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Development of Process Flow Sheet for Recovering Strategic Mineral Monazite from a Lean-Grade Bramhagiri Coastal Placer Deposit, Odisha, India

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Abstract: The present investigation deals with the development of a process flow sheet for recovering strategic mineral monazite concentrate from a lean-grade offshore placer deposit of the Bramhagiri coast along the southeast coast of Odisha, India.In the present study, both dry and wet processes are investigated to improve the recovery and purity of monazite. The results of the pre-concentration studies reveal that by using multi-stage spiral concentrators, the Total Heavy Minerals [THM] have been upgraded to 97.8% with a monazite content of 0.33% from a feed sample containing 4.72% total heavy minerals and 0.01% monazite content. The beneficiation studies revealed that the feed was initially subjected to a high-tension separator, and the non-conducting fraction of the high-tension roll was further subjected to magnetic separation. The magnetic product was again subjected to a flotation process followed by cleaning of the flotation product using a magnetic separator. This magnetic product contains 98.89% monazite with 84% recovery and 0.28% yield from a spiral product containing 0.33% monazite and qualifies for extracting rare earths. It is worth recovering monazite mineral from even lean-grade deposits, as it is a source of uranium, thorium, and rare earth elements and is very high in demand for humankind due to technological advancements. In view of this, monazite recovery is not to be considered for the economic profitability of the process but for strategic requirements.

Keywords: monazite; rare earths; flow sheet development; flotation; place deposits

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1. Introduction

Monazite is a vital phosphate mineral of thorium and rare earths [(Ce, La, Nd, Th, Y) PO_4]. It is radioactive due to the presence of uranium and thorium. Significant quantities of monazite are available in South Africa, Madagascar, India, Malaysia, Vietnam, and Brazil. The global monazite market size was at USD 53.38 million in 2021 and is poised to grow from USD 54.61 million in 2022 to USD 65.5 million by 2030, growing at a CAGR of 2.3% in the forecast period 2023–2030 [1]. Due to its strategic importance, the increasing demand for rare earths in the energy, electronics, aerospace, and automobile industries has resulted in various approaches to recovering monazite. It is one of the primary resources for obtaining strategic and critical elements needed for multiple industrial applications. The clean energy drive has increased the demand for neodymium-iron-boron (NdFeB) magnets sourced from monazite mineral.

Geologically, placer monazite is classified under secondary deposits. These deposits are formed and distributed by the combined action of rivers, ocean currents, and strong coastal winds. It occurs with other associated industrial placer heavy minerals such as ilmenite, garnet, rutile, zircon, and sillimanite at very low concentrations and is recovered as a by-product. The beneficiation processes for the recovery of total heavy minerals are specific, and dedicated flow sheets are adopted due to variations in mineral compositions. Processes for monazite beneficiation depend upon the nature and association of valuable strategic and critical industrial and gangue minerals present [2–5]. The common extraction processes adopted for recovering monazite include multi-stage cleaning using gravity, conductivity, magnetism, and flotation. The literature reveals that many researchers have attempted to recover monazite from placer deposits for characterization studies only. A series of mineral-processing equipment, such as high-tension roller separators, high-intensity magnetic separators followed by low-intensity magnetic separators, gravity tables, etc., are used to recover high-grade monazite. The process of separation of monazite used by all the researchers is almost similar. Kwanho Kim et al. [3] attempted to separate monazite from placer deposit using magnetic separation. In their study, they separated conducting and magnetic mineral ilmenite by using a low-intensity magnetic separator [0.8T]. The non-magnetic mineral concentrate has been subjected to a high-intensity magnetic separator [1.4T]. The magnetic fraction is the monazite mineral concentrate. The non-magnetic fraction is further subjected to a gravity separator followed by a high-intensity magnetic separator to obtain monazite concentrate. The study of monazite chemistry and its distribution along the coast of the Neendakara–Kayamkulam belt, Kerala, India, has also been carried out by Anita et al. [6]. The flotation process for fine-grained monazite has also been investigated using special reagents to depress other valuable minerals and gangue minerals to avoid co-flotation along with monazite concentrate [7–22]. The beneficiation process for recovery of placer monazite does not require either a closed circuit or the open circuit comminution process.

The monazite resources in India are shown in Figure 1. Figure 1A shows the monazite occurrence in different states of India [23]. It reveals that monazite occurs all along the coastal belt and is restricted to mostly the southern part of India. It is seen from Figure 1B that Andhra Pradesh State possesses more (3.78 million ton (mt)) monazite resources, followed by Odisha (3.16 mt), Tamilnadu (2.47 mt), Kerala (1.84 mt), West Bengal (1.2 mt), etc. [24].

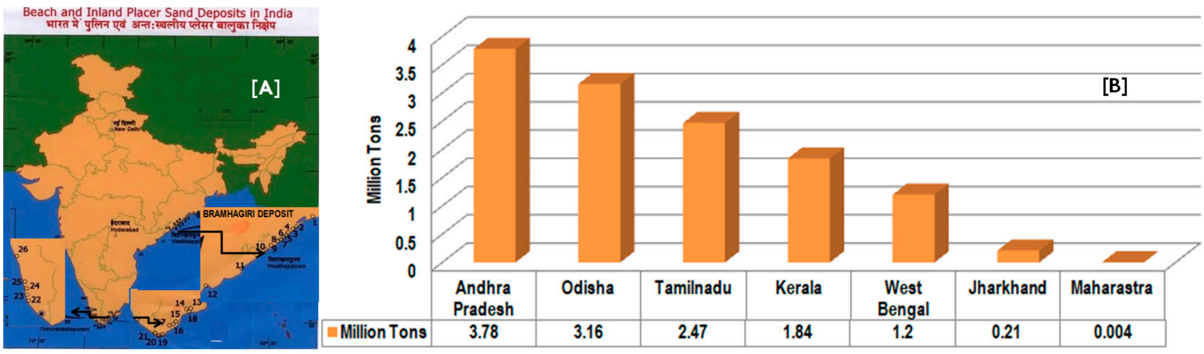
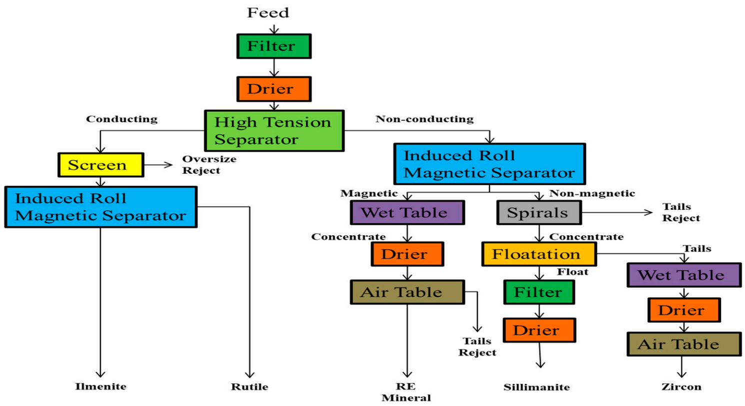


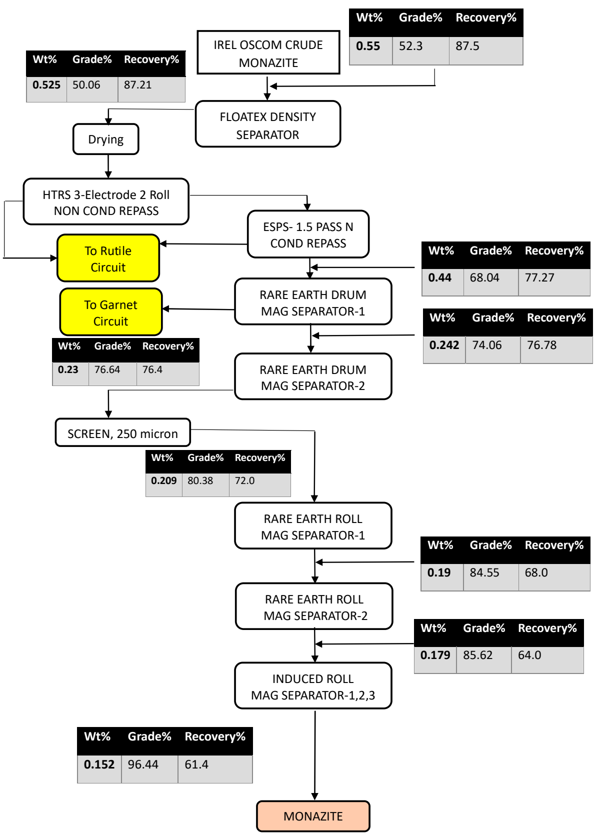
Figure 1. Monazite resources in different states of India [23,24]. (**A**) Monazite occurrences in India. (**B**) Monazite content in million tons in each state of India.Number in Map: 1. Bramhagiri, 2. Chatrapur, 3. Gopalpur, 4. Barua, 5. Bhavanapadu, 6. Kalingapatnam, 7. Srikurmam, 8. Koyyam, 9. Kandalavalasa, 10. Bhimunipatnam, 11. Kakinada, 12. Suryalanka, 13. Sevalapattiteris, 14. Naduvalakurichiteris, 15. KudiralMozhiteris, 16. Viayapuramteris, 17. Navaldi, 18. Navipalyur, 19. Kudankulam, 20. Manavalakurichi, 21. Vayakkalur, 22. Chavara, 23. Kayamkulam, 24. Arattupuzha, 25. Thotapalli, 26. Ponnani, 27. Ratnagiri.

