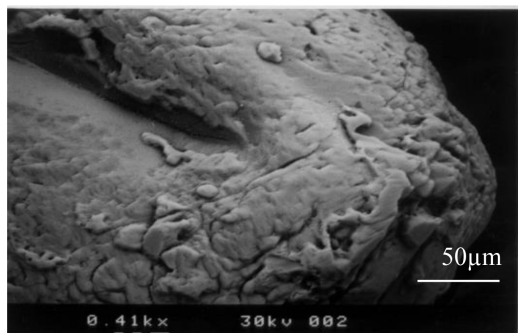
Figure 10. A light-microscopic photograph shows heavy mineral inclusions inside the grain and iron oxide stains in the fissures of the scrubbed sand sample.



Dry sieved quartz grain with fine particles and kaolinite flakes on the surface.



Wet sieved grain with little clay flakes and fine particles.



Scrubbed grain with clean surface.

Figure 11. SEM photographs of quartz grain from the (500 - 106 μm) size fraction of the (SS) sample.

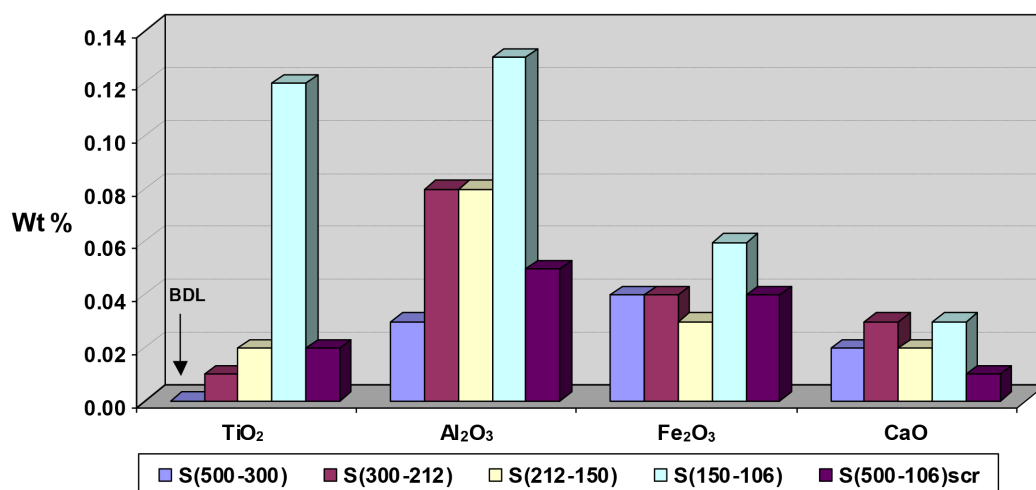


Figure 12. The chemical results of the contaminant oxide contents of the scrubbed (500 - 106 μm) size fraction in *Trial B* and the scrubbed size fractions in *Trial A* of the (SS) sample. (BDL: *Below Detected Limit*).

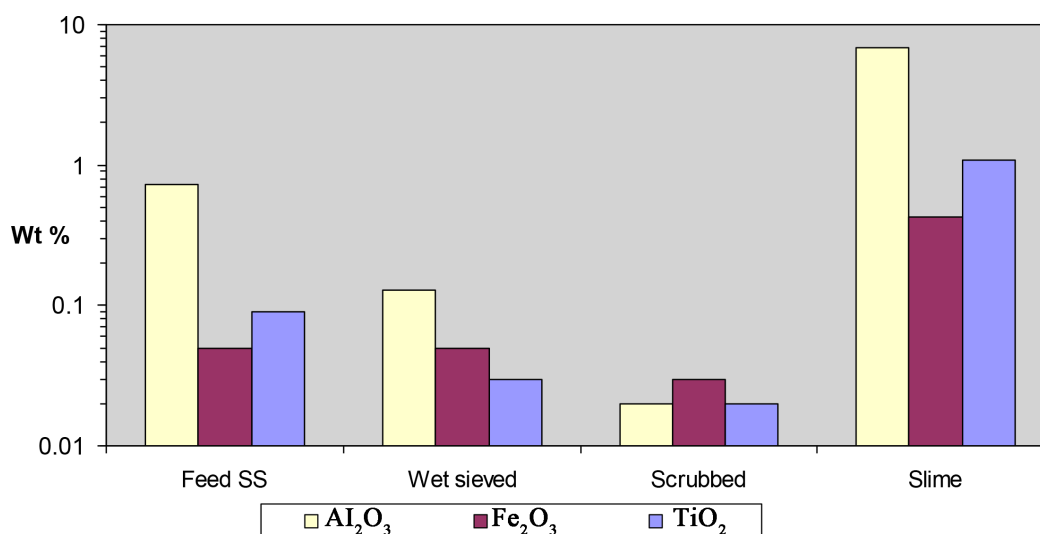


Figure 13. Variation of major contaminant oxide contents for the bulk, wet sieved, scrubbed, and slime of the sample.

3.2.2. Scrubbing and Heavy Liquid Separation

In **Phase-2**, the trials included applying further attrition scrubbing tests under the same conditions but at different time intervals of 2, 4, 6, 8, and 10 minutes and separation of the heavy minerals. The aim of this stage was to determine the optimum time to scrub the sample for the pilot study (**Figure 14**). The heavy minerals recovered were studied. Quantitative study indicated that the heavy minerals in the studied fractions (500 - 106 μm) were found to be 0.04% by weight.

The chemical results showed that the contents of most of the major oxides decreased while the SiO₂ contents increased with higher scrubbing times. The results of the major contaminant oxides (*i.e.*, Al₂O₃, TiO₂, CaO, and Fe₂O₃) contents were plotted to observe their variations with scrubbing time (**Figure 15**).

