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Recovery Potential of Rare Earth Elements (REEs) from the Gem Mining Waste of Sri Lanka: A Case Study for Mine Waste Management

Nimila Dushyantha [1,2,*], I. M. Saman K. Ilankoon [3,*] , N. P. Ratnayake [1], H. M. R. Premasiri [1],
P. G. R. Dharmaratne [1], A. M. K. B. Abeysinghe [1], L. P. S. Rohitha [1], Rohana Chandrajith [4] , A. S. Ratnayake [2] ,
D. M. D. O. K. Dissanayake [1] and N. M. Batapola [1]

[1] Department of Earth Resources Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka
[2] Department of Applied Earth Sciences, Faculty of Applied Sciences, Uva Wellassa University, Passaara Road, Badulla 90000, Sri Lanka
[3] Discipline of Chemical Engineering, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway, Subang Jaya 47500, Malaysia
[4] Department of Geology, Faculty of Science, University of Peradeniya, Peradeniya 20400, Sri Lanka
[*] Correspondence: nimila.dush@gmail.com (N.D.); saman.ilankoon@monash.edu (I.M.S.K.I.)

Abstract: Sri Lanka is one of the wealthiest countries in terms of gems. Therefore, gem mining is extensively carried out in many areas of Sri Lanka, including districts such as Ratnapura, Monaragala, Matale, and Kalutara. During the mining process, only valuable gemstones are collected, and the remaining gravel fraction with many heavy minerals is discarded. Therefore, the gem mining industry produces a large amount of waste that is mainly used only for backfilling. To sustainably manage this waste stream, gem mining waste collected from a gem pit at Wagawatta in the Kalutara district in Sri Lanka was investigated for value recovery, specifically for rare-earth elements (REEs). The gem-bearing alluvial layer contained 0.3% rare-earth oxide (REO) that could easily be upgraded up to 2.8% (LREEs = 94%) with wet sieving and subsequent density separation via a shaking table. Therefore, the concentrates of gem mine tailings with REE-bearing minerals have the potential to be a secondary source for LREEs. The organic-rich clay layer underlying the gem-bearing alluvial layer contained 0.6% REO with 49% HREEs, including Gd, Dy, Er, Yb, and especially Y enrichments. Detailed explorations are thus necessary to assess the REE potential in Sri Lanka's gem mining waste, and value recovery flowsheets should be subsequently developed to economically extract REEs. In addition, the presence of high U concentrations (800 mg/kg) in the concentrated samples could be alarming when considering the health and safety of the people engaged in gem mining. This aspect also requires detailed research studies.

Keywords: gem mining waste; rare-earth elements; Sri Lankan gems; tailing management; uranium

1. Introduction

Since the mining industry produces large volumes of tailings, mine tailings of past and present mining activities have become a potential secondary source for many critical raw materials, including rare earth elements (REEs). Several authors presented mine waste management and value recoveries for different mine waste materials, such as copper [1,2], vanadium [1], gold [3], and REEs [4].

REEs are a set of 17 elements comprising 15 lanthanides, Y, and Sc. They are further categorised into two subgroups, namely, light rare earth elements (LREEs) (from La to Eu) and heavy rare earth elements (HREEs) (from Gd to Lu, including Y). Despite the crustal abundance, these elements are typically not found in nature in high concentrations, and similar chemical properties complicate the separation processes [5]. Therefore, the mining and processing of REEs are complex and expensive [6]. These elements have

become indispensable ingredients in the global industrial revolution due to their unique properties such as high thermal stability, strong magnetism, and high electric conductivity. As a result, they are used in various applications in high-tech, green energy, military, and aerospace industries [5,7]. Therefore, the demand for REEs is continuously increasing, especially considering the developments of electric vehicles and wind turbines. However, the Chinese rare earth industry mainly fulfils the current global rare earth consumption, including value-added products such as rare earth magnets [5]. These factors have attracted significant attention to the exploration and extraction of REEs from new and secondary sources [8] to diversify global rare earth supply chains [5].

The enrichments of REEs were reported in uranium, iron-ore, and titanium mine tailings in Australia, Kazakhstan, and Sweden [9,10], and the authors in [11] investigated the economic viability of extracting REEs from iron-ore mine tailings in the Kiruna mine. In this context, the authors in [12,13] reported that gem-bearing sediments are enriched in rare earth-bearing minerals. However, in Sri Lanka, it has not been attempted to utilise gem mining waste to produce REE concentrates through physical separation techniques. This article thus addresses that research gap, considering the significance of the gem mining industry to the gross domestic product (GDP) in Sri Lanka. It is of paramount importance to design economic mineral processing techniques for waste materials such as gem mining waste in Sri Lanka while considering local socio-techno-economic factors.

Since 250 BCE, Sri Lanka has been famous for its wide variety of gems, gem industry, and international gem trading. Some gemstones have adorned crowns and thrones in the royal coronations and religious functions of ancient rulers [14]. The export value of precious and semiprecious stones was USD 145 million and 141 million in 2017 and 2018, respectively. This is equivalent to 1.3% and 1.2% of the total exports in 2017 and 2018, respectively [15]. This implies the requirement for the sustainable management and development of the gem mining industry in Sri Lanka, including the generated mining waste. Mitigating the damage to fragile ecosystems during gem mining is imperative, and artisanal gem mining activities in Madagascar [16] and Myanmar [17] have caused adverse environmental effects.