Monazite is considered the principal source of rare earths, although it occurs in trace mineral concentrations in Indian placer deposits. It has unique mineralogy and mineral liberation characteristics. About 12.47 million tons of monazite (containing ~55%–60% total rare earth elements oxide) resource is available in the coastal beach placer sands of Kerala, Tamil Nadu, Odisha, Andhra Pradesh, Maharashtra, and Gujarat, and in the inland placers of Jharkhand, West Bengal, and Tamil Nadu [23].

Hence, an attempt is made in the present investigation to recover high-grade monazite from lean-grade offshore sand of the Bramhagiri coastal deposit. The literature reveals that so far, no researcher or industry has attempted to recover monazite and recommended a flowsheet with mass balance from such a low concentration. Hence, research work on such a new project can benefit the nation by satisfying the demand for rare earths and meeting strategic requirements. Generalized typical flow sheets from Indian Rare Earth (India) Limited for the recovery of individual heavy minerals and recovery of monazite are shown in Figure 2.



(**a**) Flow sheet for recovery of individual heavy minerals



(**b**) Flowsheet for recovery of monazite

Figure 2. Typical flow sheet from IREL (India) Limited for (**a**) recovery of individual heavy minerals and (**b**) recovery of monazite.

2. Materials and Methods

2a. Sample location and collection: A bulk offshore back dune sand sample of about 15 tons was collected in a grid pattern using the auger method along Brahmagiri beach sand placer deposit stretches for 15 km from Sipasurubili via GiralaNala to Village Bhabuniaand Bramhagiri with an average width of 1.91 km in Puri district, Odisha. The details of the sample location are shown in Figure 3. A representative 100 kg sample was drawn out from the bulk 15 tons of samples for size and mineralogical data.
2b. Characteristics of the sample: The collected sample is free-flow sand, and it contains heavy minerals like ilmenite, rutile, garnet, zircon, sillimanite, and monazite. The gangue mineral is mainly quartz. A trace amount of shell is present in the bulk sample. The bulk density of the sample is 1.5 gm/cc, and the average true density is around 2.8 g/cc. The total heavy mineral content in the bulk sample is 4.7%.
2c. Concentration methodology: A typical graphical presentation of the experimental setup for recovering monazite minerals and the experimental procedure for recovering the monazite mineral concentrate is shown in Figure 4. The bulk sample of 15 tons in a batch of 30 kg was subjected to sequential spirals [Compact Turbo (CT) spiral from MT Mineral Technologies as rougher concentrator and High Gradient (HG8) spiral from MT Mineral Technologies as cleaner concentrator] for obtaining total heavy minerals. In all cases, 15% by weight of solid concentration was subjected to a spiral without any wash water. The total heavy minerals were estimated using the standard sink float method, using an organic liquid bromoform of 2.89 specific gravity.

Figure 3. Sample location map [Odisha State, PuriDist, Bramhagiri Mandal, Sipasurubili location].

The total heavy mineral concentrate obtained using the spiral concentrator was subjected to an electrostatic separator (Carrara HTR400 from MT Mineral Technologies) at 100 °C. Ilmenite is a conducting and magnetic mineral, whereas rutile is only a conducting mineral. To separate ilmenite and rutile, a temperature above 60 °C is essential at corona stat. Hence, a 100 °C temperature has been maintained to ensure that the effective temperature of >60 °C is maintained in the process. After several stage cleanings, the conducting fraction is stored separately for titanium-bearing minerals. The non-conducting mineral concentrate was further subjected to a magnetic separator using the Rare Earth Drum Magnetic Separator (REDMS fromCarpco with 250 mm dia. drum). The magnetic fraction was further subjected to another magnetic separator using the Rare Earth Roller Magnetic Separator (RERMSfromSvenko with 6-inch dia. roll). A corona stat plate (Coronastat

HTS from Ore Kinetics) and Induced Roll Magnetic Separators (IRMS from MT Mineral Technologies with 160 dia. roll) were also used to recover monazite.

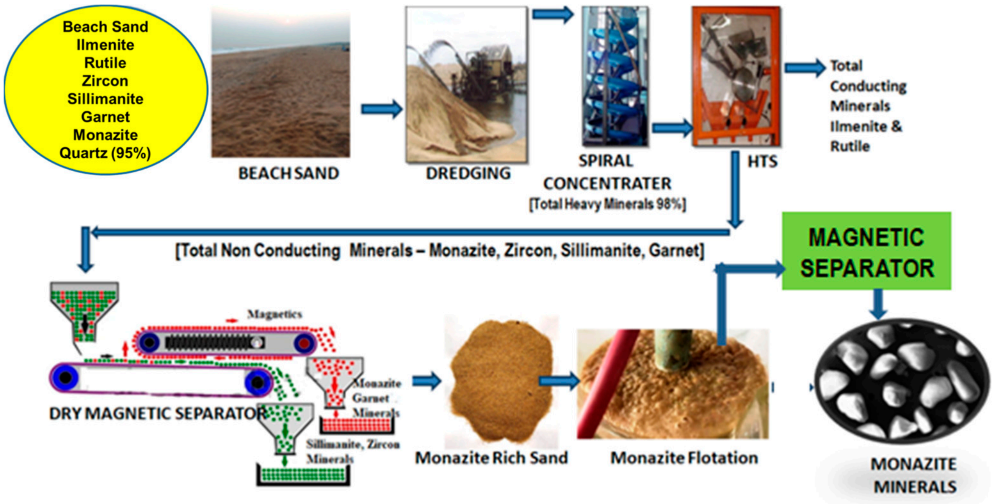


Figure 4. Graphical presentation of the experimental setup for recovering monazite minerals.

In another case, the magnetic fraction was subjected to batch conventional flotation using a Denver laboratory model cell. In the flotation experiment for the recovery of monazite, sodium silicate (1.2 kg/t) was used as a depressant to depress the quartz. Oleic acid (1.2 kg/t) was used as the collector, and pine oil (0.6 kg/t) was used as a frother. The operating conditions were: pH 9, conditioning time–5 min and froth collection time–5 min. The froth, which contains monazite mineral concentrate, was further subjected to a magnetic separator to enrich the monazite mineral concentrate using the RERMS magnetic separator. Mineralogical modal analysis was carried out on the closed-size fractions, concentrates, and tailings obtained from different unit operations by using a binocular microscope. Size analyses were carried out using IS standard sieves.

3. Results and Discussions

3.1. Physical, Chemical, Mineralogical, Structural, and Wettability Characteristics

The physical, chemical, mineralogical, structural, and wettability characteristics of beach sand minerals of the Bramhagiri coast are given in Table 1. The data indicate six major to minor minerals in the sample, such as ilmenite, garnet, sillimanite, zircon, rutile, and monazite. It is very clear from the data that all the minerals have higher specific gravity than 2.6 sp.gr (quartz mineral), and hence, a bulk total heavy mineral concentrate can be achieved using gravity concentration. In gravity concentration, particle shape, crystal system, chemical composition, crystal structure, etc., of all these six minerals do not have much influence as far as gravity concentration is concerned. Ilmenite and rutile minerals have conducting properties and, hence, can be separated from the total heavy minerals by using high-tension roll separators. Among these two minerals, only ilmenite is magnetic, and hence, it can be separated from rutile by using magnetic separators. Sillimanite has the lowest contact angle compared to other minerals, and hence, it has the highest flotability character at pH 9 in the presence of oleic acid as a collector and frother [24]. Moreover, sillimanite adsorbs the oleic acid and promotes the flotation of sillimanite. Hence, it can be separated from zircon and monazite. Monazite is weakly magnetic compared to zircon. Hence, monazite and zircon minerals can be separated using magnetic separation. These are the general physical beneficiation aspects for the recovery of individual heavy minerals. In practice, it takes different routes and needs different processes forthe recovery of high-grade minerals.

Table 1. Physical, chemical, mineralogical, structural, and wettability characteristics of beach sand minerals of Bramhagiri coast.

Mineral	Garnet	Ilmenite	Monazite	Rutile	Sillimanite	Zircon
#Order of abundance(1–6)	2	1	6	4	3	5
#Chemical Composition	$R_3R_2(SiO_4)_3$	$FeTiO_3$	(La,Ce)PO_4	TiO_2	Al_2SiO_5	$ZrSiO_4$
##Crystal system	Isometric, Hexa-octahedral	Trigonal	Monoclinic	Tetragonal	Orthorhombic	Tetragonal
##Particle shape	Rounded to sub-rounded	Elongated, smooth curves sub-rounded	Rounded to sub-rounded	Smooth curves sub-rounded	Flaky, fibrous, angular, needle	Crystalline sub-rounded
#Size range, µm	75–600	75–600	75–150	75–600	75–600	75–600
#Specific Gravity, g/cc	4.11	4.45 to 4.54	4.6–5.4	4.18 to 4.25	3.20 to 3.25	4.60 to 4.70
#Hardness, Mohs scale	6.5 to 7.5	5.5 to 6.0	5–5.5	6.0 to 6.5	6.0 to 7.0	7.5
#Magnetic property Tesla-T	Moderately magnetic	Magnetic	Paramagnetic, 1.5 Tesla	Strongly paramagnetic	Diamagnetic	Diamagnetic
#Electrical Conductivity	Non-Conducting	Conducting	Non-Conducting	Conducting	Non-Conducting	Non-Conducting
#Contact angle degree	24.5°	80°	$60 \pm 5°$	32°	21–30°	>90°
##PZC @pH	7	3.8	5.3	6.3	5.5	5.1
#Floatability Oleic acid@ 9 pH	Not-Floatable	Not-Floatable	Floatable	Not-Floatable	Weakly-Floatable	Not-Floatable
#IR Spectra	Two peaks at around 900 and 1000 cm^{-1}.	Flat in the IR range	Two peaks at 946 and 988 cm^{-1}.	Peak at around 1041 cm^{-1}.	Peak at 1177 cm^{-1}.	Peak in the region 900–1050 cm^{-1}

#: present study; ##: references [24,25].

