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Identification and Economic Potentiality of Mineral Sands Resources of Hatiya Island, Bangladesh

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Abstract: Hatiya is the second largest island of Bangladesh and is situated near the Meghna River estuary in the central coastal zone of Bangladesh. This island hosts a few scenic beaches with a huge deposit of mineral sands. Representative mineral sand samples from various beaches of this island were collected during the year 2019, and analyzed for different mineralogical contents using state-of-the-art techniques, such as WD-XRF, XRD, SEM and EDX. This study determined various mineralogical contents, such as SiO_2 (73.58%), micas (40.30%), Al_2O_3 (12.13%), TiO_2 (0.56%), MgO (1.31%), Fe_2O_3 (4.71%), K_2O (3.1%), Na_2O (1.92%), CaO (3.16%), some earth metals, and heavy minerals, such as ilmenite (14.77%), garnet (11.02%), rutile (14.94%), magnetite (15.26%), and zircon (13.63%), were identified in the analyzed samples. It is suggested that the studied sand can be utilized as a raw material in the glass industry, due to its high SiO_2 content. The approximate prices of heavy and light minerals, such as garnet (USD 75–USD 210/mt), ilmenite (USD 110/mt), magnetite (USD 84/mt), rutile (USD 840/mt), zircon (USD 1050/mt) and micas (USD 109/mt), some oxides such as K_2O (USD 350–400/mt), CaO (USD 350–450/mt), Al_2O_3 (USD 1000-USD 1300/mt), TiO_2 (USD 4000–4500/mt), and Fe_2O_3 (USD 650–1500/mt), and some other heavy metals (Rb, Th, Ba, V, Cr, Cs, Ni and Co), indicates a great economic value of the sand of the Hatiya Island beaches. This study recommends that Hatiya Island's minerals should be mined responsibly and used effectively, to enhance the nation's economy.

Keywords: beach sand; silica; heavy and light minerals; valuable oxides; heavy metals; pilot plant

1. Introduction

Hatiya Island is located at the mouth of the Meghna River estuary in the northern littoral of the Bay of Bengal, within the territory of Bangladesh. This island has some scenic coastal beaches, including several satellite islands near the Meghna River estuary. This river forms the country's largest estuarine ecosystem, providing great aquatic biodiversity and a huge deposit of mineral sands [1,2]. The deposition of heavy minerals (HM) in the old beach or river system (an alluvial), plays a key role in forming the mineral sands. The notable minerals in the beach sands are identified as zircon, ilmenite, rutile, and their weathered equivalents. The southern and south-eastern coastlines of the country contain up to 20 to 25% (by weight) of heavy minerals [3,4], which are considered as high-grade mineral deposits [4]. There are two main types of placer minerals: the beach placer and alluvial placer [5]. The beach placer formation was affected during the geological past by the emergence and submergence of the coast [6]. The beach placer is formed through the process of chemical weathering or mechanical bulk rock and their reformatting along a continental shelf [7]. Across the coastal shorelines/beaches or river channels, these heavy minerals gather in placer deposits formed by chemical or mechanical concentrations of mineral particles from the debris storm [8]. It is deposited by a hydraulic process that occurs in very low concentrations in different types of fiery and transformed rocks, but also through the physicochemical process, the heavy minerals are concentrated by hindering the weathering process. With a comparatively high specific gravity, the thick and thin materials slowly sorted towards the edge and deep seawater from the sediments [9]. Along the present coastal belt, many sea or river beaches periodically rise at a remarkable distance from the inland. The sea level water rises or changes the geological pattern or setting, the geochemical leaching, the physicochemical characteristics of the origin rocks, climatic factors, drainage patterns, displacement of sands drift overthrown by the wind long-distance, and the long-time upward motion of the shorelines has formatted the sea or river beaches [10,11]. By the dynamic ways (wave, currents and wind actions), the shoreline zone deposits contain a notable quantity of heavy minerals assembled within the seacoast. Heavy mineral sand deposits (HMSDs) have also been formed, due to coastal geomorphology, neotectonics, and continental shelf morphology. In-shore sorting, transport, and deposition of placer minerals have been affected by coastal hydraulic processes (longshore currents, wave velocity and wind speed) [6].

The study aims to determine whether heavy mineral deposits exist in the sands of the Hatiya beaches or not, by examining their mineralogy, morphology, and composition. In this regard, state-of-the-art-techniques such as wavelength dispersive X-ray fluorescence (WDXRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX), have been used to evaluate and quantify the relative amount of mineral contents and characteristics. Additionally, the economic worth of these sand deposits is determined by evaluating the minerals, oxides and metal contents and contrasting them with other deposits and the prices of these minerals.

2. Materials and Methods

2.1. Evolutionary History and the Geological Settings of the Hatiya Trough

During the Precambrian era, the Indian Plate (IP) was a focal point of the Gondwana supercontinent (GS), and it began to split apart in the Middle Jurassic (170–175 Ma) [2]. The IP shifted and detached from its surrounding cratonic blocks (55.9 Ma) [12]. Geotectonic Province 1 (Bengal Basin's stable shelf) was formed from the IP. Prior to 50–55 Ma, the Indian and Eurasian Plates clashed, lifting the Indian Plate onto the Eurasian Plate. The tectonics and erosion formed the Himalayas [12–14]. The Hatiya Trough is part of the Bengal Basin's tectonic map [2,14]. The Indian Plate's ocean sediment exited the Bengal Basin [15–18]. The Bengal Foredeep Basin (BFB) has profited the most from the deepest trough's sediment. Bengal deep-sea Fan opens into the Hatiya and Faridpur Troughs [2]. Oligocene sediments from the Himalayas fill the Bengal Basin [19]. The Bengal Basin has two tectonic states: the Indian platform and the deeper basin. The Chittagong-Tripura Folded Belt is in the southeast, the Surma subbasin (Sylhet Trough) is in the northeast, and the deeper Bengal Basin, which includes the Hatiya Trough, is in the northwest (Chandpur Barishal) [20–22]. The Hatiya and Faridpur Troughs are separated by the Chandpur-Barisal High [23]. The Indian Plate lies 16 km below the Hatiya Trough's 18 km sediment layer [16]. In the Hatiya Trough, Plio-Pleistocene sediments cover the Holocene layers by 480 m [24]. The Hatiya Trough is one of the five tectonic zones in the deep basin [20,23,25]. The 200-m bathymetric contour limits the basin boundary in the Hatiya Trough, south of the Bay of Bengal deltaic zone. This waterway formed when sediments were deposited (Figure 1a), and the reservoir where the Pliocene anticlines are developed. Late Miocene to early Pliocene channels are eroded (Figure 1b) [24]. The minor arc-derived sediments from the Trans-Himalaya or Paleogene Indo-Burman Ranges were present, although the lithology existed from the Miocene to the recent past [25]. Only the Bhuban Formation has a gas-producing sand zone [20]. Recent GPS-derived geodetic data shows that the Hatiya Trough subsidence rates vary [26]. The Hatiya beaches, in this way, deposits valuable mineral sands.