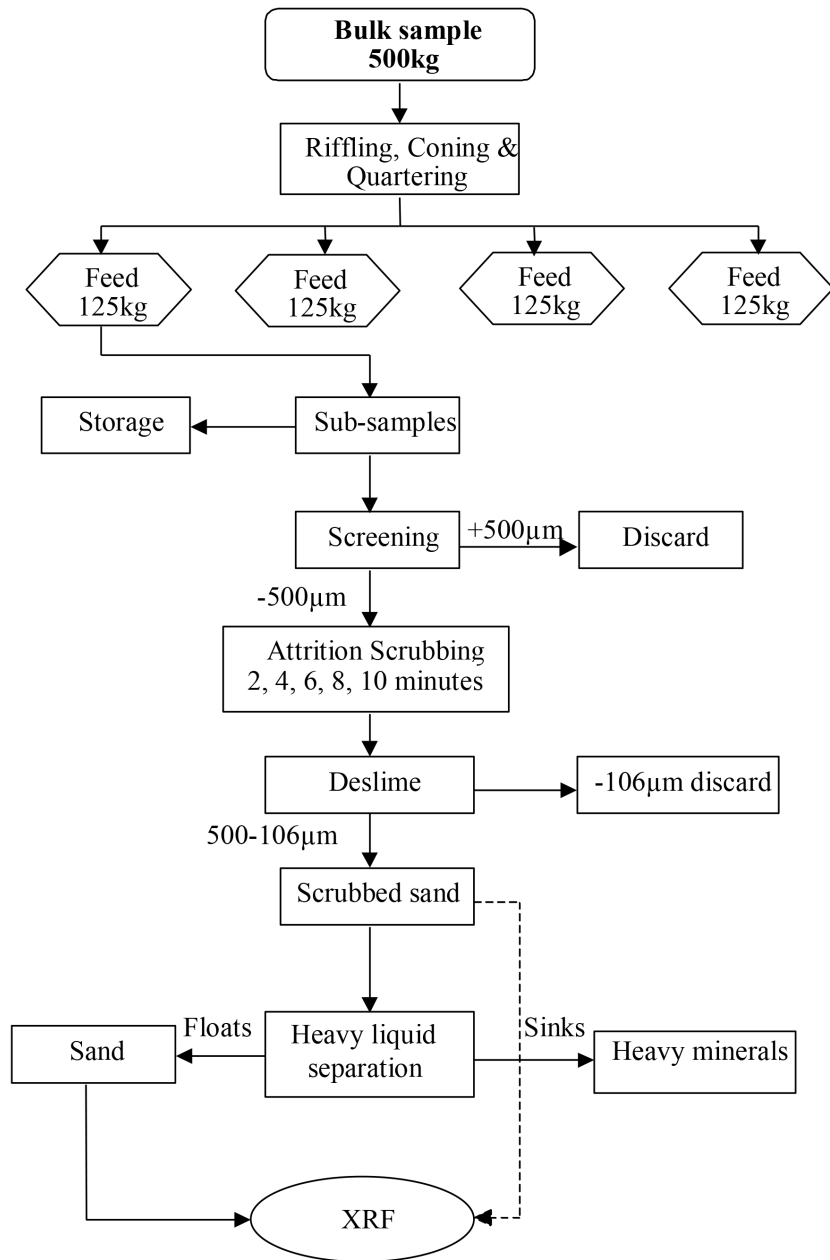


Figure 14. Phase-2 flowchart illustrating the procedures for the silica sand (SS).

This showed that the optimum results were achieved by scrubbing the $-500\ \mu\text{m}$ size fraction sample for 8 minutes followed by desliming at $106\ \mu\text{m}$. The values of the major contaminant oxide contents of the bulk sample, wet sieved, scrubbed for 8 minutes and heavy liquid float products were compared to assess the processing method. It could be noticed that there was a dramatic change in the values from the bulk to the wet sieved and then to the scrubbed products, while there was little change in the floats (Figure 16).

The results of the scrubbed sand product are presented against the chemical specifications for glass sand of the British Standard [16] and the Sibelco Company grade (Table 6). The comparison indicates that the results of the scrubbed

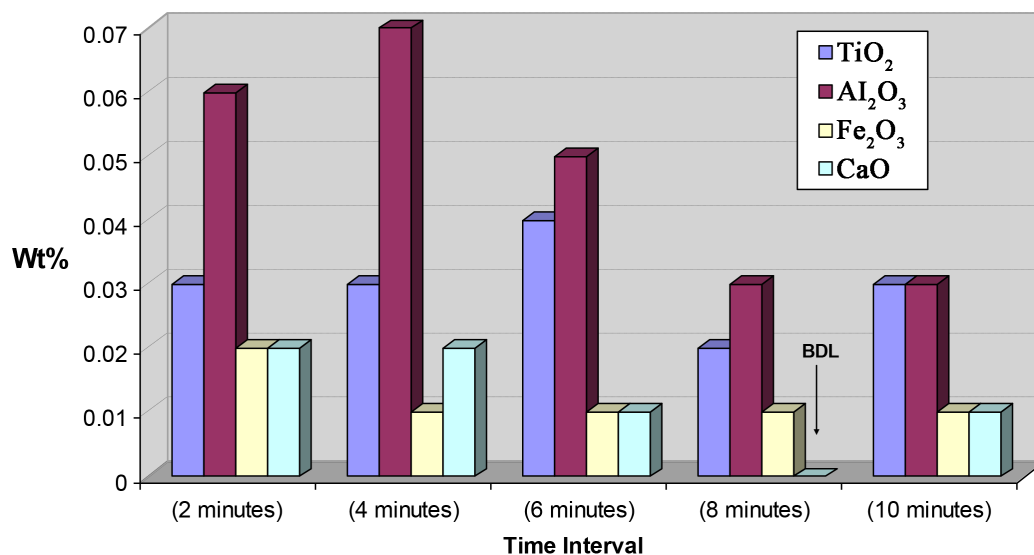


Figure 15. Effect of attrition scrubbing at different time intervals on the major contaminant oxide contents-(SS) sample. (BDL: Below Detection Limit).

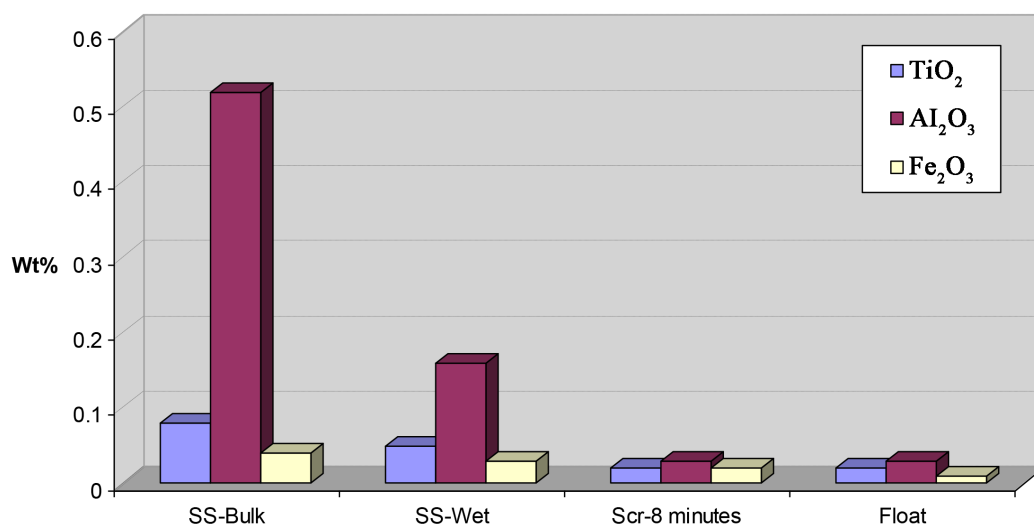


Figure 16. Variation of major contaminant oxide contents for the bulk, wet sieved (wet), scrubbed (Scr) to 8 minutes and heavy liquid floats.