Secondary gem deposits are primarily found in Sri Lanka as sedimentary rocks and placers. During gem mining, gem-bearing sediments are piled up near the pit head and mechanically washed or manually panned using rattan baskets (i.e., storage vessels produced from rattan palm fibres) to separate the heavy fractions of sediments [14,18]. A fraction of the generated gem mining waste is only used for backfilling. Even though mining activities are regulated by the National Gem and Jewellery Authority, gem mining is a traditional industry in Sri Lanka [14]. Thus, a significant volume of gem mining waste has accumulated in gem pits. In addition, current gem mining activities in gem mining areas (Figure 1) produce additional volumes of gem mining waste. However, the waste volumes have not been estimated. Existing volumes typically result in environmental issues such as land degradation, river-bank and soil erosion, sedimentation, landslides, groundwater pollution and reduced irrigation efficiency. In addition, the gem pits with accumulated water become breeding grounds for mosquitoes; thus, this affects the health and safety of the people living around gem mining areas. These research gaps highlight the requirements of sustainable gem mining activities in Sri Lanka, including gem mining waste management and repurposing strategies. However, these are not explicitly addressed in the gem mining industry in Sri Lanka and other countries, such as Madagascar and Myanmar. This study was thus designed to address the identified research gaps. In this context, gem mining waste could also be a potential source for the economic extraction of REEs. Therefore, this study assesses the REE potential of gem mining waste in Sri Lanka by performing economic value concentration processes. Thus, the physical separation methods of wet sieving and density separation are investigated.
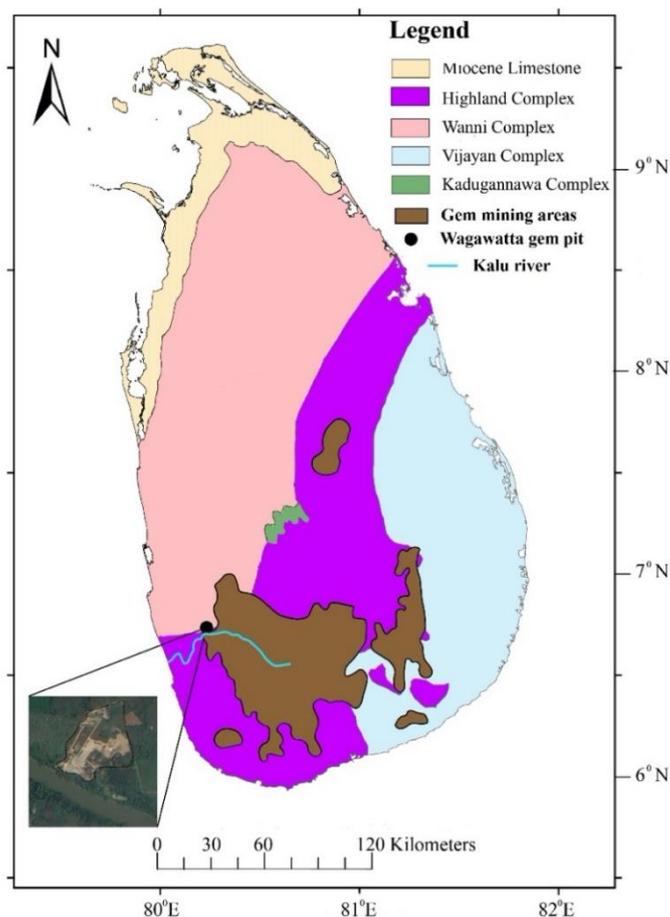
Figure 1. Location of the gem pit in Wagawatta on a simplified geological map of Sri Lanka (source: reproduced from [19] with permission from Precambrian Research) with the main gem mining areas [20].

2. Study Area

Geologically, the Precambrian basement rocks of Sri Lanka are divided into three main lithotectonic divisions: the Highland, Vijayan, and Wanni Complexes [19]. In addition, the island's northern and northwestern coastal belts are underlain by Miocene limestones (Figure 1). Among these complexes, gem deposits are abundantly found in the southern part of the Highland Complex (Figure 1). In addition, this area consists of REE-bearing mineral sources such as granites and pegmatites [14].

Kalu Ganga River has the second largest river basin in Sri Lanka, with a 2766 km^2 drainage area originating from the central hills [21,22]. Since Sri Lanka is a tropical country, a high yield of sediments is evident due to the extreme weathering conditions [23–25]. In this context, after the weathering and decomposition of the gem-bearing source rocks in the catchment area, the Kalu Ganga River transports these sediments and redeposits them as alluvial layers, especially in old river channels and flood plains where the gemstones are found [14]. A gem pit in Wagawatta in the Kalutara district was thus selected for this study. The gem layer is deposited in an old river channel with an organic-rich clay layer underneath the alluvial gem-bearing gravel layer (Figure 2).

In Sri Lankan gem mining, the alluvial layer is subjected to wet sieving or/and panning to find gemstones. Miners typically discard the remaining fractions, including gem gravel and fine tailing fractions containing heavy minerals, as waste. In this study, the authors employed such a fine tailing fraction with heavy minerals as the feed of the shaking table (Figure 3). In addition, the organic layer was mined to find the gem-bearing alluvial layers underneath. In this process, the mined organic layer is thus stored on site. Lastly, all the waste materials, including gem gravel, fine tailings with heavy minerals, and the organic