Physical and chemical characteristics: The size analysis of the bulk sample given in Table 2 indicates that the sample contains a d_{80} passing size of 380 µm. The bulk sample size is coarse and free-flow sand. Distinctly, the sand is more liberated from below 212-micron size fraction.

Table 2. The size analysis of the bulk feed sample.

Size, µm	Weight, %	Cumulative, % Passing
850	-	100
600	27.92	99.47
300	40.22	71.55
212	24.81	31.33
150	3.43	6.52
106	2.68	3.09
90	0.33	0.41
75	0.53	0.08
−75	0.08	-
d_{80} passing size		380 µm

The mineral chemistry of monazite can be discussed using the data given in Table 3. The data indicate that the U_3O_8 content is almost similar for Tamilnadu and Kerala states (0.33 to 0.35%), whereas for Odisha, the U_3O_8 is 0.19% lower than for the Tamilnadu and Kerala states. Other elements are closely varying. The ThO_2 is 8.62 to 9.5%, P_2O_5 is 27.6 to

28.5%, La_2O_3 is 12.42 to 12.7%, CeO_2 is 27.85 to 28.5%, Pr_6O_{11} is 3.16 to 3.81%, Nd_2O_3 is 10.48 to 11.58%, Sm_2O_3 is 1.56 to 1.9%, Eu_2O_3 is 0.02 to 0.08%, Gd_2O_3 is 1.37 to 0.68%, Y_2O_3 is 0.34 to 0.48%, and PbO is 0.2 to 0.27% and vary in Tamilnadu, Kerala, and Odisha states.

Table 3. Monazite analysis of different states of India.

Elements	Tamilnadu	Kerala	Odisha	Elements	Tamilnadu	Kerala	Odisha
			Weight, %				
U_3O_8	0.35	0.33	0.19	Nd_2O_3	10.73	10.48	11.58
ThO_2	8.75	8.62	9.5	Sm_2O_3	1.56	1.61	1.9
P_2O_5	27.9	27.6	28.5	Eu_2O_3	0.02	0.026	0.08
La_2O_3	12.42	12.46	12.7	Gd_2O_3	0.68	0.69	1.37
CeO_2	28.5	27.9	27.85	Y_2O_3	0.34	0.39	0.48
Pr_6O_{11}	3.81	3.58	3.16	PbO	0.2	0.2	0.27

3.2. Mineralogical Modal Analysis

The mineralogical modal analysis of the bulk feed sample and modal analysis of the bulk feed sample in a close size range are shown in Figures 5 and 6. The data seen in Figure 5 reveal that the monazite mineral concentration is 0.01% by weight. The other minerals, such as ilmenite, sillimanite, and garnet, are in more or less range of concentration [1.56%, 1.53%, and 1.39% by weight, respectively]. The presence of rutile 0.05% and zircon 0.03% by weight is recorded. The quartz mineral, which is the major gangue mineral, accounts for 95.28% by weight. The data given in Figure 6 on the mineralogical modal analysis of each close size fraction indicate that the bulk feed sample contains total heavy minerals containing ilmenite, garnet, monazite, rutile, zircon, and sillimanite. It can be clearly seen from Figure 6 that monazite mineral is concentrated only at the size range of –150–+90 µm. Hence, it is very difficult to separate the monazite mineral, which is present in the mass population of other minerals ranging from 600 to below 75 µm size ranges.Monazite is the heaviest mineral (5.4 sp.gr) among all the other heavy minerals; hence, it can be recovered during the gravity concentration along with all other heavy minerals.The processes for separating monazite minerals from other heavy minerals depend on the particle size, specific gravity, conductivity, and magnetic and surface characteristics of minerals.

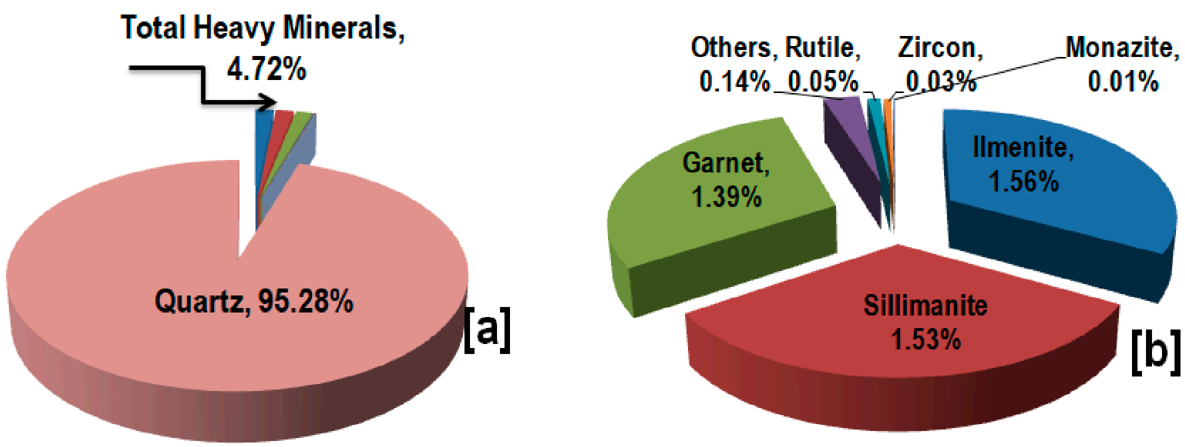
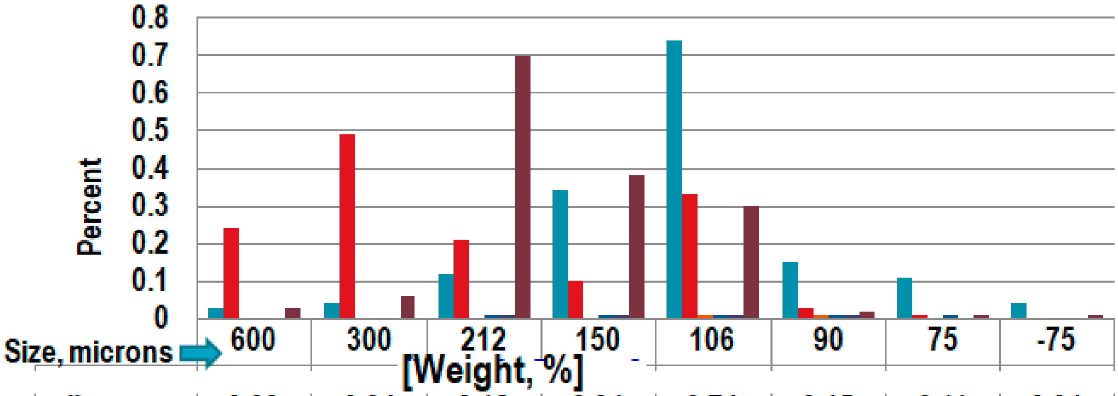


Figure 5. Mineralogical modal analysis of (**a**) bulk feed sample and (**b**) distribution of heavy minerals in the bulk feed.



	600	300	212	150	106	90	75	-75
Ilmenite	0.03	0.04	0.12	0.34	0.74	0.15	0.11	0.04
Garnet	0.24	0.49	0.21	0.1	0.33	0.03	0.01	0
Monazite	0	0	0	0	0.01	0.01	0	0
Rutile	0	0	0.01	0.01	0.01	0.01	0.01	0
Zircon	0	0	0.01	0.01	0.01	0.01	0	0
Sillmanite	0.03	0.06	0.7	0.38	0.3	0.02	0.01	0.01

Figure 6. Mineralogical modal analysis of the bulk feed sample in a close size range.

3.3. Gravity Concentration to Recover Total Heavy Minerals

Gravity concentration is the primary step for recovering total heavy minerals from the bulk raw sand. Spiral concentrators are used to recover total heavy minerals. In this case, a rougher concentration was used in CT spirals. Cleaning and scavenging were performed on HG8 Cleaner spirals to obtain 90–98% of Total Heavy Minerals [THM]. A summary of results obtained from a judicious combination of CT rougher spiral and HG8 Cleaner spiral concentrators using a feed sample weighing 15 tons of material, the batch-wise operation to recover total heavy minerals from raw sand, is shown in Table 4. The data given in Table 4 reveal that overall, 97.8% THM can be achieved with 68.4% recovery and 3.3% yield from a feed sample containing 4.72% THM.

Table 4. Summary of results obtained from a judicious combination of CT rougher spiral and HG8 Cleaner spiral concentrators.