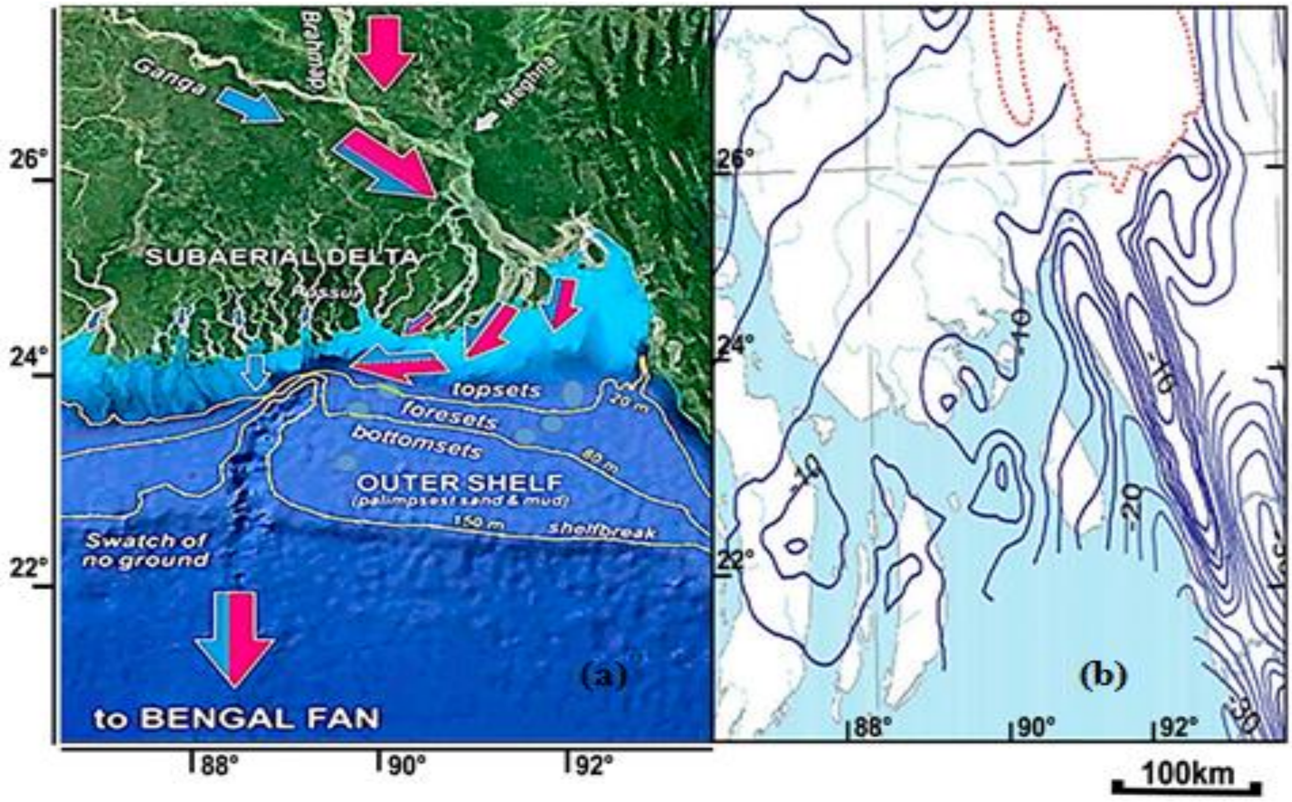

Figure 1. (**a**). Sediment in transit across the Bengal system [27–31], (**b**). Map of the Hatiya Trough region of the Bengal Basin showing the Bouguer gravity anomalies (Lambert Conformal Conic with Everest 1969 spheroid) [32].

2.2. Sample Collection and Analysis

The present study area is located at Hatiya Upazila in the Noakhali district of Bangladesh. It is a stable sand beach area which extends over a length of 10 km and a width of 1 km from the Meghna River's upstream to downstream (22°02′21.1″ N; 90°58′33.5″ E—22°17′59.6″ N; 91°10′44.2″ E) (Figure 2). The study covers an approximate area of 10 km × 1 km, from where five successive sites were chosen for sampling and assigned the sampling codes of NDB, DCB, NB, QBB, and RBB. One or two mixed samples were collected from each location's river bed and beach sand, to ensure the representativeness of the sampling location (based on our physical observation), with respect to the whole beach. Using the global positioning system (GPS), the sample locations were recorded in degrees, minutes, and seconds (latitudinal and longitudinal position). The distance between each sampling location/point was approximately 2 km. During the summer of 2019, all samples were collected using a spade at a depth of 1 m, then placed in polyethylene bags and transported to the Bangladesh Council of Scientific and Industrial Research (BCSIR) laboratory for subsequent processing. Each sample weighs approximately 1 kg. The samples were allowed to dry in the open air, at room temperature.