layer, are used for backfilling the gem mining pit [26]. The authors thus focused on all these waste materials in this work.
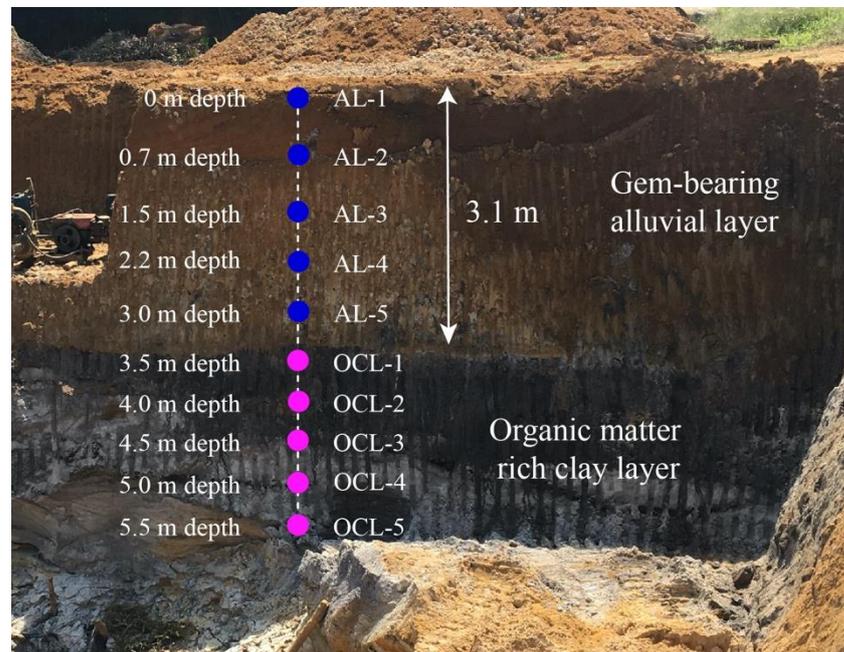
Figure 2. Sample locations with an illustration of the gem-bearing alluvial layer and organic-rich clay layers of the gem pit.
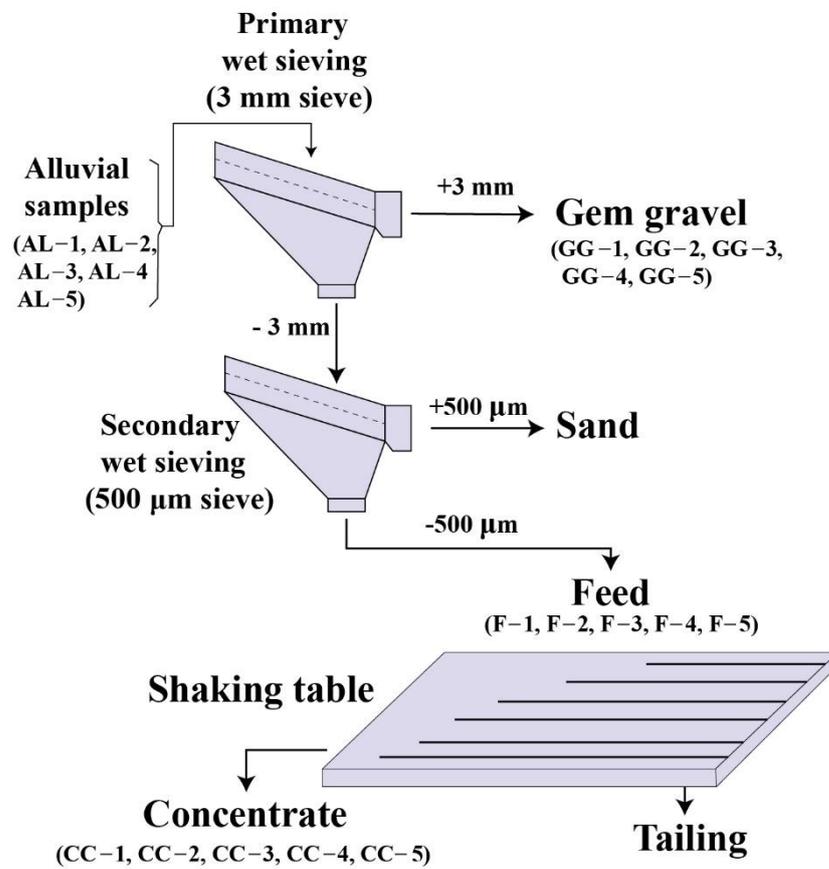
Figure 3. Physical separation flowsheet of gem-bearing alluvial samples.

3. Materials and Methods

3.1. Sample Collection

Five samples from the gem-bearing alluvial layer (AL-1 to AL-5) and five samples from the organic-rich clay layer (OCL-1 to OCL-5) were collected at different heights of the gem pit (Figure 2).

3.2. Physical Separation

Gem-bearing sediment samples in the alluvial layer (AL-1 to AL-5) were subjected to primary wet sieving using a 3 mm sieve. The oversized fraction (>3 mm) was obtained as the gem gravel samples (GG-1 to GG-5), and the undersized fraction (<3 mm) was further subjected to secondary wet sieving using a 500 μm sieve (Figure 3). After the secondary wet sieving, the oversized fraction (>500 μm) was obtained as the sand fraction. The undersized fraction (<500 μm or Samples F-1 to F-5) was further subjected to a density separation process via a shaking table (Figure 3). After the separation, the heavy fraction was considered to be the concentrate (CC-1 to CC-5). The lighter fraction was taken as the tailing (T-1 to T-5) (Figure 3). The density separation was conducted using a Wilfley shaking table employed at a deck angle of 8°, stoke amplitude of 10 mm, and wash water flow rate of 3 L/min for 1 kg of feed (pulp density 25% w/w). Optimal deck angle and stroke amplitude values were employed on the basis of preliminary experiments.