Details	Weight, %	THM, Wt.%	Recovery, %
Concentrate	3.3	97.80	68.4
Tailing	96.7	1.55	31.6
Total	100	4.72	100

A flow sheet drawn with a mass balance from a feed weighing 15 tons of material and the batch-wise operation to recover total heavy minerals from raw sand using a judicious combination of CT rougher spiral and HG8 Cleaner spiral concentrators is shown in Figure 7. It can be clearly seen from Figure 7 that by using one CT rougher spiral and two HG8 Cleaner spirals, a product containing 97.04% THM with 33.3% recovery and 1.62% yield can be achieved. The middlings obtained from these spirals were subjected to further processing using HG8 spirals in two stages [roughing and cleaning], and a product was achieved containing 98.6% THM with 35% recovery and 1.68% yield. It is important to mention here that the physical observations of middlings of the CT rougher spiral (which contain almost feed-grade 4.4% THM possessing critical minerals such as ilmenite, zircon, and monazite at lower size ranges) and the tailings of the HG8 spiral (which also contain the same feed-grade 4.36% THM) have been considered as feedstock containing more of the lighter heavy minerals like sillimanite and the pyribole group of minerals.

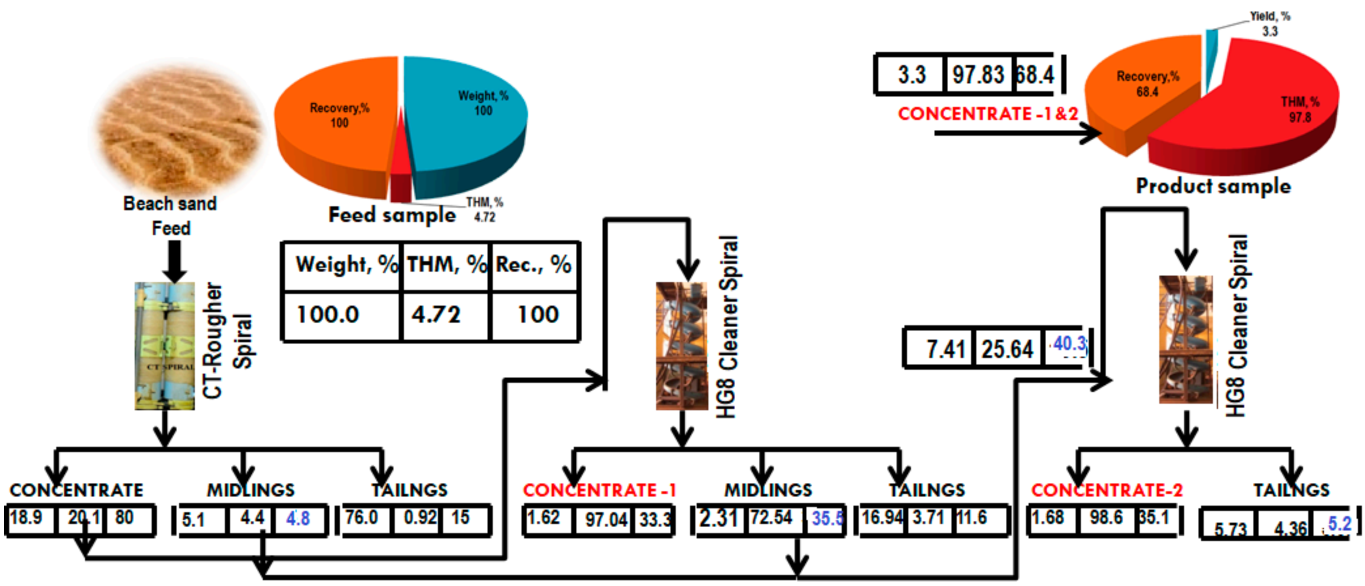


Figure 7. Flow sheet with the mass balance to recover total heavy minerals from raw sand using a judicious combination of CT rougher spiral and HG8 Cleaner spiral concentrators [feed 15 tons material, batch-wise operation].

The overall product obtained from these two concentrates contains 97.8% THMwith 68.4% recovery and 3.3% yield from a feed sample containing 4.72% THM. Typical microphotographs of these mineral concentrate grains are shown in Figure 8. Figure 8 shows that the total heavy minerals obtained using these two spirals contain ilmenite, rutile, garnet, zircon, sillimanite, and monazite. The mineralogical modal analyses of CT spiral feed and the overall product obtained from all spirals and tailings are given in Table 2 and shown in Figure 9. The spiral feed data contain 0.01% monazite, which has been enriched to 0.33%, and values lost in tailings are 0.0003% by weight.

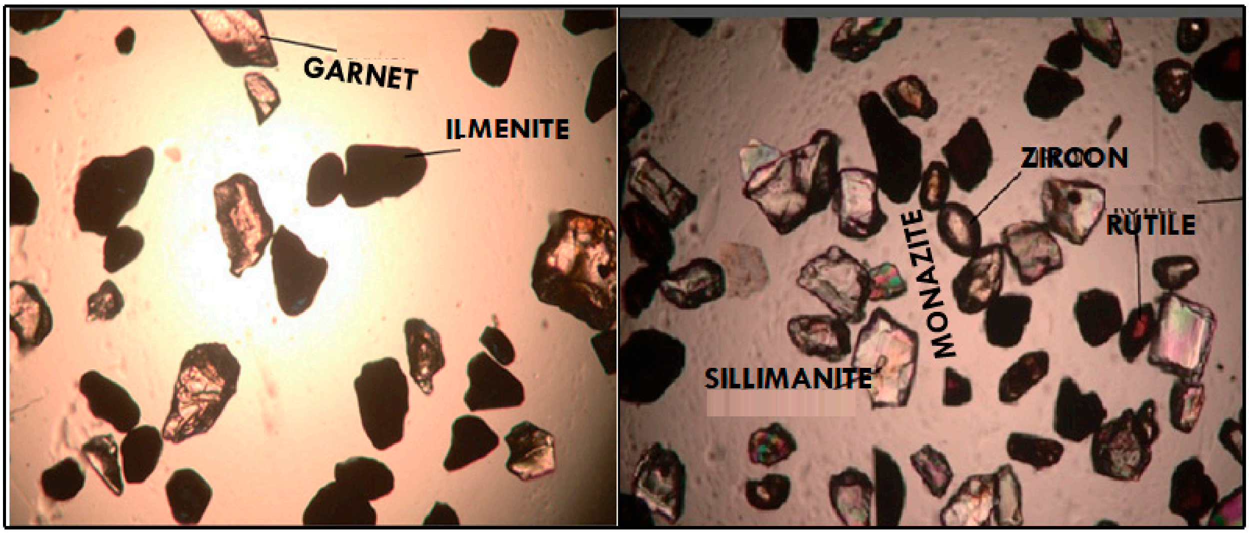


Figure 8. Spiral concentrate (Total Heavy Mineral Grains).

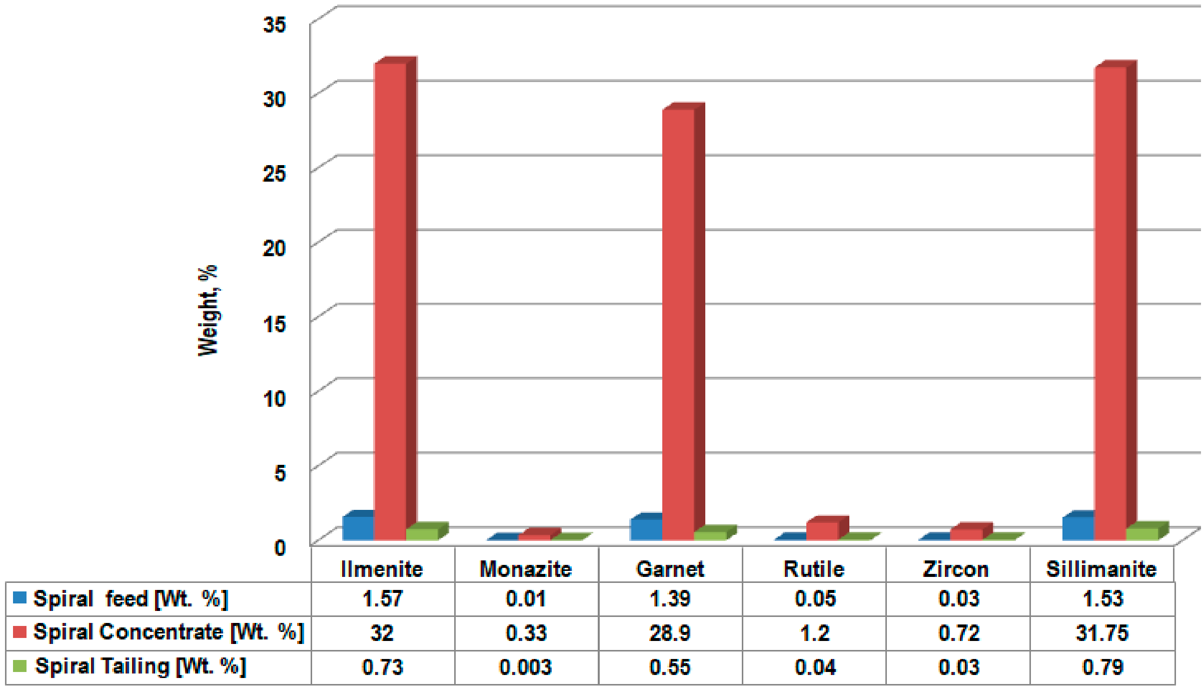


Figure 9. Mineralogical modal analysis data were obtained from feed, CT rougher spiral, and HG8 spiral cleaner concentrators.