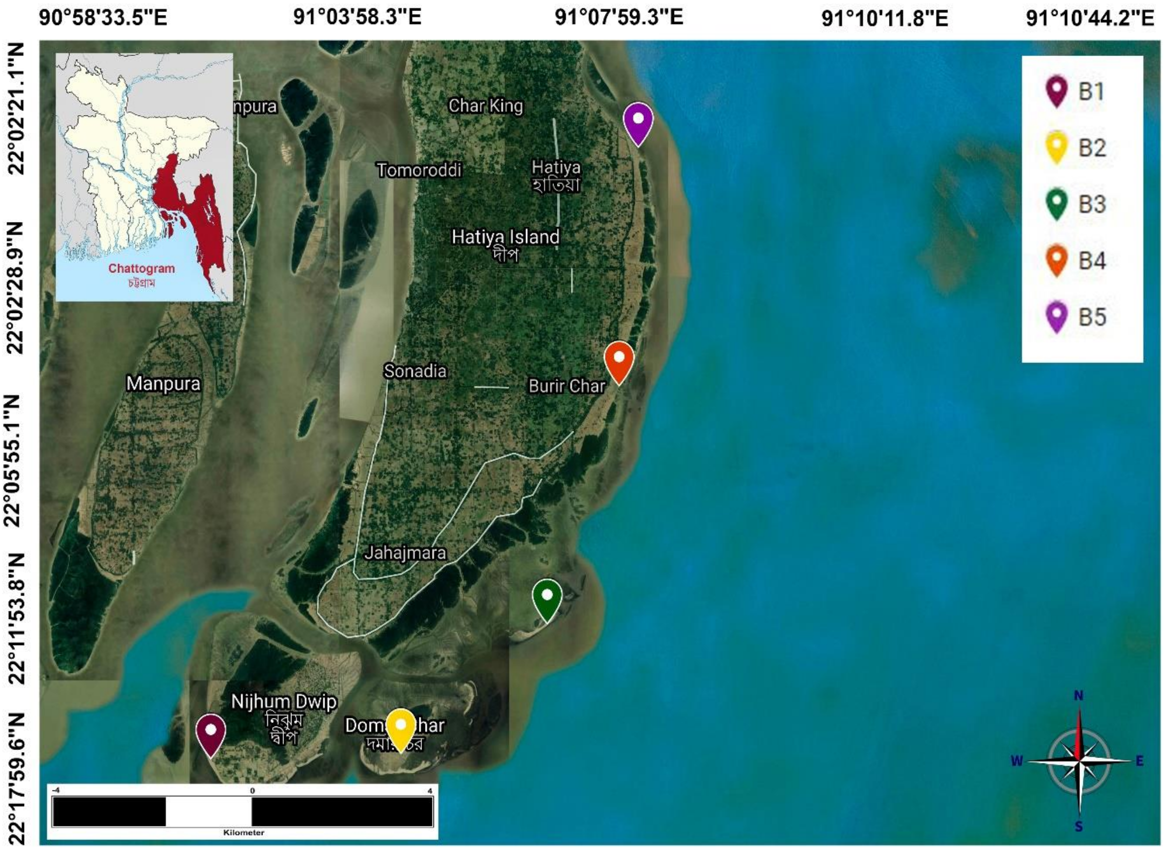

Figure 2. Location map of the sampling points (Google Map).

The raw sand samples were dried under direct sunlight to remove the moisture content prior to the laboratory analyses. Each sample (1 kg) was sieved, using a sieve shaker (model U.S. sieve 35, 60, 120, 230, and 325 mesh). HCl (1N) and distilled water were used for vigorous washing and dispelling of the samples' organic substances. The percentages of total heavy minerals (THMs) were computed. Magnetic minerals (magnetite) were isolated from the heavy mineral fractions using a hand magnet, and the weight % was calculated. Using a laboratory shaking table, the heavy and light minerals were separated, based on their density and specific gravity. According to their specific densities, the minerals are categorized as either light (specific density less than 2.9 g/cm^3) or heavy (specific density greater than 2.9 g/cm^3). Under the transmitted and reflected light techniques (using a binocular microscope and polarizing microscope), an accurate measurement of the heavy minerals (HMs) in the fragments was made. Following the ribbon method, each countable mineral in the sample (crystal clear, such as kyanite and zircon; not clear, such as ilmenite) was calculated by enumerating a minimum of 200 grains.

The elemental compositions of the heavy metal fractions were evaluated using the WD-XRF and powder XRD methods. The XRD analysis, as well as WD-XRF analysis, is the composition identification technique with the microscopic study. The constituents such as quartz, feldspar, hornblende, monazite, ilmenite, biotite, kyanite, and garnet are described by the XRD diagram of the para-magnetic portion (Figure 3a,b). The auto-matching data from the X'Pert High Score Plus' software of the XRD system and the X-ray diffractometer (Smartlab SE, Rigaku, Japan) were used for the interpretation of data, digitally. The X-ray generator (40 kV, 50 mA), 1D (scan) mode, scan speed/duration (50.00°/min), step width (0.01°), and scan axis/2, were applied in the XRD analysis of the samples. The following parameters were used in the XRD study: filter 1D for Cu, filter K range of 5 to 80 degrees, length-limiting slit 10 mm, selection slit B.B., incident slit box 1/2 degree with detector HyPix-400 (horizontal). Hand-polished grain, gradually down to 10 mm and diamond paste was used for the SEM analysis. Carbon-coated polished face and a FEI Quanta

500 scanning electron microscopy image (SEM, Model: EVO18, Manufacture: Carl Zeiss AG, CoO: U.K.), and energy-dispersive X-ray spectroscopy (EDS, Model: EDAX Team, Manufacture: EDAX, CoO: USA) were used. The elemental compositions, including the heavy and light elements, were identified using the Rigaku ZSX Primus WD-XRF machine and X-ray fluorescence (XRF) technique, according to a standard procedure for the WD-XRF analysis. Here, a 4 kW Rh-Anode X-ray tube with an end window was used to detect the light and heavy elements at 30 kV-100 mA and 40 kV-60 mA, respectively.