In addition, particle size distributions (PSDs) of the feed (F-1 to F-5), concentrate (CC-1 to CC-5), and tailings (T-1 to T-5) were ascertained using a laser particle size analyser (AimSizer HMK CD-02). The PSDs are shown in Figure 4. The D_{50} values for the feed, concentrate, and tailings were 90.2, 35.9 and 65.5 μm, respectively. In addition, D_{10} values were 20.3, 10.6 and 10.3 μm for the feed, concentrate, and tailings, respectively. Furthermore, the determined D_{90} values of the feed, concentrate, and tailings were 324.1, 152.1 and 327.6 μm, respectively.
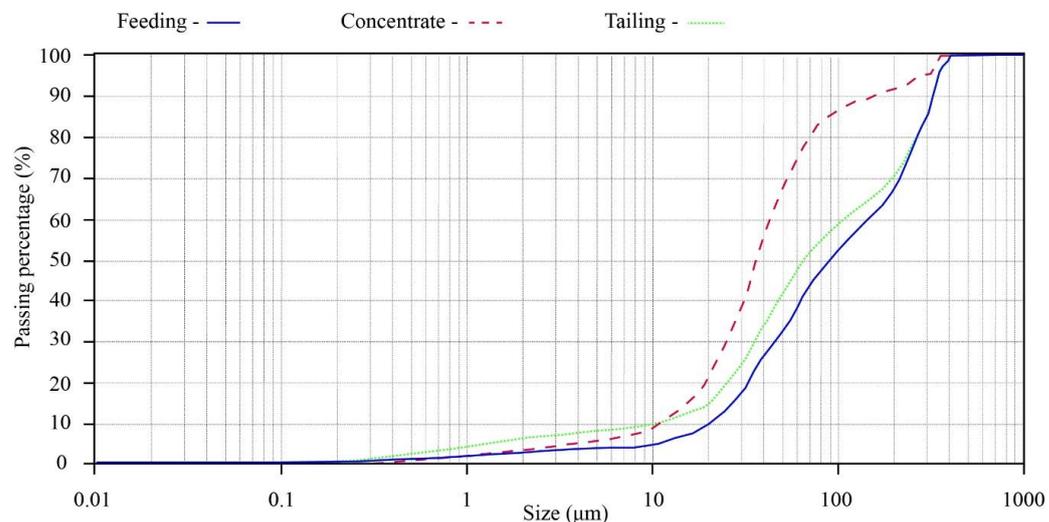
Figure 4. Particle size distributions of the feed (F-1 to F-5), concentrate (CC-1 to CC-5), and tailing (T1-T5) samples resulted from the physical separation process employed in Figure 3.

3.3. Sample Analysis

3.3.1. REE and U Analysis

All the samples were oven-dried at 105 °C, and the dried samples were then powdered using a laboratory Tema mill. The powdered samples were sieved with a 63 μm sieve, and the representative samples were selected via coning and quartering for further analysis.

Subsamples (0.2 g) were digested with an HNO_3 and HCl mixture (1 mL:3 mL) and 1 mL of H_2O_2 using a Mars-6 microwave digester (CEM; Mathews, NC) equipped with EasyPrep Plus high-pressure vessels. The digested samples were diluted with deionized

water and then analysed with an inductively coupled plasma mass spectrometer (ICP-MS) (ICapQ-Thermo Fisher, Bremen, Germany). The instrument was calibrated according to multielemental ICP-MS standards (Sigma-Aldrich, Germany). Quality control in the analysis was maintained using certified international reference samples (San Joaquin NIST SRM 2709a from Sigma-Aldrich, Germany), replicate analysis, and blanks at every tenth sample.

3.3.2. Mineralogical Analysis of Concentrated Samples

Mineralogical compositions of samples were determined with powder X-ray diffraction (XRD) using a BRUKER D8 advance eco X-ray diffractometer with normal operating conditions. Phase analysis was carried out using the International Centre for Diffraction database (ICDD). In addition, scanning electron microscopic (SEM) and energy-dispersive spectrometric (EDS) analyses were carried out using a Carl Zeiss EVO-18 instrument with an EDS element on the SEM.

4. Results and Discussion

4.1. REE Concentrations of Alluvial and Gem Gravel Samples

The average total rare earth element (TREE) concentrations of alluvial (AL) and gem gravel (GG) samples were 2188 and 819 mg/kg, respectively (Table 1). These results reveal that REEs are associated with the finer fraction of the alluvial layer (<3 mm), since the gem gravels contained a relatively low content of REEs. Both alluvial and gem gravel samples showed a higher fraction of LREEs (85% and 80%, respectively) over HREEs (12% and 16%, respectively). The rare earth oxide (REO) grades of alluvial (AL) and gem gravel (GG) samples were 0.3% and 0.1%, respectively (Table 1).