Table 6. Results of the bulk, wet sieved and scrubbed (500 - 106 μm) fraction of the (SS) sample compared to glass manufacturing specifications.

Major Oxides	Bulk (%)	Wet sieved (%)	Scrubbed for 8 minutes (%)	* Grade-A, Glass sand Ref. [16]
SiO ₂	98.51	99.41	99.62	99.70
Al ₂ O ₃	0.73	0.16	0.04	0.20
Fe ₂ O ₃	0.04	0.03	0.01	0.01 - 0.013
TiO ₂	0.09	0.04	0.02	0.02 (**)
CaO + MgO	0.08	0.02	0.01	0.02 (**)
Na ₂ O + K ₂ O	0.11	0.09	0.02	0.02 (**)

*Grade (A) stands for optical and ophthalmic glass; **Sibelco Company Grade.

sand of (500 - 106 μm) size fraction could be compared to the Grade-A quality for glass manufacturing.

4. Pilot Study

The results showed that scrubbing the raw material, separating the heavy minerals, and screening to produce the required size fraction were able to produce high quality glass sand fraction. The results were encouraging enough to move forward to pilot scale.

Representative sample of about 125 kg were dry screened at 4 mm to remove lumps and big pieces in order to avoid causing problems with the attrition scrubbing unit and allowing the passing -4 mm material to proceed safely to other stages.

The -4 mm material of the sample were scrubbed using pilot Eimco attrition unit (30 litre single cell). The sample was scrubbed in stages at a feed concentration of 70% solids by weight (pulp density 1.773), at 1000 rpm, and for 8 minutes scrubbing time. The scrubbed sand, at a concentration of around 30% solids by weight was transferred to a mineral spiral separator of 5 1/4 turns for gravity separation. The procedures for processing the (SS) bulk sample are illustrated in **Figure 17**.

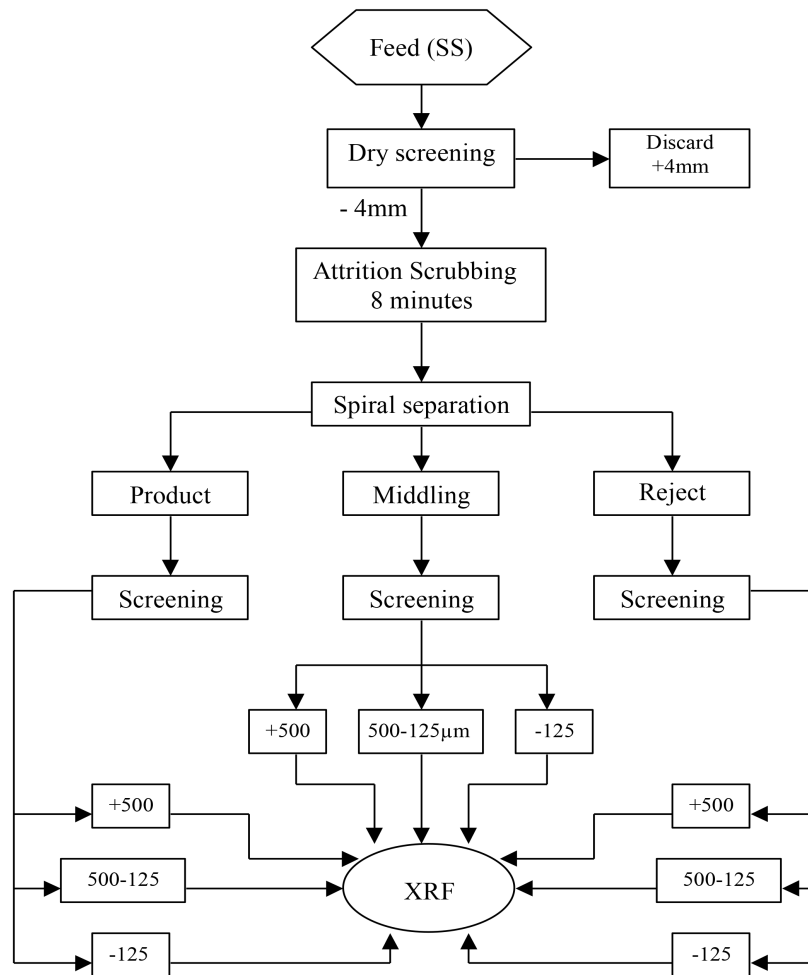


Figure 17. A flowchart showing processing procedures of the (SS) bulk sample.

4.1. Spiral Separation

Spiral separation was used as a gravity method to reduce or remove the heavy minerals including iron [17]. It was found that most of the iron content in the samples are as inclusions inside quartz grains or attached to them, or as part of the heavy mineral composition such as tourmaline (Fe-bearing mineral) and ilmenite. Therefore, it was considered that the spiral would be more effective than magnetic separation in reducing both heavy minerals and iron oxides.

The processed material at the base of the spiral was split into three separate streams; product, middling, and reject. Samples from each stream were screened into three size fractions; +500, 500 - 125, and -125 μm .