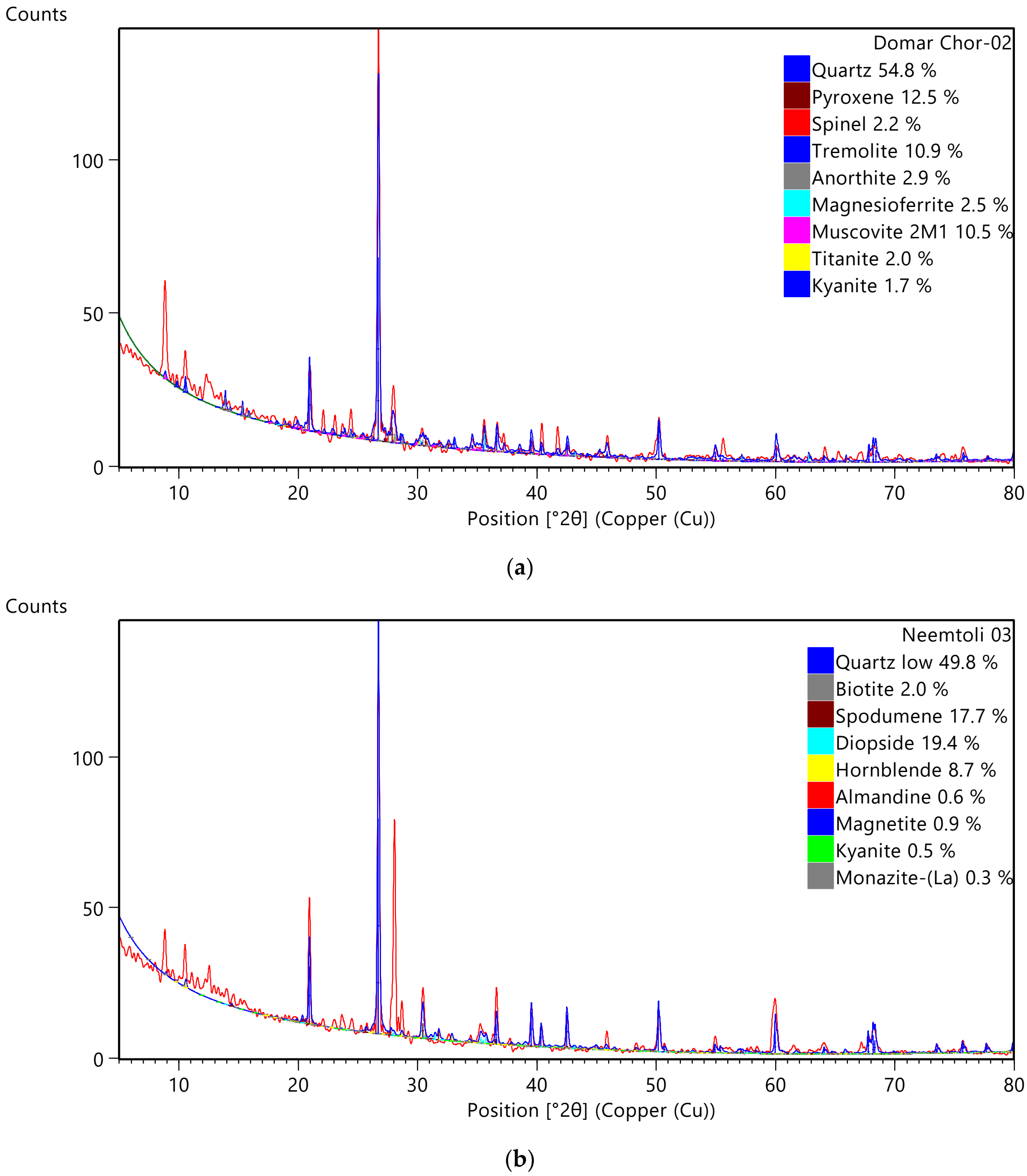

Figure 3. (**a**) XRD pattern of the magnetic component of Domar Char Beach sand. (**b**) XRD pattern of the magnetic component of Neemtoli Beach sand.

3. Results and Discussion

The beach sand's particle size distribution is presented in Table 1. It has been found that the highest percentage of the grain size distribution, ranged from 125–180 µm (67.46%) in the sand of the Hatiya beaches. The measured distribution varies with the distance from the source to the deposited area. The grain size distribution highly influences the separation of heavy minerals. The visual identification of the average heavy minerals fractions of five locations has been found to be 14.73% (see Table 2). The fractions were made under transmitted and reflected light techniques (using polarizing and binocular microscopes).

Table 1. Grain size distribution of the raw sand through the sieve analyzer.

Grain Size (μm)	Nijuhm Dwip Beach	Domar Char Beach	Nimtoli Beach	Qazir Bazar Beach	Rahmat Bazar Beach
180–250	7.6	3.4	4.1	5.3	5.7
125–180	71.5	63.6	67.7	68.7	65.8
90–125	19.0	28.0	24.8	23.8	25.9
63–90	1.1	3.7	2.2	1.8	2.1
45–63	0.2	0.3	0.2	0.2	0.3
Pan	0.2	0.2	0.2	0.2	0.2

Table 2. The visual detection of the heavy minerals fractions using the transmitted and reflected light techniques.

Locations	Heavy (%)	Light (%)
Nijuhm Dwip Beach	11.53	88.47
Domar Char Beach	15.46	84.54
Nimtoli Beach	16.12	83.88
Qazir Bazar Beach	16.10	83.9
Rahmat Bazar Beach	14.45	85.55

According to the results of the X-ray diffractogram (XRD) analysis, all samples were found to be quartz-rich (>55%). The minor constituents were biotite, enstatite, pargasite, muscovite, sodalite, diopside, magnesite, pyroxen, spinel, tremolite, anorthite, magnesioferrite, titanite, kyanite, periclass, and spodumene. According to the XRD results, the heavy minerals (HM) such as sillimanite, garnet (almandine), zircon, rutile, ilmenite, xenotime, monazite, and kyanite, as well as other minerals from the amphibole and pyroxene group, were found in the HM concentrates made from the bulk sediments. There are numerous distinct minerals, and many of them have overlapping peaks, making it difficult to distinguish them using the XRD method. Enstatite is the primary mineral that can be seen at the magnetic part's maximum intensity, along with biotite, pargasite, muscovite, sodalite, diopside, magnesite, pyroxen, spinel, tremolite, anorthite, magnesioferrite, titanite, kyanite, periclass, spodumene, hornblende, almandine, and monazite, all show in Figure 3a,b and supplementary Figure S1a–c. The auto-matching data from the X'Pert High Score Plus' software of the XRD system and the X-ray diffractometer (Smartlab SE, Rigaku, Japan) were used for the digital data interpretation.

The percentage of the valuable heavy mineral (VHM) concentration is given in Table 3 and they were calculated from the XRD chart by counting the mean value. The individual mineral concentration has been notably high in the Hatiya Island beach sands but the physical separation technique is not established yet. Specific concentrations of the heavy minerals determined in the sands of Nijhum Dwip Beach, Domar Char Beach, Nimtoli Beach, and Qazir Bazar Beach are garnet (11.02%), ilmenite (14.77%), magnetite (15.26%), rutile (14.94%), zircon (13.63%), and the light mineral is micas (14.30%).

Table 3. The concentration of the valuable heavy mineral (VHM) percentage was determined using the XRD technique.

Sample ID	Nijuhm Dwip Beach	Domar Char Beach	Nimtoli Beach	Qazir Bazar Beach	Rahmat Bazar Beach
Magnetite (%)	1.65	2.21	2.1	2.63	2.46
Ilmenite (%)	2.52	3.38	3.8	3.2	3.3
Rutile (%)	2.04	2.73	2.8	2.62	2.38
Zircon (%)	2.23	2.99	3.02	3.1	2.62
Garnet (%)	2.58	3.46	3.54	3.39	2.88
Total	11.02	14.77	15.26	14.94	13.64

For rechecking, cross-checking, or the verification of the heavy metal concentrations, we have applied the XRD, WD-XRF and SEM techniques. The grain size distributions were calculated from the SEM images of the refined grain mounts. Various minerals have been identified from the elemental settings. According to Table 3, ilmenite, zircon, garnet, rutile, and magnetite have been shown as individual sand grains. Each SEM (Figure 4) was subsampled for these fractions. Epoxy resin and refined oil were used in the SEM analysis when the grains were mounted. The scale on the SEM image was used to calibrate the software. Prior to processing through SEM Image, the analyzed particles (the grain size of each density fraction) function was used for measurement. The images were collected at a magnification to capture over five hundred grains per image. A magnification of 500X was used, and circularity was set to 0.0–1.0.