4.2. REE Concentrations of Organic-Rich Clay Samples

The average TREE concentration of the organic-rich clay layer (OCL) was 5348 mg/kg, whereas HREEs such as Gd, Dy, Er, Yb and Y showed higher average concentrations (191, 219, 167, 135 and 1766 mg/kg, respectively) compared to other HREEs. As a result, HREEs were 49%, almost the same as the LREE percentage of 48% (the remaining 3% was Sc) (Table 1). In addition, the REO percentage of this clay layer was 0.6. LREEs and HREEs were thus enriched in the organic-rich clay layer (OCL) compared to the alluvial layer (Figure 5).
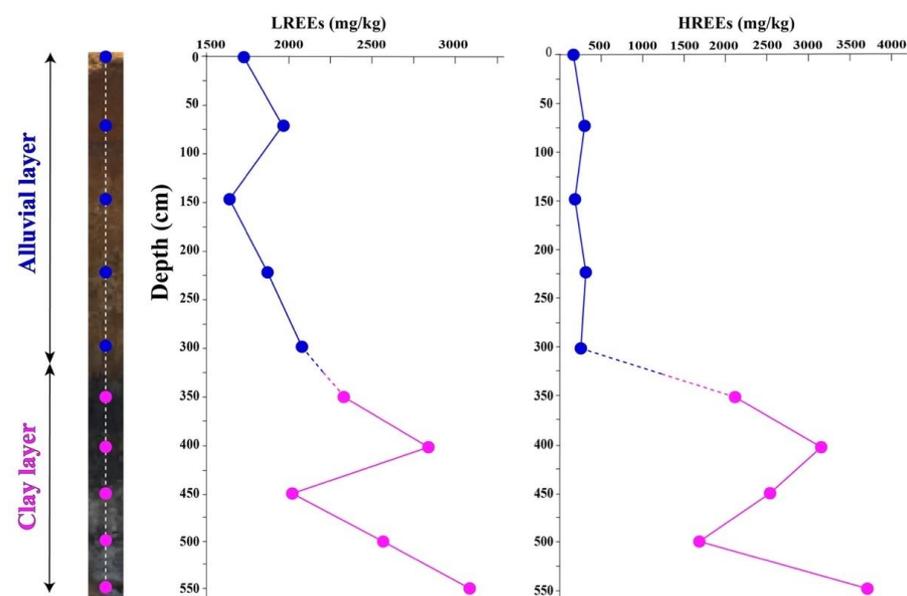
Figure 5. Distribution of LREEs and HREEs in the vertical cross-section, including alluvial (AL) and organic-rich clay (OCL) layers.

Table 1. REE and U concentrations (mg/kg) of alluvial (AL), gem gravel (GG), and organic-rich clay later (OCL) samples (bdl—below the detection limit, AVG—average, SD—standard deviation).

| Sample ID	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Sc	LREE	HREE	TREE	LREE%	HREE%	Sc%	REO%	U
AL-1	413	875	93	308	48	11	46	13	24	12	17	11	15	bdl	98	51	1746	237	2034	86	12	2	-	8.3
AL-2	483	955	121	343	50	12	58	14	27	16	20	12	17	bdl	122	74	1963	285	2322	85	12	3	-	9.1
AL-3	370	833	80	308	59	13	55	15	25	14	18	11	17	bdl	92	34	1662	246	1941	86	13	1	-	8.6
AL-4	440	913	108	343	61	14	67	16	27	17	21	12	19	bdl	117	57	1878	294	2229	84	13	3	-	9.4
AL-5	525	998	134	343	39	10	49	12	26	14	19	12	16	bdl	128	92	2047	275	2414	85	11	4	-	8.8
AL-AVG	446	915	107	329	51	12	55	14	26	14	19	12	17	bdl	111	62	1859	267	2188	85	12	3	0.3	8.8
STD	60	65	21	19	9.1	1.6	8	1.6	1.2	1.7	1.2	0.5	1.4	-	16	22	156	25	197	-	-	-	-	0.4
GG-1	133	268	35	108	23	10	21	10	11	10	8.5	9	8.3	bdl	30	31	576	108	715	81	15	4	-	6.3
GG-2	171	333	47	145	30	11	28	12	12	12	12	11	10	bdl	47	44	736	143	923	80	15	5	-	8.1
GG-3	109	217	35	92	18	11	18	11	11	12	10	11	10	bdl	19	29	481	101	611	79	17	4	-	8.7
GG-4	147	282	47	129	25	12	25	12	12	14	13	13	12	bdl	36	42	641	137	819	78	17	5	-	10.5
GG-5	195	383	47	162	35	10	31	11	12	10	11	9	8	bdl	58	47	831	150	1027	82	14	4	-	5.7
GG-AVG	151	296	42	127	26	11	24	11	12	11	11	11	10	bdl	38	39	653	128	819	80	16	4	0.1	7.9
STD	33	64	6.7	28	6.4	0.7	5.2	0.8	0.4	1.6	1.7	1.7	1.7	-	15	8	136	22	165	-	-	-	-	1.9
OCL-1	553	973	135	505	115	25	172	32	179	46	129	24	107	13	1473	113	2304	2174	4591	50	47	3	-	7.6
OCL-2	658	1205	178	624	149	33	212	57	248	79	207	48	162	18	2105	150	2846	3135	6131	46	51	3	-	8.9
OCL-3	493	850	123	450	93	31	147	30	171	39	86	11	85	15	1043	92	2039	1627	3758	54	43	3	-	8.4
OCL-4	598	1083	166	569	127	39	186	55	239	72	165	36	140	21	1675	129	2581	2588	5298	50	47	3	-	9.7
OCL-5	718	1328	190	679	171	27	238	58	256	85	250	61	183	16	2535	171	3111	3682	6963	42	55	3	-	8.1
OCL-AVG	604	1088	158	565	131	31	191	46	219	64	167	36	135	17	1766	131	2576	2641	5348	48	49	3	0.6	8.5
STD	88	188	29	91	30	6	35	14	40	20	64	20	40	3	575	31	425	803	1258	-	-	-	-	0.8

Economic concentrations of HREEs are abundantly found in ion-adsorption clay (IAC) deposits in South China and Madagascar in economic extractions. The REO percentage of IAC deposits in China varies from 0.05 to 0.2 [27], whereas the HREE concentrations of IAC deposits in Madagascar goes up to 1570 mg/kg [28]. Gd, Dy, Er, Yb, and especially Y in both deposits mainly contribute to the enriched HREE content. In this context, the organic-rich clay layer (OCL) in this gem deposit showed a similar variation, with a high content of Y, and possessed a potential source of HREEs, especially for Y. Therefore, the development of a suitable extraction method is necessary to extract HREEs from the organic-rich clay layer in this geochemical formation.