3.4. Dry Process forRecovering Monazite Mineral Concentrate

Dry beneficiation studies were carried out using a spiral concentrator feed containing 0.33% monazite by using a high-tension separator using a Corona stat roller separator, rare earth drum, and rare earth roller magnetic separators;a Corona stat plate separator and final cleaning using an induced magnetic separator were used for the recovery of monazite mineral concentrate. The detailed results are presented in Table 5a–h.The results of a high-tension separator using a Corona stat roll on spiral concentrate, which contains 0.33% monazite, have been upgraded to 1.77% monazite in the non-conducting fraction. The conducting fraction is totally titanium-bearing minerals.

Conducting fractions and non-conducting fractions are separately fed to a rare earth drum magnetic separator. There is significant observation to achieve monazite content using a conducting separator. The non-conducting fraction has been upgraded to a non-magnetic fraction, which is 9.92% monazite by weight. The non-magnetic fraction has been further subjected to a rare earth roller magnetic separator, and the results obtained indicate that the magnetic fraction contains 52.3% monazite by weight (Figure 10).

Table 5. Dry beneficiation studies on recovery of monazite mineral concentrate from total heavy mineral concentrate [containing 0.33% monazite] obtained using a gravity separator using spiral concentrator [feed containing 0.01% monazite].

(**a**) Results of high-tension separator using Corona stat roll.

Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Conducting fraction	82.73	0.03	7.5
Non-Conducting fraction	17.27	1.77	92.5
Total	100	0.33	100

Table 5. *Cont.*

(**b**) Results of magnetic separator using rare earth drum magnetic separator [Feed 5a Conducting fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	94.7	0.0009	2.8
Non-Magnetic fraction	5.3	0.55	97.2
Total	100	0.03	100
(**c**) Results of magnetic separator using rare earth drum magnetic separator [Feed 5a Non-Conducting fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	82.2	0.005	0.2
Non-Magnetic fraction	17.8	9.92	99.8
Total	100	1.77	100
(**d**) Results of magnetic separator using rare earth roller magnetic separator [Feed 5c Non-Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	17.9	52.3	94.6
Non-Magnetic fraction	82.1	0.65	5.4
Total	100	9.9	100
(**e**) Results of HTRS separator on rare earth roller magnetic product [feed 5d Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Conducting fraction	20.0	5.7	2.1
Non-Conducting fraction	80.0	64.0	97.9
Total	100	52.3	100
(**f**) Results of REDMS separator on HTRS roller Non-Conducting fraction [feed 5d Non-Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	52.3	54.20	44.5
Non-Magnetic fraction	47.7	74.06	55.5
Total	52.3	64.00	100
(**g**) Results of magnetic separator using rare earth roller magnetic separator [feed 5f Non-Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	95.2	75.88	97.6
Non-Magnetic fraction	4.8	37.60	2.4
Total	100	74.06	100
(**h**) Results of magnetic separator using induced roller magnetic separator [feed 5g Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	95.2	75.88	97.6
Non-Magnetic fraction	4.8	37.60	2.4
Total	100	74.06	100

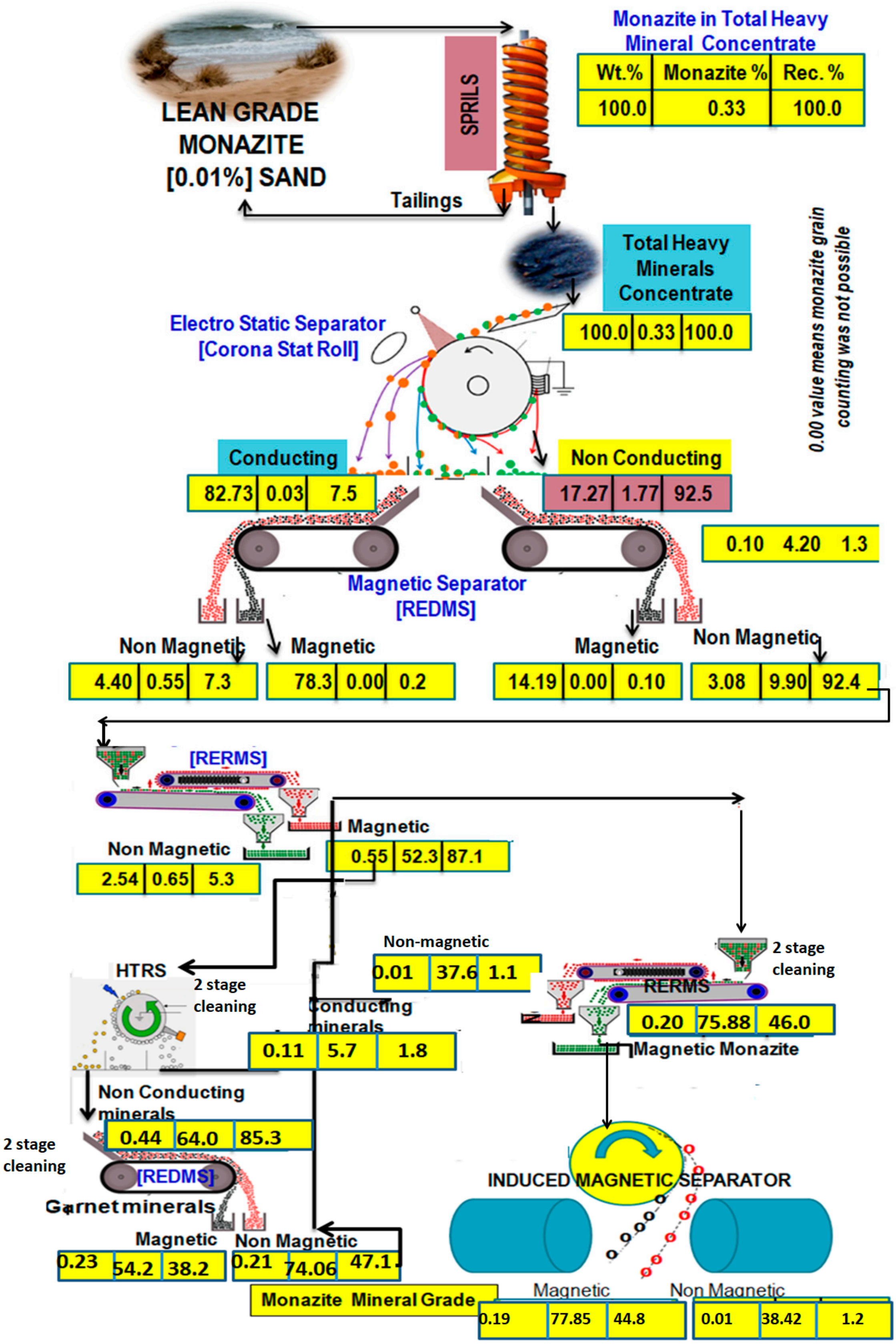


Figure 10. Dry process for recovery of monazite flow sheet with the mass balance from a lean-grade shore placer back dune sand sample.

It is a very important observation to mention here that the monazite grains are finer in size than other valuable minerals. This observation is supported by the present data shown in Figure 6. It is a fact that the finer range of minerals cannot be separated effectively from the other population of heavy minerals. In view of this, an attempt is made to use an electrostatic separator plate type, which is designed for the recovery of fine-conducting minerals. Thus, to purify the monazite from other associated titanium minerals, an attempt is made to use a plate separator. It may be necessary to explain the principle of operation of the electrostatic separator, which is being used for fine particles. In the coastal area, where the mineral separation plants are commissioned to recover all individual heavy minerals, the humidity is very high, which results in the fine particles absorbing the humidity instantly and retaining the moisture along the surface of the mineral and among the inter-space of mass of minerals.

The results of the high-tension roller separator [HTRS] on the rare earth roller magnetic product [Table 5d] are given in Table 5e. A Roll Magnetic Separator [RMS] is a roll-type dry magnetic separator with twin rollers, one with a fixed magnet having a high field intensity and gradient. Ore particles are conveyed to the magnetic field by means of a belt fixed to the separator. The performance of Roll Magnetic Separators is found to be superior as compared to other magnets as they make it possible to separate very fine low-magnetic minerals with a high recovery. The data obtained from the roller magnetic separator indicate that monazite product can be enriched to 64% monazite by weight in the non-conducting fraction. However, the value loss is around 5% monazite in the conducting fraction. The non-conducting fraction has been further processed using a rare earth drum magnetic separator [REDMS; Table 5f], which separates magnetic particles by attracting them due to high magnetic field strength and separates them from the non-magnetic particles. The magnetic fraction has been enriched to 74.06% monazite [Table 5f] from a feed containing 64% monazite. However, the monazite mineral losses are significantly high. A total 54.2% monazite by weight is found to be present in the magnetic fraction. In the present investigation, magnetic particles cannot be firmly held until they are carried out of the magnetic field.

The non-magnetic fraction of REDMS, which contains 74.06% monazite by weight [Table 5f], has been further subjected [Table 5g] to a Rare Earth Roller Magnetic Separator [RERMS]. Magnetic roll separators are effective for the concentration of dry granular materials with particle sizes in the range of 75 microns to millimetres. It is observed from the results [Table 5g] that there is no significant effect on the enrichment of monazite content even though the particle ranges are within the specification of the unit. It has enriched from 74.06 to 75.88% monazite content. The reason may be that as the magnetic roll generates very little static charge on the surface, there is a maximum carryover of coarse particles into the magnetic fraction. Thus, it could not produce a good grade and recovery of valuable monazite minerals. Hence, further experiments were carried out on the induced roller magnetic separator, and the results are given in Table 5h.