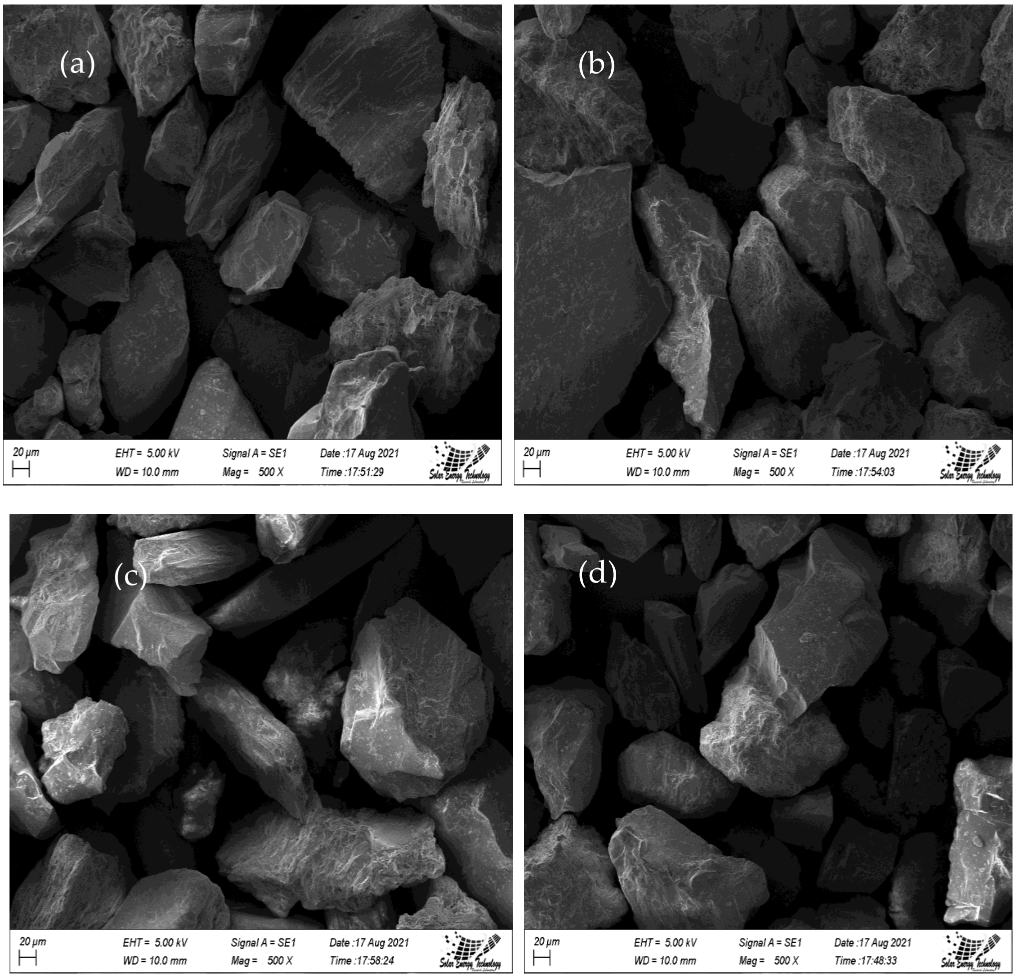

Figure 4. *Cont.*

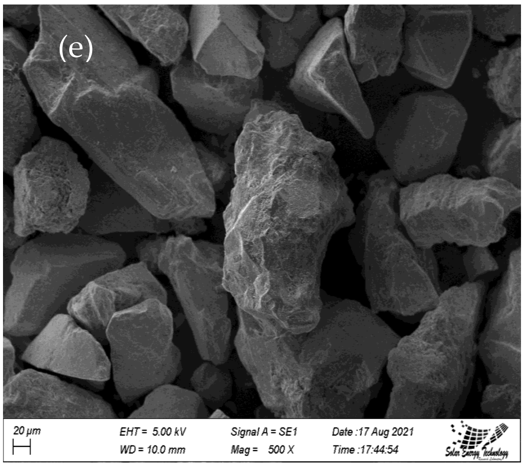

Figure 4. (**a**–**e**). SEM images of Nijhum Dwip, Domar Char, Nimtoli, Qazir Bazar and Rahmat Bazar grains, respectively; scale bar = 20 µm.

These particles are pure magnetite particles because they are free of debris. The heavy fraction and ilmenite have a tighter size range than the super heavy fraction, which has a wide range of grain sizes, including some fine grains (Figure 5). There is a good agreement between the two sizing techniques for the ilmenite portion, whose grain size was assessed using an SEM-EDX (Figure 6) and a Malvern particle sizer.