4.3. REE Concentrations of Concentrated Samples

The average REE concentration and REO grade of the concentrated samples (CC1-CC5) were 24,670 mg/kg and 2.8%, respectively (Table 2). This clearly showed that the wet sieving and subsequent density separation process via a shaking table significantly enriched the REE content in the concentrated samples, which upgraded the REO percentage by almost 10-fold compared to the original alluvial samples. The LREEs percentage in the concentrated samples accounted for about 94% of the TREE contents (Table 2). Therefore, these concentrated samples could be a secondary source for REEs, particularly for LREEs. In addition, the wet sieving and density separation process via a shaking table is a promising physical separation method to upgrade the REO grade of gem mining waste before further physical beneficiations and chemical leaching.

4.4. REE Patterns of Collected Samples

Figure 6 illustrates the chondrite-normalised REE patterns of the studied samples. Significant enrichments of LREEs in the concentrated samples (CC) and HREEs in the organic-rich clay (OCL) samples were evident in these normalised patterns. All samples showed positive Ce anomalies and significantly negative Eu anomalies. Comparing the chondrite-normalised patterns of IAC deposits in China, the organic-rich clay layer shows that HREEs such as Gd, Dy, Er and Yb were enriched in the organic-rich clay layer.
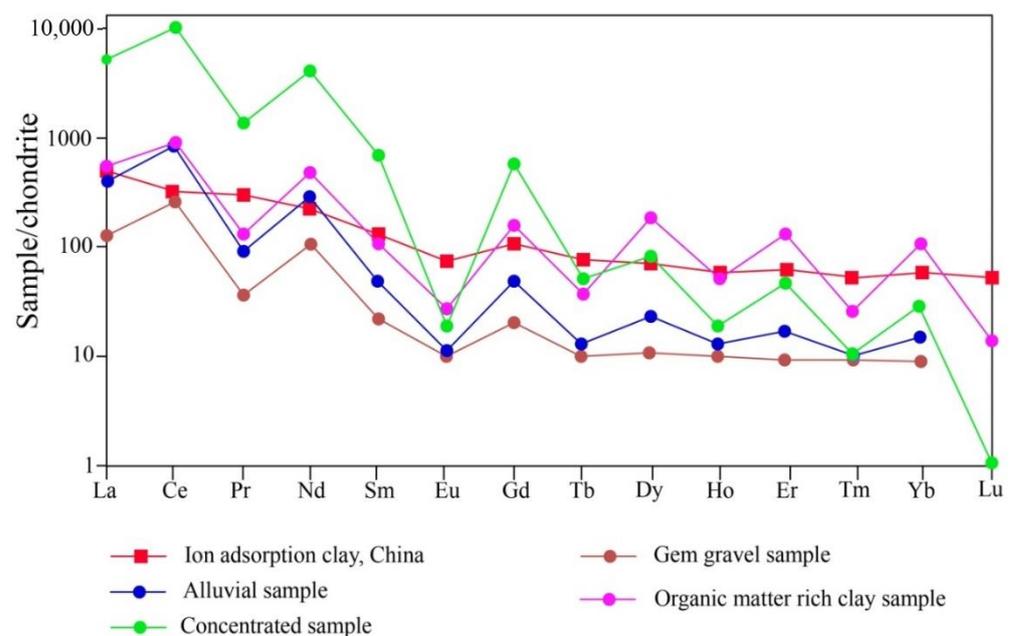
Figure 6. Chondrite-normalised REE patterns of the studied samples. Since Lu concentrations were below the detection limit, Lu values in alluvial and gem gravel samples are not plotted in this figure. Published REE values of IAC deposits in China and chondrite-normalised factors were adapted from [29,30], respectively.

Table 2. REE and U concentrations (mg/kg) of feed (F) and concentrated (CC) samples. (bdl—below the detection limit, AVG—average, SD—standard deviation).

Sample ID	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Sc	LREE	HREE	TREE	LREE%	HREE%	Sc%	REO%	U
F-1	2854	6116	656	2238	392	11	271	27	43	11	25	7	14	bdl	123	66	12,266	521	12,854	95	5	0	-	457
F-2	2671	6012	682	2101	329	10	281	23	45	13	29	9	17	bdl	144	83	11,805	521	12,449	95	5	0		511
F-3	2816	5928	671	2865	389	12	278	21	39	12	27	5	18	bdl	137	74	12,681	561	13,292	95	5	0		472
F-4	2743	6231	599	2003	401	14	269	29	46	25	21	7	15	bdl	116	90	11,991	537	12,609	95	5	0		443
F-5	2903	6193	612	2362	381	11	288	30	44	10	29	9	11	bdl	126	87	12,462	528	13,096	95	5	0		470
F-AVG	2797	6096	644	2314	378	12	277	26	43	14	26	7	15	bdl	129	80	12,241	534	12,860	95	5	0	1.4	471
STD	92	126	37	337	29	2	8	4	3	6	3	2	3	-	11	10	352	17	344	0	0	0	-	25
CC-1	6138	12,455	1435	4953	718	25	635	52	103	23	52	14	34	1.5	293	77	25,722	1206	27,005	95	5	1	-	794
CC-2	5198	10,478	1768	3465	880	17	738	68	77	18	72	8.5	22	0.8	360	110	21,804	1364	23,279	94	3	1	-	806
CC-3	6020	11,868	1235	5513	685	22	615	47	97	24	41	14	43	1.5	234	52	25,342	1116	26,510	96	5	1	-	717
CC-4	5080	9890	1568	4025	848	14	718	62	71	19	62	8.3	32	0.8	302	86	21,424	1274	22,783	94	6	1	-	871
CC-5	5315	11,065	1968	2905	913	20	758	73	84	17	83	8.8	13	0.8	419	135	22,185	1455	23,774	93	5	1	-	814
CC-AVG	5550	11,151	1595	4172	809	19	693	60	86	20	62	11	29	1.1	321	92	23,295	1283	24,670	94	5	1	2.8	800
STD	492	1033	285	1065	101	4	64	11	13	3	16	3	12	0.4	70	32	2064	132	1945	-	2	-	-	-