Two timed-samples at low yield and high yield product arrangements of the sample were obtained by changing the position of the knife-edge splitter at the base of the spiral (Figure 18). The products (silica sand), middling and rejects

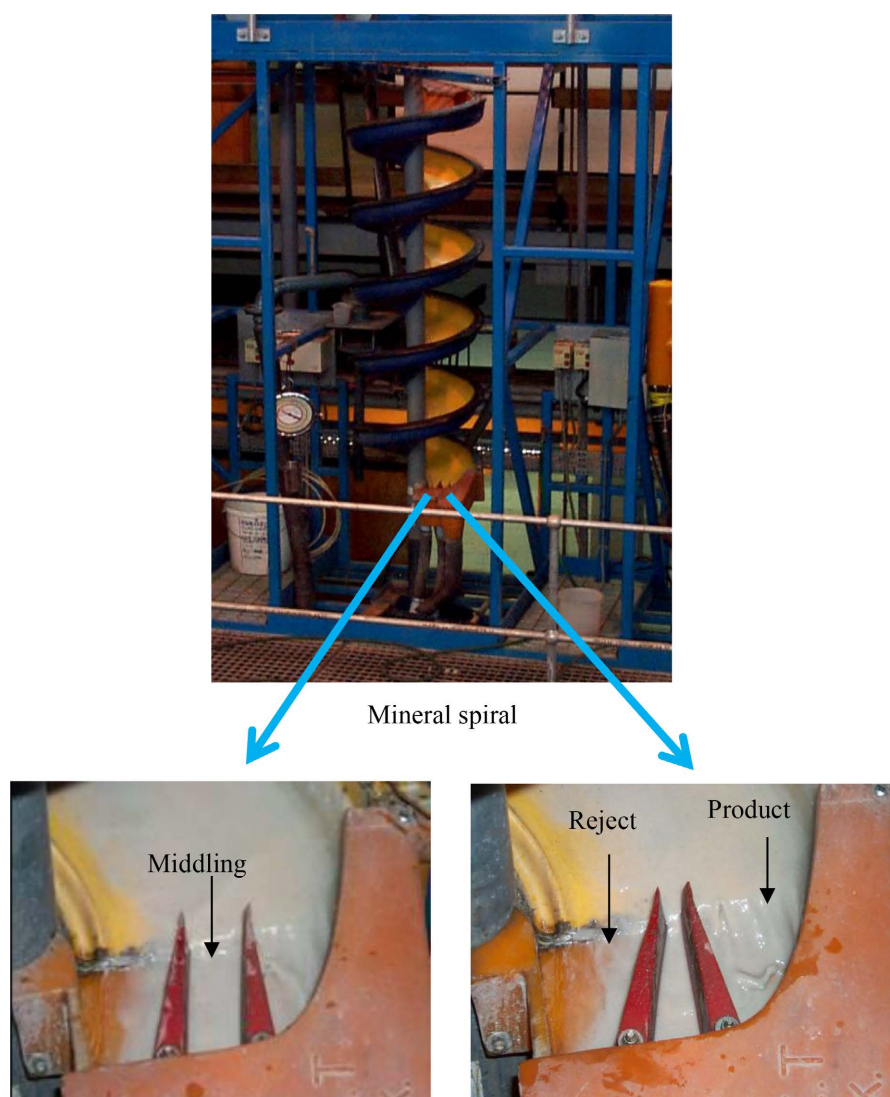


Figure 18. Knife-edge splitters at the base of the mineral spiral. Left photograph shows *low yield* splitting. Right photograph shows *high yield* splitting.

(fine and heavy minerals) of the material were wet screened. The size fractions of +500, 500 - 125, and the -125 μm were weighed wet and then dried. All the size fractions were chemically analysed by XRF and the results of the high and low yield runs of the silica sand sample are tabulated in *Annex (B)*. The results showed that the silica content increased in the 500 - 125 μm fraction for both the high and low yield runs. The contaminant oxides such as Fe_2O_3 , TiO_2 increased in the rejects and particularly in the -125 μm size fraction. This indicated that the heavy particles were concentrated in the reject due to gravity separation.

4.2. Results of Mass Balance

10-second timed samples were collected simultaneously from the product, middling and reject streams for both the high and low yield runs. The wet weight of the timed samples was recorded followed by sieving into three size fractions; +500, 500 - 125, and -125 μm . All fractions were then dried and weighed allowing the percentage solids by weight, yield and the mass flowrate in kg/h to be calculated (**Table 7**).

The results of the high yield run showed that the reconstituted feed at 32.9% solids by weight (pulp density 1.258) and a dry mass flowrate of 2304 kg/h generated a product of 31% solids by weight at 2033 kg/h dry mass flowrate and a yield of 88.2%. In the low yield run, the reconstituted feed at 31.8% solids by weight (pulp density 1.247) and a dry mass flowrate of 2396 kg/h produced a product of 25.7% solids by weight at 1643 kg/h dry mass flowrate and a yield of 68.55%. While the volume of water used was 4.7 m^3/h and 5.14 m^3/h for the high and low yield respectively.

Table 7. Mass balance results of the (SS) sample using the mineral spiral.

	Weight (kg)		Mass flowrate (kg/h)		Solids (%wt)	Yield (%)	Water (m^3/h)
	Wet	Dry	Wet	Dry			
High yield							
Product	18.20	5.65	6552.00	2032.60	31.00	88.22	4.52
Middling	1.11	0.69	399.60	248.10	62.10	10.77	0.15
Reject	0.16	0.07	55.80	23.40	41.90	1.02	0.03
Reconstituted Feed	19.47	6.40	7007.40	2304.00	32.90	100.00	4.70
Low yield							
Product	17.73	4.56	6382.80	1642.70	25.70	68.55	4.74
Middling	2.22	1.47	799.20	529.20	66.20	22.09	0.27
Reject	0.97	0.62	349.20	224.30	64.20	9.36	0.13
Reconstituted Feed	20.92	6.66	7531.20	2396.20	31.80	100.00	5.14

4.3. Silica Grade and Recovery Results

Recovery, in non-metallic ores, refers to the percentage of the total mineral contained in the ore that is recovered into the concentrate, *i.e.* the valuable end product. Grade refers to the content of the marketable end product in the material. Metallurgical efficiency is expressed by a recovery-grade curve showing the inverse relationship between recovery and concentrate grade. The recovery is calculated on the basis of the Two-Product formula in accounting for valuable mineral. The formula is based on that the input material equalling the output material [18]. Therefore;

$$\text{Recovery} = (C/c/Ff) * 100\%,$$

where, *C* is the concentrate weight and *c* is the concentrate assay, *F* is the feed weight and *f* is the feed assay.

In order to assess the metallurgical performance of the spiral separator, the grade and recovery of the silica and the contaminant oxides assays were calculated for both the high and low yield runs. The results of grade and recovery of the silica assay of the (SS) sample are presented in **Table 8** and **Table 9**.