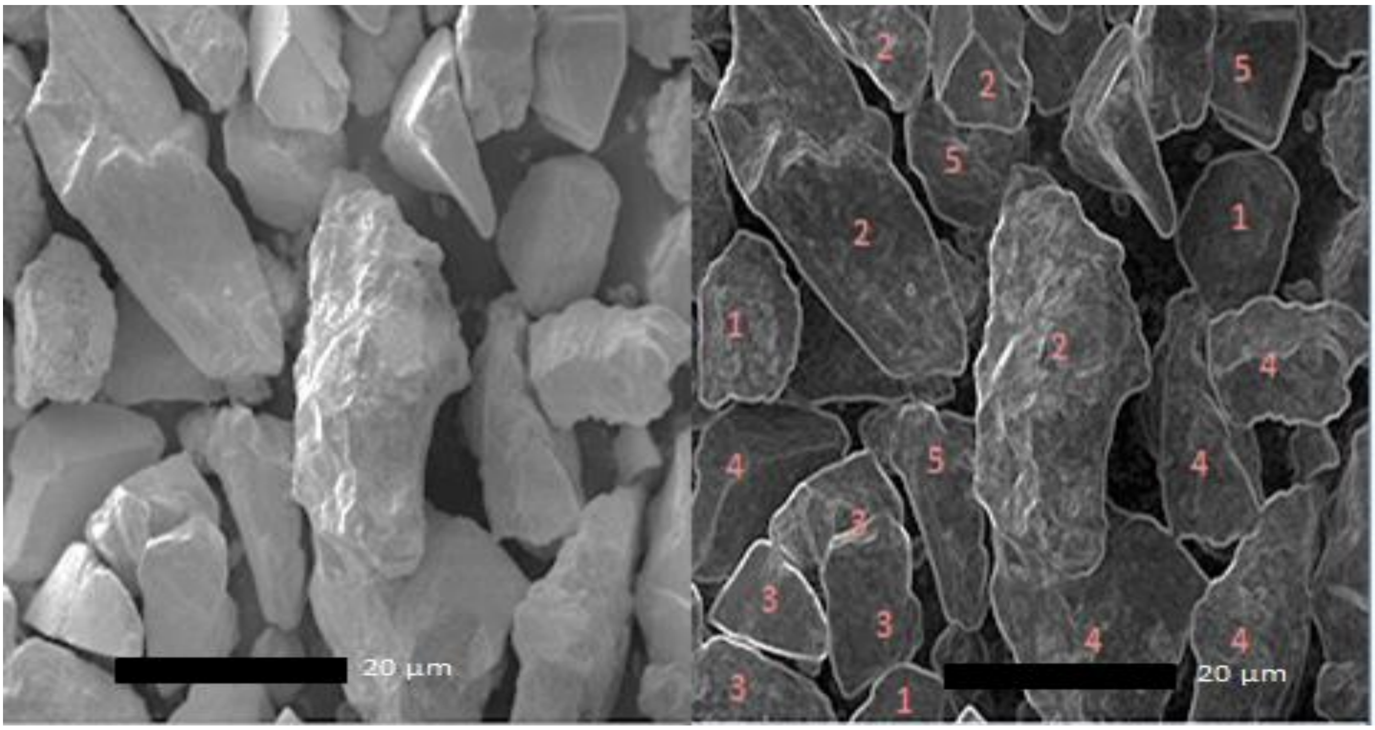

Figure 5. Backscatter electron (BSE) image of the selected sand grains from the mineral fraction with constituents identified through EDS analysis of every single grain. The numbers 1 represent ilmenite, 2 for monazite, 3 for zircon, 4 for titanite, and 5 for magnetite; Scale bar = 20 µm.

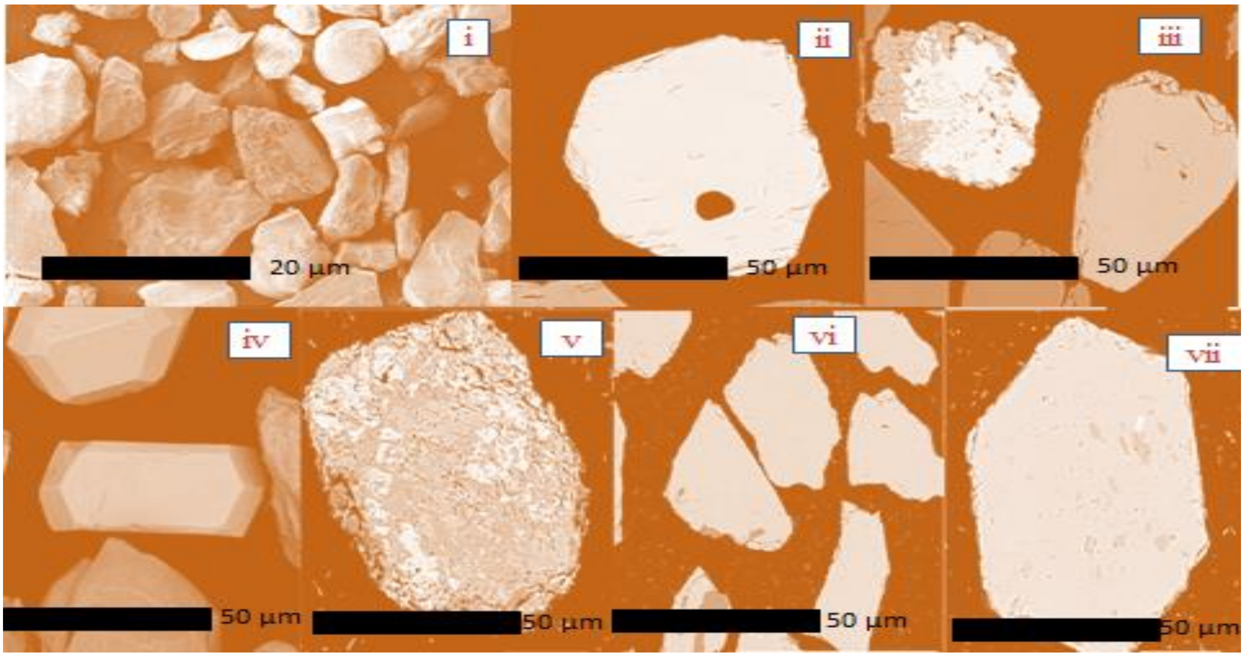

Figure 6. SEM images and elemental diagrams of several mineral grains in polished sections. (**i**) Different ilmenite grains; (**ii**) monazite; (**iii**) titanite (Left top corner) and allanite (right); (**iv**) zircon; (**v**) a piece of mixed titanium rock that contains white ilmenite, light grey rutile, and dark grey titanite; (**vi**) quartz and ilmenite in garnet; (**vii**) zircon-containing garnet with the absence of Fe and Mn; Scale bar: (**i**) = 20 µm, and (**ii**) to (**vii**) = 50 µm.

Furthermore, the elemental composition of the studied sand samples was assessed using the mineral processing method, and the values are presented in Table 4.

Table 4. Geochemistry of the raw sand carried out through WD-XRF.

Element Oxide	Nijuhm Dwip Beach (%)	Domar Char Beach (%)	Nimtoli Beach (%)	Qazir Bazar Beach (%)	Rahmat Bazar Beach (%)
Na_2O	1.8750	1.8926	1.9775	1.8892	1.9432
MgO	1.0458	1.3530	1.4019	1.4231	1.3241
Al_2O_3	12.4931	11.2313	11.2718	13.2312	12.4352
SiO_2	73.7829	72.6981	72.8619	74.6754	73.8764
K_2O	3.8309	2.6984	2.7399	2.9087	3.3246
CaO	2.0908	3.3745	3.2516	3.7865	3.3457
Fe_2O_3	3.6400	5.0577	4.8818	5.0865	4.9087
P_2O_5	0.0918	0.1561	0.1506	0.1312	0.1643
SO_3	0.0697	0.0538	0.1012	0.0601	0.1023
Cl	0.0845	0.1541	0.1200	0.1432	0.1210
TiO_2	0.3351	0.5806	0.6416	0.5708	0.6534
V_2O_5	0.0112	0.0196	0.0127	0.0167	0.0121
Cr_2O_3	0.4756	0.4750	0.3943	0.3869	0.3943
MnO	0.0488	0.0924	0.0906	0.1023	0.0839
Co_2O_3	0.0008	0.0010	0.0011	0.0006	0.0009
NiO	0.0240	0.0147	0.0130	0.0206	0.0187
CuO	0.0047	0.0051	0.0060	0.0055	0.0030
ZnO	0.0046	0.0053	0.0045	0.0067	0.0034
Rb_2O	0.0135	0.0086	0.0093	0.0089	0.0088
SrO	0.0253	0.0251	0.0242	0.0310	0.0190
Y_2O_3	0.0088	0.0093	0.0114	0.0076	0.0213
ZrO_2	0.0118	0.0341	0.0401	0.0378	0.0475
BaO	0.0570	0.0596	0.0512	0.0640	0.0328