*4.5. REE Yield, Grade, and Recovery of Separation Experiments*

During the shaking-table tests, the average yield of the concentrate was 37%, whereas tailing accounted for 63% of the yield (Table 3). The TREO grades of feed, concentrate, and tailings were 1.4, 2.8 and 0.6, respectively. The recovery of TREO via the shaking table was 74%. The recoveries of LREO (light rare earth oxide) and HREO (heavy rare earth oxide) via the shaking table with respect to the feed were 74% ($La_2O_3 = 76$, $Ce_2O_3 = 71$, $Pr_2O_3 = 87$, $Nd_2O_3 = 74$, $Sm_2O_3 = 73$ and $Eu_2O_3 = 75$) and 90% ($Gd_2O_3 = 91$, $Tb_2O_3 = 79$, $Dy_2O_3 = 81$, $Ho_2O_3 = 72$, $Er_2O_3 = 87$, $Tm_2O_3 = 65$, $Yb_2O_3 = 79$ and $Y_2O_3 = 95$), respectively. The results reveal that the shaking-table separation could remove major gangue minerals in the feed and enrich REEs in the concentrate. Due to the high recoveries, grade, and enrichment factors of REEs, the concentrate (CC) possessed a high potential of being a secondary source for REEs, particularly for LREEs.

**Table 3.** Results of physical separation through Wilfley shaking table.

Product	Yield %	LERO		HREO		TREO	
		Grade %	Recovery %	Grade %	Recovery %	Grade %	Recovery %
Feed	100	1.33	100	0.06	100	1.4	100
Concentrate	37	2.65	74	0.14	90	2.8	74
Tailing	63	0.54	26	0.01	10	0.6	20

4.6. REE-Bearing Minerals in the Concentrate

REE-bearing minerals such as monazite, zircon, and xenotime were identified in the concentrate (Figure 7). In addition, the SEM/EDX spot analysis indicates the presence of LREEs, Y and phosphorus in the surface sediment samples (Figure 8). The presence of monazite and zircon justified the high concentrations of LREEs. In contrast, xenotime acted as the main HREE-bearing mineral, particularly for Y.
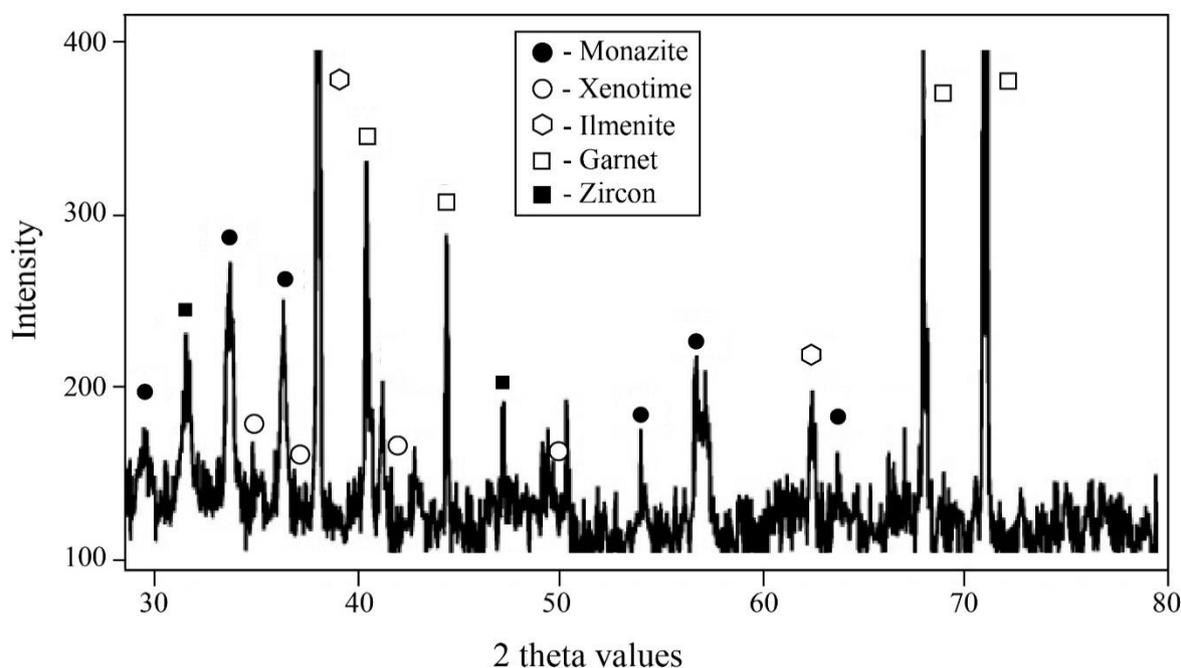
Figure 7. Concentrate's XRD patterns indicating REE-bearing and other heavy minerals.
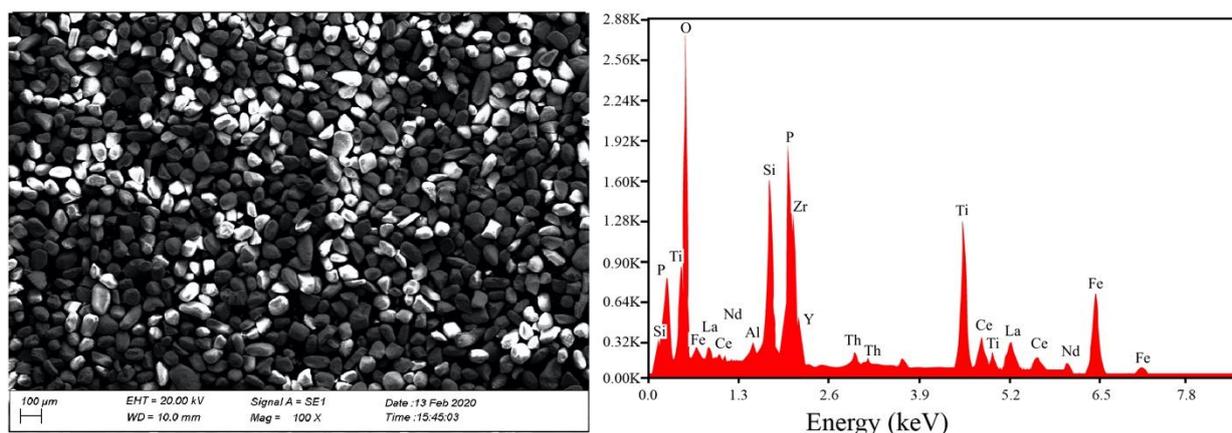
Figure 8. SEM/EDX spot analysis of the concentrate.