The Induced Roll Magnetic Separator (IRMS) is used for the continuous separation of smaller paramagnetic particles, and it is also used for mineral purification in a wide range of applications in the mineral processing industries. The high magnetic field in an Induced Roll Magnetic Separator is created via electromagnetism.In operation, the material is fed from a hopper or vibratory feeder at a controlled rate onto the high-intensity magnetic roll. Paramagnetic material is attracted onto the roll face or is deflected towards the roll. Non-magnetic material is released from the face at a normal trajectory.Captured magnetic material is discharged off the roll face at a point of lower magnetic intensity, aided by a brush. The data obtained from induced rollers reveal that enrichment of monazite from 75.88% to 77.85% monazite mineral concentration has been achieved in a magnetic fraction [Table 5h]. However, the loss of the value of 38.42% monazite is noticed in the non-magnetic fraction. It may be noted here that the magnetic separation of monazite minerals is based on a three-way competition between [1] magnetic forces, [2] gravitational or inertial forces, and [3] inter-particle attractive and repulsive forces. Thus, the combination of these forces determines the outcome of any given magnetic separation and is much affected by the nature of the feed, such as size distribution, magnetic susceptibility, and other physical and chemical characteristics. In view of these factors involved, as expected, further enrichment with reference to monazite concentration could not take place. It can be clearly seen from the data presented in the flowsheet with the mass balance drawn for recovery of total monazite in Figure 10. It is observed from the flowsheet that the end product obtained contains 77.85% monazite with 40% recovery and 0.19% yield from a series of electrostatic separators and magnetic separators, which is a totally dry process. It may be noted here that Kwanho Kim and SoobokJeong [26] studied the separation of monazite from Korean placer deposit using magnetic separation and achieved an end product containing the total rare earth oxide (TREO) (%) of the REE-bearing mineral monazite concentrates which reached 45.0%. Asnani et al. [26] studied the recovery of monazite from red sediments of badlands topography of the southeast coast of India and its characterization for industrial applications and found that 67% recovery was achieved by using a series of dry magnetic separators. Moumar et al. [5] studied monazite recovery using magnetic and gravity separation of medium-grade zircon concentrate from a Senegalese heavy mineral sands deposit and concluded that a monazite grade containing 4.5% with 40% recovery could be possible by using a combination of gravity and magnetic separators. Since magnetic separation alone does not produce the desired grade of monazite, an attempt is made for flotation of the magnetic product.

3.5. Judicious Combination of Dry and Wet Processes to Recover Monazite Concentrate

The feed sample weighing 15 tons contains 0.01% monazite and has been subjected to a spiral, and the product obtained contains 0.33% monazite. A high-tension separator using a corona stat roll has been used on the spiral product to separate titania minerals initially in the conducting fraction, and the non-conducting minerals, which contain 1.77%monazite, have been enriched to 9.92% monazite by using a rare earth drum magnetic separator and, further, have been upgraded to 52.3% monazite by using a rare earth roller magnetic separator. These data have been reported earlier in Table 5d.

Since the end product was obtained using a totally dry process using high-tension separators, magnetic separators are not satisfactory. An alternate method using flotation followed by magnetic separation studies has been further carried out on a feed sample containing 52.3% monazite.

In this second approach, instead of a high-tension separator, the flotation process has been attempted to recover fine-grained monazite. It is a known fact and industrially accepted that flotation is a process for fine-particle separation [27–32]. In view of this, an attempt is made in the present investigation to float monazite by using a flotation process. A few researchers also attempted to recover monazite minerals from other associated minerals by using a flotation process [8–22,32]. The results of the beneficiation studies using the flotation process to enrich the monazite content are presented in Table 6a–g.

Table 6. Beneficiation studies including wet and dry processes on recovery of monazite mineral concentrate from total heavy mineral concentrate [containing 0.33% monazite] obtained using a gravity separator using spiral concentrator [feed containing 0.01% monazite].

(**a**) Results of high-tension separator using corona stat roll			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Conducting fraction	82.73	0.03	7.5
Non-Conducting fraction	17.27	1.77	92.5
Total	100	0.33	100

Table 6. *Cont.*

(b) Results of magnetic separator using rare earth drum magnetic separator [Feed Table 6a Conducting fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	94.7	0.0009	2.8
Non-Magnetic fraction	5.3	0.55	97.2
Total	100	0.03	100

(c) Results of magnetic separator using rare earth drum magnetic separator [Feed Table 6b Non-Conducting fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	82.2	0.005	0.2
Non-Magnetic fraction	17.8	9.92	99.8
Total	100	1.77	100

(d) Results of magnetic separator using rare earth roller magnetic separator [Feed Table 6c Non-Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	17.9	52.3	94.6
Non-Magnetic fraction	82.1	0.65	5.4
Total	100	9.9	100

(e) Results of flotation studies using conventional cell [Feed Table 6d Magnetic fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Concentrate -froth	70.9	72.3	98.1
Tailing	29.1	3.4	1.9
Total	100	52.3	100

(f) Results of 2nd stage flotation studies using cleaner conventional cell [Feed Table 6e Concentrate- froth fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Concentrate -froth	74.4	95.67	98.5
Tailing	25.6	4.20	1.5
Total	100	72.25	100

(g) Results of magnetic separator using rare earth roller magnetic separator [Feed Table 6f Concentrate- froth fraction]			
Details	**Weight, %**	**Monazite, %**	**Recovery, %**
Magnetic fraction	96.6	98.89	99.9
Non-Magnetic fraction	3.4	3.50	0.1
Total	100	95.67	100

(h) Summary of selected tailings for recirculation to recover monazite mineral.				
Reference No	**Product details**	**Weight, %**	**Monazite, %**	**Recovery, %**
6b	Non-Magnetic fraction	4.40	0.55	7.3
6d	Non-Magnetic fraction	2.54	0.65	5.3
6e	Flotation Tailing	0.16	3.40	1.6
6f	Flotation Tailing	0.10	4.20	1.3
6g	Non-Magnetic fraction	0.01	3.50	0.1
Total	Total	7.21	0.70	15.6

The rare earth roller magnetic separator magnetic fraction product containing 52.3% monazite has been subjected to conventional flotation. The froth product has been enriched to 72.3% [monazite Table 6e] from a feed sample containing 52.3% monazite [Table 6d]. This froth concentrate has been further subjected to cleaner flotation cells, and experiments were carried out without any addition of chemicals. The flotation product achieved contains 95.67% monazite [Table 6f]. This may be due to the fact that flotation froth products may contain both weakly magnetic monazite minerals, paramagnetic monazite minerals, etc. Moreover, since this monazite grade is not acceptable by industries, this product has to be cleaned using high-intensityhigh-gradient magnetic separators. In view of this, this product was cleaned by using a rare earth roller magnetic separator and achieved a grade containing 98.89% monazite [Table 6g]. All the non-magnetic fractions and flotation tailings [Table 6b,d–g] containing 0.70% monazite with an overall 7.21% weight were preserved for further recovery of monazite. It is important to discuss the effect of oleic acid addition to water. The nonpolar end of the oleic acid molecule is hydrophobic. As a result, when a drop of an oleic acid solution is placed on the surface of the water, the oleic acid molecules form a thin layer as the alcohol evaporates. In this process, the 'oleic acid adsorbed monazite' can be floated very easily when compared to other minerals associated with monazite, and hence, a flotation process has been attempted on the magnetic fractions.

The flow sheet with the mass balance drawn on the recovery of total monazite is shown in Figure 11. It is observed from the flowsheet that the end product obtained using flotation contains 95.7% monazite with 84% recovery and 0.29% yield.

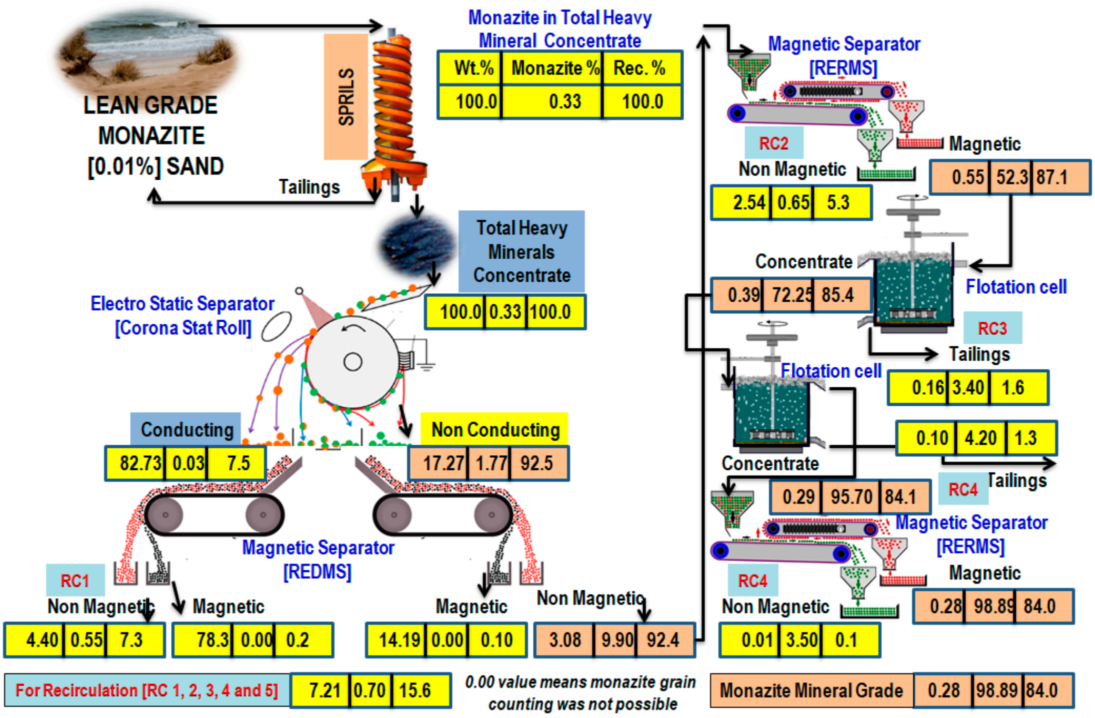


Figure 11. Process flow sheet for the recovery of monazite with mass balance on a lean-grade shore placer sample.