The results showed that the silica content increased in the middling (99.36% and 99.43% by weight) rather than in the products (99.18% and 98.99%) of both high and low yield runs, when compared to the silica content (99.20% and 99.12%) of the reconstituted feed of high and low yield respectively. This was due to the effect of the presence of remaining clay and fine mineral particles such as gypsum and calcite in the $-125 \mu\text{m}$ fraction of the product (see chemical analysis in *Annex (B)* for details).

Table 8. Grade and recovery of the silica content/High yield run-(SS) sample.

	Size (μm)	Dry weight		Grade SiO ₂ (%)	Recovery (%)
		(kg)	(%)		
Product	+500	1.40	21.90	99.40	21.95
	500 - 125	3.98	62.18	99.66	62.47
	-125	0.26	4.12	90.81	3.78
Sub-total		5.65	88.20	99.18	88.19
Middling	+500	0.13	1.98	99.19	1.98
	500 - 125	0.54	8.37	99.49	8.40
	-125	0.03	0.42	97.66	0.42
Sub-total		0.69	10.78	99.36	10.80
Reject	+500	0.007	0.11	99.17	0.11
	500 - 125	0.048	0.75	98.90	0.75
	-125	0.01	0.16	98.33	0.15
Sub-total		0.07	1.02	98.84	1.01
Reconstituted feed		6.40	100.00	99.20	100.00

4.4. Grade and Recovery of the Glass Sand Fraction

Although the spiral was able to concentrate most of the heavy minerals into the reject and to upgrade the silica content in the product, the results of the size fractions (+500, 500 - 125, and -125 μm) showed the silica content value was the highest in the Glass Sand Fraction of 500 - 125 μm . Therefore, the results of selected size fractions (+500, 500 - 125, and -125 μm) were considered. The silica grade and recovery in the size fractions of the high and low yield products were calculated and the results are displayed in **Table 10**.

In order to display the results in clearer way, the silica grades and recoveries by size fraction for both the high and low yield products were plotted. Also, the SiO_2 content of the British Standard (BS: 2975, 1988) for Glass Sand -Grade A- was plotted on the same diagram for comparison (**Figure 19**).

The results showed that the silica content was increased from 98.99% - 99.18% in the all size (product) to 99.58% - 99.66% in the 500 - 125 μm size fraction in

Table 9. Grade and recovery of the silica content/Low yield run- (SS) sample.

	Size (μm)	Dry weight		Grade SiO_2 (%)	Recovery (%)
		(kg)	(%)		
Product	+500	1.11	16.60	99.37	16.69
	500 - 125	3.19	47.90	99.58	48.15
	-125	0.27	4.00	90.32	3.63
Sub-total		4.56	68.60	98.99	68.47
Middling	+500	0.27	4.10	99.20	4.12
	500 - 125	1.16	17.50	99.51	17.53
	-125	0.03	0.50	98.35	0.51
Sub-total		1.47	22.10	99.43	22.15
Reject	+500	0.10	1.50	99.19	1.53
	500 - 125	0.47	7.10	99.47	7.15
	-125	0.05	0.70	98.15	0.70
Sub-total		0.62	9.40	99.32	9.38
Reconstituted feed		6.66	100.00	99.12	100.00

Table 10. Silica grade and recovery of the product in high and low yield runs with regard to size, (SS) sample.

Size fraction (μm)	High-Yield Product		Low-Yield Product	
	Grade SiO_2 (%)	Recovery (%)	Grade SiO_2 (%)	Recovery (%)
All sizes	99.18	88.19	98.99	68.47
+125	99.60	84.42	99.50	64.84
500 - 125	99.66	62.47	99.58	48.15

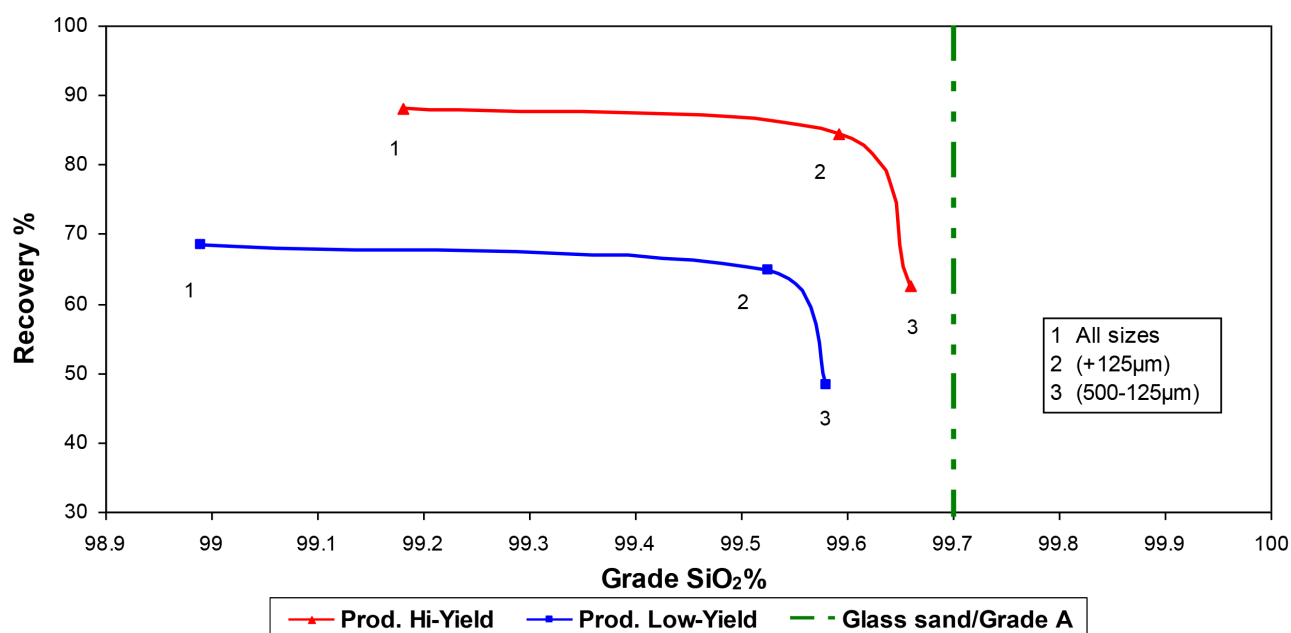


Figure 19. Silica grade and recovery relationship of the All, +125 µm and 500 - 125 µm size fractions of the high and low yield runs of the (SS) sample.

Table 11. Grade of major contaminant oxides with the silica recovery of the high yield product (SS) sample.