The chemical compounds, such as aluminum oxide (Al_2O_3), sodium oxide (Na_2O), calcium oxide (CaO), potassium oxide (K_2O), and magnesium oxide (MgO) had low concentrations in the Hatiya beach sand samples, while silicon dioxide (SiO_2) had significantly high concentrations (73.58 percent). However, this study revealed a low feldspar concentration (2–4%), due to the greater silica percentage. This result indicates that the sand is suitable for the glass-producing industry. Additionally, it has been found that the sands at the Hatiya beaches, where magnetite minerals are present, contain a sizeable amount of iron oxide (Fe_2O_3) (4.71 percent). According to the literature, beach sands may represent a significant global source of industrial minerals, including quartz (SiO_2), rutile (TiO_2), ilmenite ($FeTiO_3$), and zircon ($ZrSiO_4$), among others. It is noteworthy that the heavy mineral sands (HMS) on such deposits contain important metallic minerals, such as magnetite, zircon, rutile, ilmenite, garnet, and monazite in concentrations ranging from 13 to 70 percent [33]. The typical prices of the valuable heavy minerals determined in the sand deposits of the Hatiya beaches are presented in Table 5.

Table 5. Typical prices of the valuable heavy minerals found in the sand of the Hatiya beaches in U.S. dollars.

The Estimated Percentage of Total Heavy Minerals	Name of Mineral	% of VHM	Price USD/t	Comment
13.93	Garnet	3.17	75–210	It may be a co-product.
	Ilmenite	3.24	110	It may be a co-product.
	Magnetite	2.21	84	It may be a co-product.
	Rutile	2.514	840	It may be a co-product.
	Zircon	2.792	1050	It may be the main product.
	Micas (Light mineral)	40.30	109	It may be the main product.

Source: Mineral commodity summaries of 2016 of the U.S. Geological Survey (https://pubs.er.usgs.gov/publication/70170140, accessed on 7 May 2022).

The data shown in Table 5 indicates a great economic value of the mineral sand of Hatiya Island, therefore, this sand has a high demand from industry. Albeit, based on the introduction of the suitable physical identification and mining techniques, and the detection of the cut-off grade price, this beach may offer a great commercial value. Located on the south-eastern coastline, Hatiya Island contains several beaches (e.g., Nijhum Dwip, Domar Char, Nimtoli and Qazir Bazar), all show a record of having potentially valuable sands, together with heavy metal (HM) deposits. These HMs are chemically stable, resistant to attrition, and can stand against digenetic alterations. They can also be beneficiated in obtaining industrial-grade titanium where certain conditions are to be followed [34]. A previous study carried out by Akon [3,5], reported the presence of commercial-grade TiO_2 (90%) in rutile and ZrO_2 (65%) in zircon. Ilmenite has reportedly been found to contain a high level of iron, chromium, and manganese while having a low concentration of TiO_2 (43 percent), necessitating the beneficiation and the upgradation to make it a commercial product. Because of the wide range of sectors that utilize these HMs after the physical and chemical processing, their exploitation and sale can significantly boost up the national economy. These high-grade coastal sand deposits may greatly enhance Bangladesh's mineral sand development industry. However, considering the greater population density, sensitive environmental location and the high levels of radioactivity in the mineral deposits, many development opportunities become narrow, making exploitation potentially problematic. The mineral resource assessment of heavy mineral (HM) deposits reveals the significance of certain studies for the practical applications of HMs, including the quantification of the HM grade, identification of the mineralogical assemblage, and assessment of the quality of the contained mineral species. Garnet, rutile, zircon, monazite, limonite, and magnetite are examples of heavy mineral sands (HMSs) that typically have high specific gravities

(S.G. > 2.9), and are chemically stable [34]. A non-renewable resource (minerals) can be separated by applying several mining techniques [35]. Heavy minerals can play a key role in the economy of any country by ensuring its proper utilization of industrial and geological motives [36,37]. On the shoreline beaches in Bangladesh, a huge amount of (23% by weight) heavy mineral and low-grade (1–2%) heavy mineral deposits have been reported [38–42]. Many countries, such as India, Australia, Greece, the USA, UK are separating heavy minerals from their beach materials.

Table 5 explicitly shows the price per kilogram of the determined metals/elements in the studied sand samples. In Figure 7, we illustrate the most usable and commercially viable techniques for separating heavy minerals from the sand of the studied areas.

In the river deposits of Bangladesh, an enhanced sand recovery of 65–70% has been reported [43]. River sands in Bangladesh typically contain other valuable heavy minerals in substantial amounts, ranging from 4.5 to 17% by weight, while we found a substantial amount of valuable heavy minerals in the coastal sands, ranging from 11.53 to 16.12%. Individual heavy mineral separation from river sands has previously been found to be successful [44,45]. Glass for Europe (2020) states that silicon oxides 72.6%, sodium oxides 13.6%, calcium oxides 8.6%, and magnesium oxides 4.1%, make up about 98% of the glass in standard float glass compositions. The majority of the upgraded silica sand, or around 98% of it, was also obtained, using more than 150 mesh (i.e., approximately 90 µm size), which is also within the range of a few glass-producing sand grades [46]. Typically, 100–600 µm grains of sand are utilized in industrial-grade glass production while we found 125–180 µm grains 63.6 to 71.5 (listed in Table 1). The vast majority of glass made in the EU is soda-lime silicate glass, which is made with silica (typically at an amount of 70–75% SiO_2 in a raw material batch), sodium oxide (12–16% Na_2O), and calcium oxide (10–15%), as well as small admixtures of other chemical ingredients, to give the glass particular characteristics [47–52]. These heavy minerals may be significant by-products during the manufacturing of glass in the industry. These types of glass are widely employed in the production of both container and float glass [53,54]. Compared to other deposits (i.e., based on the reported data of the silica content in river sand and beach deposits in Bangladesh), Hatiya beaches sand has a higher silica content. More than 90% of the in-situ silica is present in the sand deposits in Bangladesh, which are used by local enterprises. The need for the physical separation and upgrading (Figure 7) of the silica sand is needed for these deposits. The white, silica, and feldspar-rich portion of the river bar sand was physically separated by the magnetic separator from the darker, magnetically-active portions. Electric separators were used to separate white-colored magnetic minerals, in order to produce fractions rich in silica for the non-conductor parts [43]. As a result, the silica-rich sand from Hatiya is a valuable raw material for the glass industry.