On cleaning this product by using a rare earth roller magnetic separator, the overall magnetic product achieved contained 98.89% monazite with 83.9% recovery and 0.28% yield. Thus, the inclusion of a flotation followed by magnetic separation processes is recommended to industries for the recovery of fine monazite from a lean-grade offshore placer deposit.

It is important to justify the present investigation to recover monazite from a very lean grade (0.01% monazite) by using judicious combinations of gravity, high-tension separators, magnetic separators, flotation, and cleaning using a magnetic separator;the product achieved contains 98.89% monazite. Because of multiple combinations of physical separation units and handling a large tonnage of material, the reproducibility of monazite at any unit operation is found difficult. However, it is worth recovering monazite mineral, which is a source of uranium and thorium as well as rare earth elements and is very high in demand for humankind due to advancements in technologies. In view of this, the recovery of monazite is not to be considered for the economic profitability of the process. However, it is observed in each mineral sand industry, in the particle size of beach sand minerals, even though it is very wide from 600 to 50 µm size range, the effective particle size range available varies for each mineral occurrence, which can clearly be seen from Figure 12. Similarly, the equipment used in the beach sand mineral industry to recover individual minerals is designed in a very wide size range from 600 to 50 µm, but the effective operating of unit operations in the industries are having its own size limitations, which can also be seen in Figure 12. Even though the present investigators are interested in discussing the effective size range relation between the unit operations and mineral size ranges, because the data are under the control of the Department of atomic energy, it is not possible to publish the sensitive data. But at reader can understand the relationship between the mineral particle size and equipment particle size limits in the beach sand industry data presented in Figure 12.

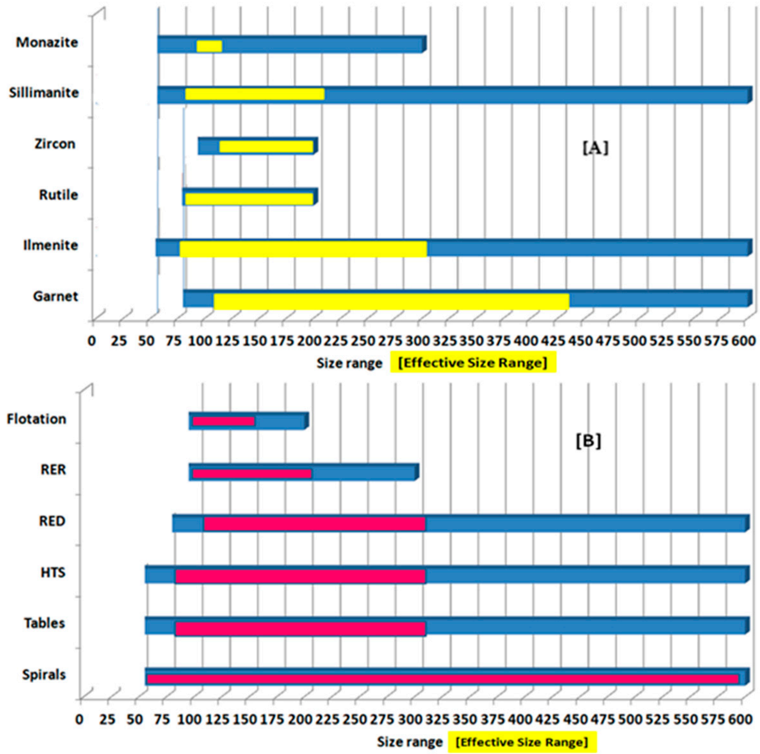


Figure 12. Beach sand particle size range and beach sand mineral processing particle size limit. (**A**) Beach sand general size range and normally available effective size range and (**B**) beach sand mineral processing equipment general particle size range limit for operation and, in practice, the limit of particle size for mineral processing equipment used in the industry.

3.6. Characterization of Monazite

Monazite grain size and shape images are shown in Figure 13a, and the size analysis of monazite is shown in Figure 13b. It can be seen from Figure 13a that the monazite grains are sub-rounded to rounded, which indicates that the monazite grains are travelled via different transport media such as streams, rivers, and wind and are concentrated at the coast. Interestingly, the monazite grains are finer in size, which can be seen from Figure 13b. The data indicate that the d_{80} passing size of monazite grains is 150 microns.

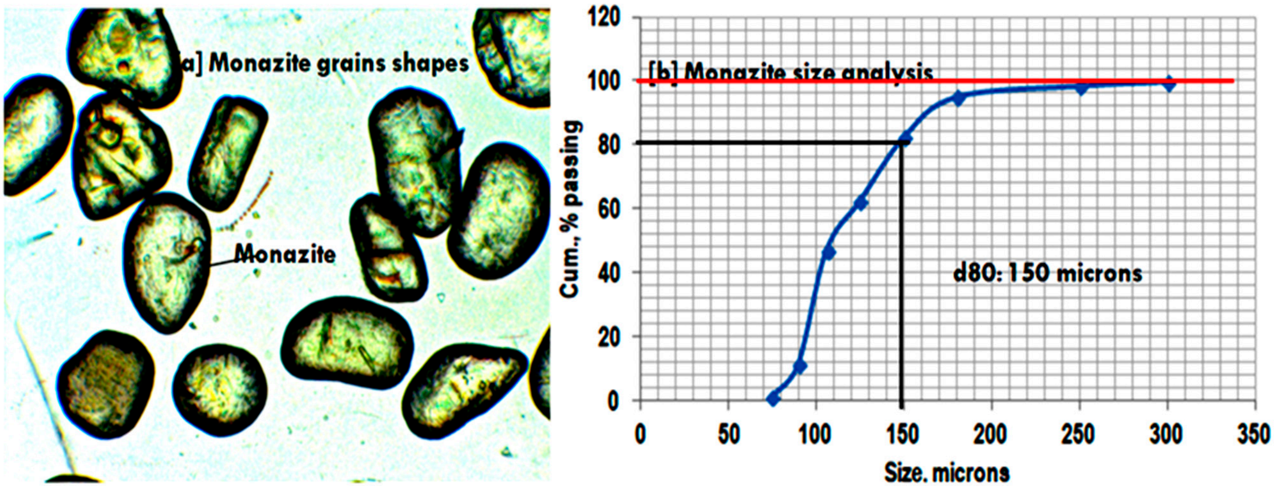


Figure 13. (**a**) Monazite grain shape and (**b**) size analysis of the product.

The monazite sample analysis is given in Table 7. The data given in Table 7 indicate that the monazite contains more cerium oxide, and hence, it can be concluded that the monazite of the Bramhagiri source is cerium monazite. This observation has been published by Deependra Singh et al. in their study on the textural and chemical characteristics of lean-grade placer monazite of the Bramhagiri Coast, Odisha, India [32].

Table 7. Monazite sample analysis, purity: 96.3% by Wt.

Constituents	Percentage	Constituents	Percentage
P_2O_5	27.4	Y_2O_3	0.42
La_2O_3	12.8	Tb_4O_7	0.11
CeO_2	27.5	Dy_2O_3	0.28
Pr_6O_{11}	3.1	ZrO_2	0.4
Nd_2O_3	10.8	Al_2O_3	0.2
Sm_2O_3	2.1	TiO_2	0.3
Eu_2O_3	0.06	SiO_2	0.9
Gd_2O_3	0.71	CaO	1.1
Fe_2O_3	0.28	MgO	0.72

The rare earth element (REE) geochemistry of monazites of the Bramhagiri coastal sand deposit has been studied using the ICP method. The average LREE concentration is 57.07%, which is more than the HREE. As per the Atomic Minerals Division (AMD) reports [32], the Odisha coastal sand contains U_3O_8 0.161% and ThO_2 8.348%. The $\sum$LREE is more than actinides (Th + U), which indicates that the provenance for monazite in the study area is garnet-bearing paragenesis rocks such as charnockites and metapelitic rock (khondalite).

4. Conclusions

The present investigation on developing a process flowsheet for recovering monazite from a lean-grade offshore placer deposit of Bramhagiri, Odisha, India, has given the following conclusions.

- The bulk raw sand weighing 15 tons contains 0.01% monazite. By using judicious CT spirals and HG8 spirals, the end product achieved from the spiral contains 0.33% monazite.