High-Yield Product Size fraction (µm)	Grade			Recovery SiO ₂ (%)
	Fe ₂ O ₃ (%)	TiO ₂ (%)	(MgO + CaO) (%)	
All sizes	0.021	0.047	0.027	88.19
+125	0.004	0.009	0.023	84.42
500 - 125	0.004	0.01	0.022	62.47

the low and high yield runs respectively. The silica content of 99.66% was very close to that of the Glass Sand -grade A- of 99.7%. The recovery of silica decreased from 88.19% in the all size to 62.47% in the specified 500 - 125 µm size fraction of the high yield and from 68.47% to 48.15% in the low yield. It was found that the silica grade and recovery increased in the high yield more than that in the low yield run. This indicated that the high silica content could be produced with a high recovery.

The grades of the major contaminant oxides *i.e.* Fe₂O₃, TiO₂, and CaO+MgO in the product of the high yield run of the (SS) sample were calculated with regard to the size fractions and displayed in **Table 11**. The Al₂O₃ content was very low (0.02%) which considered as traces when compared to the minimum accepted value (0.2%) for Al₂O₃ content of the glass sand standard.

In **Figure 20**, the grades of the contaminant oxides in the size fractions of the high yield product are plotted versus the silica recovery. The minimum contaminant level of Fe₂O₃, TiO₂, and CaO + MgO accepted by the British Standard and Sebilco Company for Glass Sand-grade -A is also plotted on the same

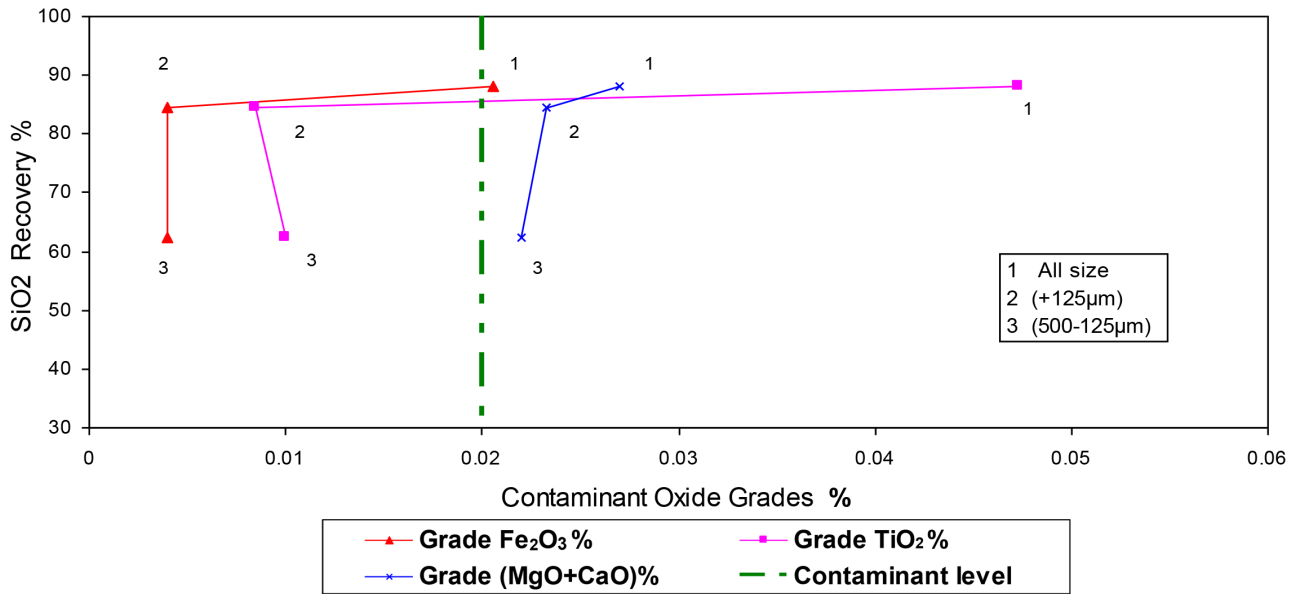


Figure 20. The contaminant oxide grades versus SiO₂ recovery of the All, +125 µm, and 500 - 125 µm size fractions of the high yield run-(SS) sample.

Table 12. Silica grades and recoveries for the combined product and middling of the high and low yield runs with regard to the size fraction-(SS) sample.

Size fraction (µm)	High-Yield Product + Middling		Low-Yield Product + Middling	
	Grade (SiO ₂ %)	Recovery (%)	Grade (SiO ₂ %)	Recovery (%)
All sizes	99.20	98.19	99.10	90.62
+125	99.57	94.80	99.51	86.49
500 - 125	99.64	70.87	99.56	65.68

diagram for comparison.

The results showed that the grades of Fe₂O₃ and TiO₂ decreased in the Glass Sand Fraction (500 - 125 µm) to less than the contaminant level of 0.02% as values were below the detection limit (0.005%). The combined CaO + MgO grade decreased as well to 0.022% in the glass sand fraction.

It was found that the silica grade of the middling was almost as good as that of the product. The recovery increased when the middling were combined with the product giving a silica grade in the combined 500 - 125 µm size fraction very close to the value of the product (Table 12). However, the results of the combined high yield produced a higher silica grade and recovery than that in the low yield run. For instance, in the high yield run, the recovery of silica in the glass sand (500 - 125 µm) fraction increased from 62.47% at grade of 99.66% to 70.87% at grade of 99.64% in the combined product and middling (Figure 21).

From the results of the combined product and middling, it could be concluded that re-passing the middling or reducing the middling band (*i.e.* widen the product band) or even producing product and reject only, would still