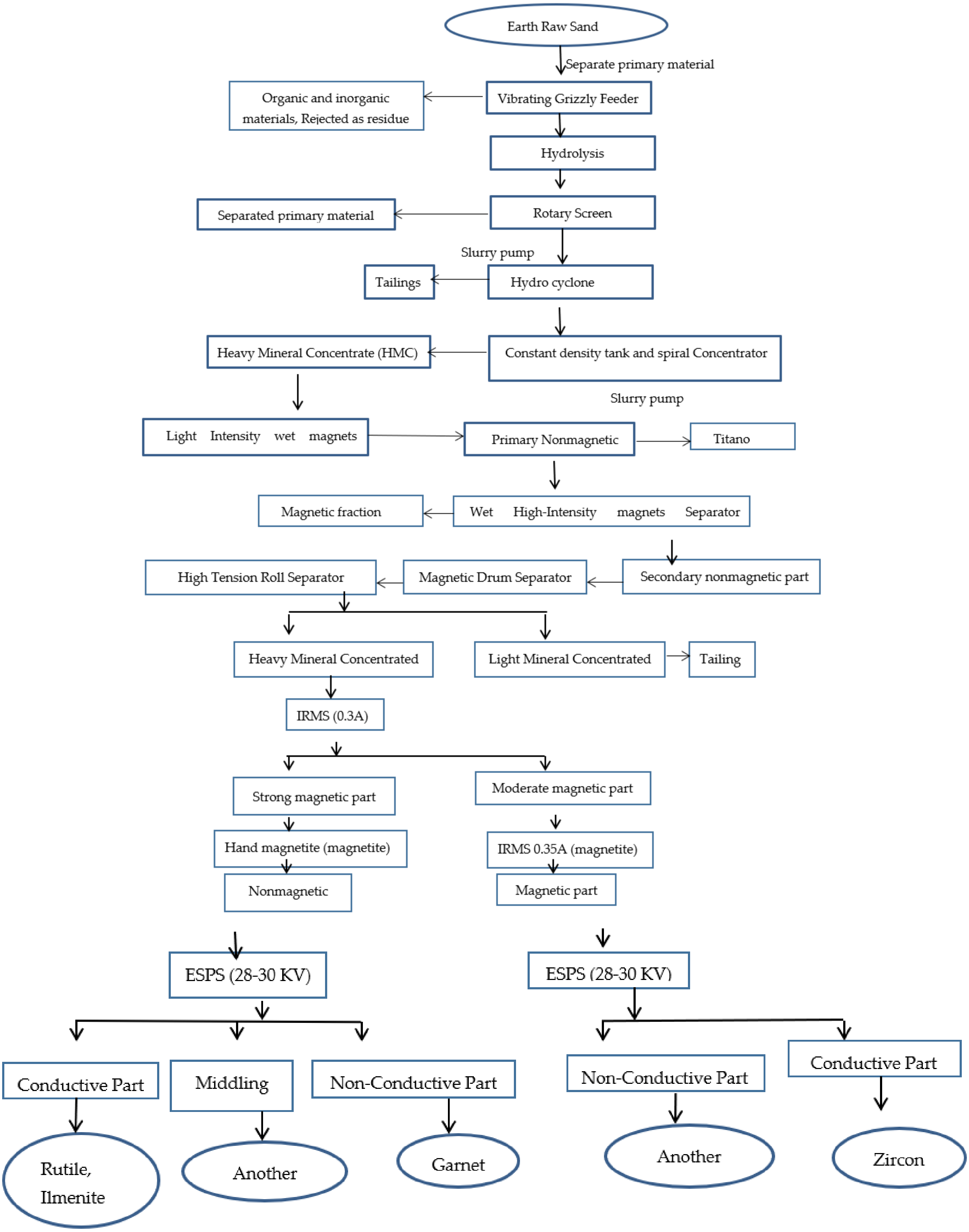

Figure 7. Flow chart of a pilot plant (wet and dry section) for the mineral separation.

4. Conclusions

The present study determines various mineralogical contents in the sands of Hatiya Island, which is located at the mouth of the Meghna River estuary along the Bay of Bengal's coastline. Several state-of-the-art-techniques were used to determine the mineralogical and metal contents; these are light minerals, such as micas (40.30%), oxides, such as SiO_2 (73.58%), Al_2O_3 (12.13%), TiO_2 (0.56%), MgO (1.31%), Fe_2O_3 (4.71%), K_2O (3.1%), Na_2O (1.92%), CaO (3.16%), as well as several valuable heavy minerals, such as ilmenite (14.77%), garnet (11.02%), rutile (14.94%), magnetite (15.26%) and zircon (13.63%), and some other heavy metals (Rb, Th, Ba, V, Cr, Cs, Ni and Co). The typical prices of the determined minerals are reported as garnet (USD 75–USD 210/mt), ilmenite (USD 110/mt), magnetite (USD 84/mt), rutile (USD 840/mt), zircon (USD 1050/mt), and micas (USD 109/mt), while the prices of oxides contents are K_2O (USD 350–400/mt), CaO (USD 350–450/mt), Al_2O_3 (USD 1000–USD 1300/mt), TiO_2 (USD 4000–4500/mt) and Fe_2O_3 (USD 650–1500/mt). Moreover, the determined heavy metals (Rb, Th, Ba, V, Cr, Cs, Ni and Co) also possess a great economic value as well as some other important aspects [55]. Particularly, the sands of the Hatiya beaches are rich in magnetite, rutile, and Ilmenite; these are the sources of Fe and Ti, respectively, and possess a good economic value, as well as great demand in the international market. This work reveals that the sandy beaches of Hatiya Island can be an asset for Bangladesh, due to its mineral sand deposit with a large concentration of valuable heavy minerals. It also suggests that Hatiya Island's sand deposits should be mined responsibly and used effectively to enhance the nation's economy. This study has also demonstrated the feasible extraction process of various minerals from the sand samples.

It should be noted that the development of mining and mineral separation plants on this island may help to reduce the unemployment problem in Bangladesh. However, a pilot plant must be set up before establishing the mining and mineral isolation plant. For this purpose, a feasibility study should be executed to evaluate the total deposit. This study highlights the following points:

- The sand deposits of the Hatiya beaches contain a huge amount of minerals, oxides and heavy metals.
- These mineral sands have a commercial value and are suitable for industrial uses.
- The mineral contents of the studied beach sands can be segregated by applying the suitable mineral processing methods.
- The separated minerals may be utilized in various industries, such as fertilizer, food processing, water purification, paint, pigment, ceramics, glass, leather, shipbuilding, aeronautics, and electronics.
- Heavy and light minerals also comprise precious elements, such as rubidium, cesium, and lithium, which possess a high economic value.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min12111436/s1, Figure S1a–c: (a) XRD pattern for the magnetic component of Rohomat Bazar's sand. (b) XRD pattern for the magnetic component of Kazir Bazar's sand. (c) XRD Pattern for the magnetic component of Nijum Dwip's sand.

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