- The first approach for recovery of monazite is by using high-tension separators and magnetic separators—a dry process resulting in a product achieved containing 77.85% monazite with 40% recovery and 0.19% yield.
- In the second approach, by introducing the flotation process on the non-conducting and magnetic fraction, the end product achieved contained 95.7% monazite with 84% recovery and 0.29% yield.
- On cleaning this flotation product by using a rare earth roller magnetic separator, the overall magnetic product achieved contains 98.89% monazite with 83.9% recovery and 0.28% yield from a spiral product containing monazite 0.33%.
- Thus, the inclusion of a flotation process followed by cleaning of the flotation product by using magnetic separation is recommended to the industries for the recovery of high-grade monazite from a lean-grade offshore placer deposit containing 4.72% total heavy minerals in which the monazite content is 0.01%.
- The d_{80} passing size of monazite is 150 microns, and this monazite contains more LREE in which cerium rare earth is significant. Thus, this monazite has significant industrial applications.
- Because of multiple combinations of physical separation units and handling a large tonnage of material, the reproducibility of monazite at any unit operation is found difficult. However, it is worth recovering monazite mineral, which is a source of uranium and thorium as well as rare earth elements and is very high in demand for humankind due to advancements in technologies. In view of this, the recovery of monazite is not to be considered for the economic profitability of the process.

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References

1. SkyQuest. *Global Monazite Market Size, Share, Growth Analysis by Type (Acid Cracking and Alkaline Cracking), by Application (Chemical Industry and Metallurgy) Industry Forecast 2023–2030*; Report ID: SQMIG15A2106; 2023; pp. 1–242. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0892687513002847 (accessed on 13 April 2023).
2. Haxel, G.B.; Hedrick, J.B.; Orris, G.J. Rare Earth Elements—Critical Resources for High Technology, USGS Fact Sheet 087–02. Available online: http://pubs.usgs.gov/fs/2002/fs087-02/ (accessed on 13 April 2023).
3. Kim, K.; Jeong, S. Separation of Monazite from Placer Deposit by Magnetic Separation. *Minerals* **2019**, *9*, 149. [CrossRef]
4. Van Gosen, B.S.; Fey, D.L.; Salah, A.K.; Verplank, P.L.; Hoefen, T.M. *Deposit Model for Heavy-Mineral Sands in Coastal Environments: Scientific Investigations*; Report 2010-5070-L; U.S. Geological Survey: Reston, VA, USA, 2014; p. 51. [CrossRef]
5. Dieye, M.; Thiam, M.; Geneyton, A.; Gueye, M. Monazite Recovery by Magnetic and Gravity Separation of Medium Grade Zircon Concentrate from Senegalese Heavy Mineral Sands Deposit. *J. Miner. Mater. Charact. Eng.* **2021**, *9*, 590–608. [CrossRef]
6. Anitha, J.K.; Joseph, S.; Rejith, R.G.; Sundararajan, M. Monazite chemistry and its distribution along the coast of Neendakara–Kayamkulam belt, Kerala, India. *SN Appl. Sci.* **2020**, *2*, 812. [CrossRef]
7. Dutta, T.; Kim, K.H.; Uchimiya, M.; Kwon, E.E.; Jeon, B.H.; Deep, A.; Yun, S.T. Global demand for rare earth resource sand strategies for green mining. *Environ. Res.* **2016**, *150*, 182–190. [CrossRef] [PubMed]

8. Ren, J.; Song, S.; Lopez-Valdivieso, A.; Lu, S. Selective flotation of bastnaesite from monazite in rare earth concentrates using potassium alum as depressant. *Int. J. Miner. Process.* **2000**, *59*, 237–245. [CrossRef]
9. Pavez, O.; Peres, A.E.C. Effect of sodium metasilicate and sodium sulfide on the floatability of monazite-zircon-rutile with oleate and hydroxamates. *Miner. Eng.* **1993**, *6*, 69–78. [CrossRef]
10. Pavez, O.; Brandao, P.R.G.; Peres, A.E.C. Adsorption of oleate and octyl-hydroxamate onto rare-earths minerals. *Miner. Eng.* **1996**, *9*, 357–366. [CrossRef]
11. Abeidu, A.M. The separation of monazite from zircon by flotation. *J. Less Common Met.* **1972**, *29*, 113–119. [CrossRef]
12. Cheng, T.W.; Holtham, P.N.; Tran, T. Froth flotation of monazite and xenotime. *Miner. Eng.* **1993**, *6*, 341–351. [CrossRef]
13. Geneyton, A.; Filippov, L.O.; Heinig, T.; Buaron, N.; Menad, N.E. Towards the efficient flotation of monazite from silicate-rich tailings with fatty acids collectors using a lanthanum salt as a selective phosphate activator. *Miner. Eng.* **2021**, *160*, 106704. [CrossRef]
14. Salatic, D. Floatability of monazite and zircon related to electrochemical changes on their surfaces. *Miner. Process. Extr. Metall.* **1967**, C231–C273.
15. Dixit, S.G.; Biswas, A.K. pH–dependence of the flotation and adsorption properties of some beach sand minerals. *Trans. AIME* **1969**, *244*, 173–178.
16. Chelgani, S.C.; Rudolph, M.; Leistner, T.; Gutzmer, J.; Peuker, U.A. A review of rare earth mineral floatation: Monazite and xenotime. *Int. J. Min. Sci. Technol.* **2015**, *25*, 877–883. [CrossRef]
17. Espiritu, E.R.L.; Waters, K.E. Flotation studies of monazite and dolomite. *Miner. Eng.* **2018**, *116*, 101–106. [CrossRef]
18. Cheng, T.W. The point of zero charge of monazite and xenotime. *Miner. Eng.* **2000**, *13*, 105–109. [CrossRef]
19. Jianzhong, C.; Yunbing, H.; Liping, C. Flotation separation on rare earth minerals and gangues. *J. Rare Earths* **2007**, *25*, 62–66.
20. NduwaMush, J.; Anderson, C.G. Surface Chemistry and Flotation Behaviour of Monazite, Apatite, Ilmenite, Quartz, Rutile, and Zircon Using Octanohydroxamic Acid Collector. In Proceedings of the Conference: SME Annual Meeting, Phoenix, AZ, USA, 21–24 February 2016. [CrossRef]
21. Abaka-Wood, G.B.; Addai-Mensah, J.; Skinner, W.; Abaka-Wood, G.B.; Addai-Mensah, J.; Skinner, W. Physico-Chemical Characterisation of Monazite, Hematite, and Quartz Minerals for Flotation. In Proceedings of the 4th UMaT Biennial International Mining and Mineral Conference, Tarkwa, Ghana, 3–6 July 2016; pp. 67–73.
22. Boulanger, J.F.; Bazin, C.; Turgeon, K. Effect of Depressants and Temperature on Bastnaesite and Monazite Flotation Separation from a Canadian Rare Earth Element (REE) Ore. *Minerals* **2019**, *9*, 225. [CrossRef]
23. Pandey, U.K.; Chandrasekaran, S. Geochronological studies (207Pb/206Pb radiogenic and Sm-Nd) on monazites and zircons from beach placers of Tamil Nadu and Kerala: Evidence on Pan-African event and their provenances. *Int. J. Earth Sci. Eng.* **2010**, *3*, 323–331. Available online: https://www.researchgate.net/publication/287708457_ (accessed on 13 April 2023).
24. Mushidi, J.; Anderson, C. Surface Chemistry and Flotation Behavior of Monazite, Apatite, Ilmenite, Quartz, Rutile, and Zircon Using Octaonohydroxamic Acid Collector. *J. Sustain. Metall.* **2016**, *3*, 62–72. [CrossRef]
25. Zhang, Z.; Ren, L.; Zhang, Y.; Bao, S. Microflotation of Fine Rutile and Garnet with Different Particle Size Fractions. *Minerals* **2022**, *12*, 1238. [CrossRef]
26. Asnani, C.K.; Rao, R.B.; Srikant, S.S.; Mandre, N.R. Recovery of monazite from red sediments of badlands topography of south east coast of India and its characterization for industrial applications. *Indian J. Geo Mar. Sci.* **2020**, *49*, 1528–1535.
27. Alsabbagh, A.H.; Mustafa, R.M. Wet gravity separation and froth floatation techniques for rare earth elements beneficiation from monazite ore in Jordan. *Heliyon* **2023**, *9*, e19597. [CrossRef] [PubMed]
28. Kusaka, E.; Nakahiro, Y.; Wakamatsu, T. Recovery of Fine Monazite Particles by Liquid-Liquid Extraction. *Mem. Fac. Eng. Kyoto Univ.* **1991**, *53*, 59–71.
29. Morales, M.A.; Jain, T.K.; Labhasetwar, V.; Leslie-Pelecky, D.L. Magnetic studies of iron oxide nano particles coated with oleic acid and Pluronic® block copolymer. *J. Appl. Phys.* **2005**, *97*, 10Q905. [CrossRef]
30. RareEarths, Indian Bureau of Mines. *Indian Minerals Yearbook—2019*, 58th ed.; Part—III: Mineral Reviews; Ministry of Mines, Government of India: New Delhi, India, 2020; pp. 24-1–24-10.
31. Abaka-Wood, G.B.; Addai-Mensah, J.; Skinner, W. Froth flotation of monazite from mixed minerals. In *Chemeca 2016: Chemical Engineering-Regeneration, Recovery and Reinvention*; Engineers Australia: Melbourne, VIC, Australia, 2016.
32. Singh, D.; Basu, S.; Mishra, B.; Prusty, S.; Kundu, T.; Rao, R. Textural and Chemical Characters of Lean Grade Placer Monazite of Bramhagiri Coast, Odisha, India. *Minerals* **2023**, *13*, 742. [CrossRef]

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