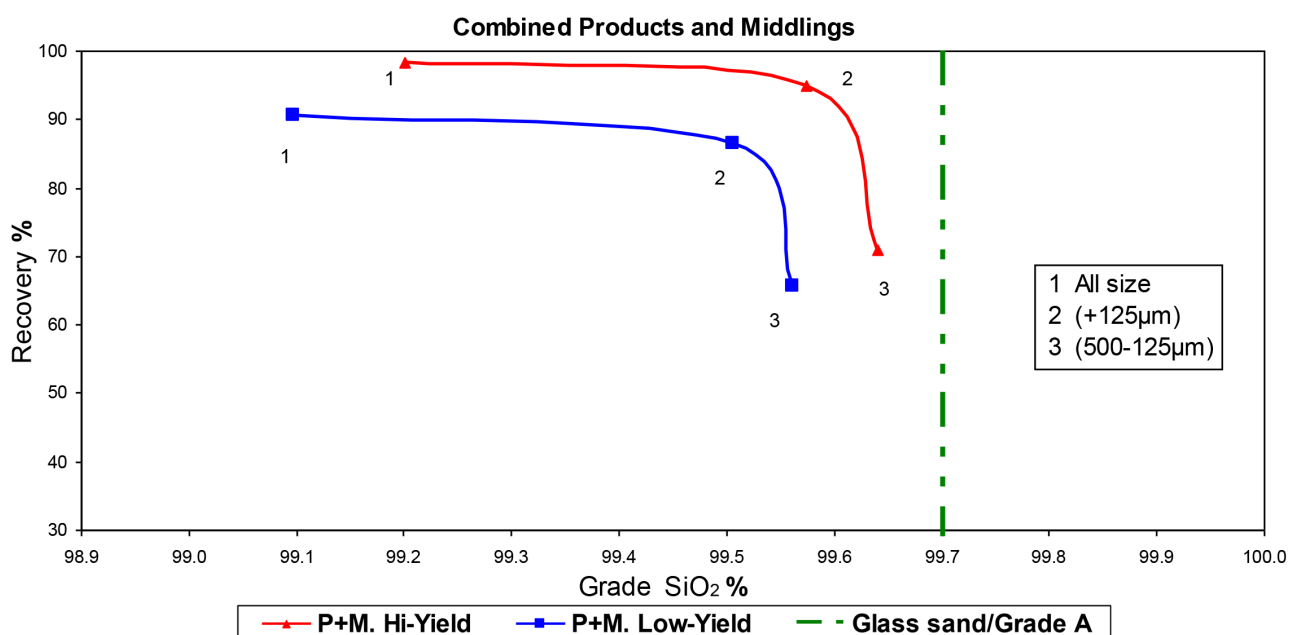


Figure 21. Silica grade and recovery relationship of the All, +125 μm , and 500 - 125 μm size fractions of the combined Product (P) and Middling (M) in the high and low yield runs of the (SS) sample.

produce a high silica grade with high recovery.

4.5. Assessment of the Pilot Study and the Glass Sand Product

Results of the pilot study showed that a glass sand product in the size range 500 - 125 μm could be produced from the silica sand at a high grade with substantial recovery using a mineral spiral.

In the case of using a single mineral spiral of 5 1/4 turns in a silica sand plant working continuously at 16 hours a day, 300 days a year, the amount of glass sand produced in the 500 - 125 μm size fraction and water consumed was calculated as in the following: -

The results of the mass balance calculation of the high yield spiral separation (see **Table 7**) showed that the dry mass flowrate of spiral product was around 2.03 tph at a recovery of 88%, while the recovery of glass sand (500 - 125 μm) fraction from the spiral was 63%. Therefore, the dry mass flowrate of the glass sand fraction would be around 8880 tpa. The amount of water required running that feed through the spiral was calculated as 4.7 m^3/h and 22,600 m^3/year . If water recovered, taking into consideration the slight increase of salinity due to the dissolved traces of salts (halite & gypsum) from the samples, the loss in the amount of water would be the moisture content of the processed sand, which was found about 6% - 8%.

Based on that, from each ton of the Lower Ordovician sandstone, an amount of 0.63 ton of glass sand product could be produced at a silica grade of 99.66% to 99.70%.

The Glass Sand Fraction produced from the Lower Ordovician sandstone was at a high enough grade that could meet the specifications of Grade-A in the British

Standard for glass sand [16]. To confirm the final results of the study, samples from the products were sent to (WBB) [19] and to (Jaspar) [20] for analysis. The results of the chemical analysis are displayed in **Table 13** and exhibit that the products are of high quality to meeting the required specifications for high quality glass sand.

The high-grade Glass Sand Fraction produced could be used in any type of glass as it can meet the specifications of Grade-A for glass sand in the British Standards, which stands for optical and ophthalmic glass. Other potential uses are as white silica sand in whiteware ceramic formulations and as white silica flour in reinforcement filler and extender applications. The high quality silica sand could also be used in metallurgical-grade silicon applications such as silicon metal and silicon alloys and in the production of soluble silicates such as sodium silicates and insoluble silicates. Other uses include in manufacturing silica bricks and lining, in hydraulic fracturing in the oil industry, in water purifying and as abrasives with regard to the required specifications for grain size distribution.

Table 13. Chemical results of the (500 - 125 μm) fraction of the spiral product for SS sample by Jaspar and WBB companies using XRF.

Oxides %	Glass Sand product	
	Ref. [20] Jaspar	Ref. [19] WBB
SiO ₂	99.8	99.5
Al ₂ O ₃	0.054	0.03
Fe ₂ O ₃	0.009	0.012
TiO ₂	0.013	0.017
Mn ₃ O ₄	<0.001	NA
MgO	<0.02	<0.03
CaO	0.04	0.02
Na ₂ O	<0.05	<0.05
K ₂ O	0.01	0.00
S	NA	0.014
Cr*	12	0.00
Cu*	0.0	NA
Co*	0.0	NA
Ni*	0.0	NA
V*	0.0	NA
LOI	0.06	0.07
Total	100.06	99.65

*ppm.

5. Conclusions

The studied samples from Dabbat Hanout area, south of Ras El-Naqb Escarpment, belonging to the Disi Sandstone Formation were mainly sub-rounded medium-grained sand and quartz was the major mineral constituent with very little kaolinite clay mineral. Schorl (Fe-tourmaline) was the most abundant heavy mineral found in the scrubbed glass sand fraction and the total amount of heavy minerals (0.04% by weight) found was to be very low but significant for the proposed end-use of the sand.

The microscopic study revealed that the source of iron oxides in the scrubbed sand was mainly from the iron stains in the quartz grains' fissures and from heavy mineral inclusions, such as ilmenite and Fe-tourmaline inside the grains.

Attrition scrubbing was performed on individual and whole size fractions at different time intervals. Optimum results in producing high recovery and clean sand grains were achieved after 8 minutes scrubbing time and treating a wider size distribution material (different grain size).

The results of the characterization study of the raw material and the upgrading trials showed that the process to upgrade silica sand required dry and wet screening to obtain the necessary size fractions, attrition scrubbing to dislodge clays and to reduce iron stains and gravity separation to remove heavy minerals including iron oxides.

The Glass Sand Fraction and the high-grade silica sand produced could be used in wide range of industrial applications from high quality glass manufacturing and metallurgical-grade silicon applications to downstream industries and construction materials.