In addition, heavy minerals such as ilmenite and garnet were enriched in the concentrate. The organic-rich clay layer showed a lower abundance of REE-bearing minerals. However, the REO was as high as 0.6% compared to the alluvial layer. Therefore, that REE minerals may have been dissolved into the groundwater in the form of REE ions due to the weathering and decomposition of the alluvial layer (Figure 2). Once groundwater penetrates through the alluvial layer, dissolved components can be migrated into the clay layer, and REE ions could be adsorbed onto the surface of the clay minerals. A similar formation could be found in IAC rare earth deposits in China [31]. Despite the low REO content, such geochemical formations render REE extraction easy and economically viable.

4.7. Mine Waste, Value Recovery and Presence of U

Considering recent trends in mine tailing management and critical metals [1,4], the investigation of REE potential in gem mining waste in Sri Lanka is crucial on two fronts, namely, value recovery from mine waste streams, and sustainable and cleaner mine waste management. In addition, significant levels of U were found in the studied samples that need to be addressed, considering the waste management aspects of gem mining in Sri Lanka. U concentrations ranged from 8.8 to 800 mg/kg in alluvial and concentrated samples, respectively (Tables 1 and 2). Since zircon, monazite and xenotime were the REEs' primary carrier minerals, U may also be enriched by these minerals in the concentrated samples. According to the soil quality guidelines (SQGs) recommended by the Canadian Council of Ministers of the Environment (CCME), the permissible U concentration for industrial land use is 300 mg/kg [32]. Therefore, the concentrated samples in this study exceeded the permissible U level.

In some gem mines in Sri Lanka, gem-bearing sediments are subjected to a density separation process using a shaking table to recover any available gold nuggets. The concentrates are thus piled up in gem mining sites without proper safe disposal procedures. Therefore, workers may be exposed to a high level of radiation, and their health could be at increased risk [33]. Detailed studies are recommended to investigate this aspect in the gem mining industry in Sri Lanka to ensure that the industry is cleaner and more sustainable.

5. Conclusions

Gem mining in Sri Lanka is intensively carried out and annually generates tonnes of mine tailings. The quantification of REE content and REO grade is essential to sustainably manage this waste stream and to assess the REE resource potential in the gem waste of Sri Lanka. In the Wagawatta gem pit, the alluvial layer contained 0.3% REO. A simple physical separation method consisting of wet sieving and subsequent density separation via a shaking table was employed to upgrade the REO up to 2.8% with a 94% LREE. Therefore, the concentrated samples are a high potential source for LREEs. The organic-rich clay layer

formed underneath the alluvial layer contained 0.6% REO and 49% HREEs. Therefore, the organic-rich clay layer could also be considered a potential HREE source.

Since this study was limited to a particular gem mine, a substantial amount of REEs could be extracted from the waste tailings in the gem mining industry. Therefore, it is necessary to assess the REE potential in gem mine waste in the entire country (this can be performed by estimating the gem mining waste generation at each mine for a given period). Subsequently, sustainable process flowsheets can be developed to extract REEs economically. In addition, it is recommended to investigate the background radiation levels in gem mining sites. Furthermore, adverse radioactive impacts must also be mitigated to maintain the sustainability of the REE extraction from the gem mining waste in Sri Lanka, fostering the United Nations Sustainable Development Goals (SDGs) such as responsible production and consumption (SDG 12), and life on land (SDG 15).

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