It could be stated that this study has achieved the objectives that the cost-effective process used was able to produce high-grade Glass Sand from Jordanian sandstone. The results of this research are of high importance to the silica sand producers and companies whom are using scrubbing and mineral spiral techniques.

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Data Availability

<http://dx.doi.org/10.17632/8293xp6hr2.1>.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Annex A

The chemical analysis of the whole rock, dry and wet sieved size fractions of the silica sand (SS) sample using XRF.

Sample No.		SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	MnO	P ₂ O ₅	LOI	Total
Bulk sample		98.51	0.09	0.73	0.02	0.05	0.08	0.01	0.02	0.01	0.01	0.45	99.99
+1180 (µm)	Dry	86.96	0.52	7.93	0.13	0.17	0.17	0.00	0.08	0.02	0.05	3.30	99.33
	Wet	92.50	0.29	4.48	0.09	0.07	0.10	0.04	0.04	0.01	0.03	1.81	99.47
+850	Dry	96.97	0.10	1.41	0.03	0.04	0.11	0.06	0.00	0.01	0.04	0.86	99.65
	Wet	98.78	0.04	0.40	0.03	0.01	0.07	0.00	0.01	0.02	0.02	0.20	99.59
+600	Dry	98.89	0.05	0.45	0.02	0.00	0.06	0.00	0.01	0.01	0.02	0.40	99.92
	Wet	98.76	0.03	0.22	0.02	0.06	0.03	0.00	0.01	0.03	0.03	0.30	99.50
+425	Dry	98.67	0.03	0.33	0.02	0.04	0.05	0.00	0.00	0.01	0.02	0.35	99.53
	Wet	99.02	0.02	0.11	0.00	0.02	0.04	0.00	0.00	0.00	0.03	0.25	99.50
+300	Dry	98.62	0.05	0.42	0.01	0.09	0.07	0.05	0.01	0.00	0.02	0.43	99.78
	Wet	99.04	0.02	0.13	0.02	0.08	0.04	0.02	0.00	0.03	0.00	0.20	99.60
+212	Dry	98.27	0.05	0.55	0.02	0.03	0.05	0.21	0.00	0.01	0.03	0.35	99.57
	Wet	99.28	0.03	0.23	0.03	0.05	0.06	0.12	0.01	0.01	0.02	0.25	100.1
+150	Dry	98.34	0.11	0.65	0.02	0.05	0.06	0.00	0.01	0.02	0.01	0.43	99.71
	Wet	99.22	0.06	0.24	0.01	0.02	0.07	0.00	0.00	0.02	0.02	0.30	99.97
+106	Dry	97.13	0.33	1.20	0.05	0.14	0.09	0.01	0.02	0.01	0.01	0.65	99.65
	Wet	98.36	0.30	0.32	0.03	0.04	0.06	0.00	0.00	0.01	0.02	0.35	99.50
+75	Dry	96.61	0.59	1.30	0.06	0.07	0.08	0.02	0.00	0.02	0.04	0.76	99.56
	Wet	97.59	0.51	0.51	0.04	0.11	0.07	0.09	0.01	0.00	0.03	0.53	99.50
+53	Dry	93.94	0.72	2.92	0.08	0.19	0.16	0.00	0.03	0.02	0.05	1.38	99.49
	Wet	97.44	0.55	0.71	0.06	0.00	0.09	0.00	0.01	0.01	0.02	0.60	99.50
+38	Dry	91.35	0.98	4.74	0.09	0.03	0.18	0.00	0.02	0.01	0.08	1.97	99.46
	Wet	97.10	0.59	1.10	0.08	0.05	0.14	0.00	0.00	0.01	0.02	0.83	99.92
-38	Dry	85.60	1.46	8.25	0.20	0.00	0.22	0.23	0.02	0.02	0.14	3.33	99.47
	Wet	77.37	1.80	13.75	0.27	0.05	0.32	0.24	0.03	0.02	0.21	5.65	99.72

Annex B

Results of the **High-yield** run of silica sand (SS) sample

Size (µm)	Product			Middling			Reject		
	+500	500 - 125	-125	+500	500 - 125	-125	+500	500 - 125	-125
SiO ₂	99.40	99.66	90.81	99.19	99.49	97.66	99.17	98.90	98.33
TiO ₂	0.00	0.01	0.84	0.01	0.01	0.46	0.01	0.15	0.81
Al ₂ O ₃	0.00	0.00	5.04	0.00	0.00	0.76	0.00	0.00	0.05
Fe ₂ O ₃	0.00	0.00	0.36	0.00	0.00	0.07	0.00	0.02	0.05
MnO	0.00	0.00	0.04	0.00	0.00	0.00	0.01	0.01	0.01
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.05	0.04	0.20	0.05	0.04	0.10	0.05	0.06	0.08

Continued

Na ₂ O	0.02	0.13	0.11	0.14	0.08	0.02	0.04	0.08	0.00
K ₂ O	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
P ₂ O ₅	0.01	0.02	0.15	0.02	0.01	0.04	0.02	0.02	0.03
LOI	0.13	0.03	2.19	0.10	0.15	0.53	0.25	0.18	0.30
Total	99.61	99.89	99.76	99.51	99.78	99.64	99.55	99.43	99.67

Results of the **Low-yield** run of silica sand (SS) sample.

Size (μm)	Product			Middling			Rejects		
	+500	500 - 125	-125	+500	500 - 125	-125	+500	500 - 125	-125
SiO ₂	99.37	99.58	90.32	99.20	99.51	98.35	99.19	99.47	98.15
TiO ₂	0.00	0.01	0.85	0.02	0.02	0.32	0.02	0.04	0.59
Al ₂ O ₃	0.00	0.00	5.16	0.00	0.00	0.29	0.03	0.00	0.14
Fe ₂ O ₃	0.00	0.00	0.41	0.00	0.00	0.04	0.01	0.01	0.04
MnO	0.00	0.02	0.01	0.00	0.01	0.02	0.00	0.00	0.02
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.06	0.04	0.20	0.02	0.04	0.08	0.05	0.05	0.08
Na ₂ O	0.08	0.00	0.02	0.03	0.03	0.04	0.11	0.06	0.08
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P ₂ O ₅	0.02	0.01	0.15	0.02	0.02	0.02	0.02	0.02	0.03
LOI	0.15	0.20	2.43	0.25	0.08	0.43	0.10	0.10	0.33
Total	99.68	99.86	99.56	99.54	99.72	99.59	99.53	99.75	99.47