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Geochemical Partitioning and Correlation of Rare Earth Elements, Thorium, and Uranium in Ion-Adsorption Clays from the Gemang Area, West Kelantan, Malaysia

Chang S.C., Fendy N.A., Shoparwe N.F., *Yusoff A.H.

Universiti Malaysia Kelantan, Malaysia

** Corresponding author email: hafidz.y@umk.edu.my*

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ABSTRACT

This study aimed to determine the geochemical partitioning of total rare earth elements (ΣREE), thorium (Th), and uranium (U) in ion-adsorption clays (IACs) from the Gemang area, West Kelantan, Malaysia, and to evaluate how this partitioning may influence selective REE recovery with limited radionuclide mobilisation. An eight-step sequential extraction procedure was applied to representative saprolitic IAC samples, and the extracted fractions were analysed by ICP-OES. Pearson correlation analysis and principal component analysis (PCA) were further used to examine associations among ΣREE, Th, U, and selected major elements. The sequential extraction results showed that ΣREE were concentrated mainly in the ion-exchangeable fraction (average 22.0%), with additional contributions from the residual fraction (15.3%) and a notably high proportion in the primary sulphide step (53.4%). In contrast, Th and U were concentrated mainly in the primary sulphide fraction (54.4% and 41.3%, respectively) and the residual fraction (26.2% and 45.0%, respectively). Major elements such as Al, Fe, Mn, Ca, and Na showed distributions consistent with clay, oxide, and refractory mineral hosts. Statistical analysis indicated a positive association between ΣREE and Ca-Na, whereas Th and U were more closely associated with Fe-Mn-bearing fractions, indicating different host controls and different mobilisation behaviour. These results suggest that a recoverable REE pool is present in the exchangeable fraction, while most Th and U remain in less labile phases under the tested operational scheme. The study therefore provides geochemical evidence that mild ammonium-salt leaching may favour selective REE recovery from Gemang IACs while limiting the release of naturally occurring radioactive materials, although further mineralogical validation and dynamic leaching tests are still required.

Keywords: rare earth elements, thorium, uranium, sequential extraction, Ion-adsorption clay, west Kelantan, correlation analysis.

Information about authors:

Chang S.C. *PhD Student at the Faculty of Bioengineering and Technology, and graduate research assistant at Gold, Rare Earth and Material Technopreneurship Centre, Universiti Malaysia Kelantan 17600 Jeli, Kelantan, Malaysia. Email: chang.shenchang@yahoo.com*

Fendy N.A. *Graduate research assistant at Gold, Rare Earth and Material Technopreneurship Centre, Universiti Malaysia Kelantan, 17600 Jeli, Kelantan, Malaysia. Email: nurafikahfendy@gmail.com*

Shoparwe N.F. *Associate Professor at the Faculty of Bioengineering and Technology, and Director at Gold, Rare Earth and Material Technopreneurship Centre (GREAT), Universiti Malaysia Kelantan, 17600 Jeli, Kelantan, Malaysia. Email: fazliani.s@umk.edu.my*

Yusoff A.H. *Associate Professor at the Faculty of Bioengineering and Technology and technical advisor at Gold, Rare Earth and Material Technopreneurship Centre (GREAT), Universiti Malaysia Kelantan, 17600, Kelantan, Malaysia. Email: hafidz.y@umk.edu.my*

Introduction

Ion-adsorption clay (IAC) deposits are an important class of secondary REE resources—particularly in subtropical and tropical weathering profiles—because they host a significant fraction of REEs as adsorbed ions on clay mineral surfaces, making low-impact extraction by ammonium-salt leaching feasible [1]. However, the co-occurrence of naturally occurring radioactive materials (NORMs) such as Th and U can complicate environmental management and product quality [[2], [3]]. This study addresses the partitioning of ΣREE, Th and U among operationally defined geochemical fractions in IACs from the Gemang area (West Kelantan, Malaysia), and the statistical relationships between these trace elements and major matrix components (Al, Fe, Mn, Ca, Na). The goal is to demonstrate mineralogical and chemical controls on element mobility and to provide evidence-based recommendations for selective in-situ leaching strategies that minimize Th/U mobilisation.

Recent studies emphasise the importance of mineralogical controls and quantitative validation (DXRD/XRD, SEM–EDS, and multivariate statistics) for interpreting sequential extraction results [[4, [5], [6]]. Building on this work, a dataset of partitioning and correlation analyses was presented using Agilent 51100 SVDV ICP-OES data, and it includes robust methodological details and QA/QC to strengthen reproducibility.

Experimental part

Sampling and Study Area

The study samples were collected from drill core G3 (Gemang area, West Kelantan) at depths of 7.5–10.0 m, from the B horizons of a weathered granitic saprolite profile developed under humid tropical conditions. Representative intervals (7.5, 8.0, 8.5, 9.0, 9.5, 10.0 m) were sampled. Samples were air-dried, gently crushed, and sieved to <63 µm.

Table 1 - Sequential Extraction Steps

Step	Target	Reagent	Time (h)	Temperature (℃)
1	Water Soluble, Free Ion	Deionized Water	1	Room
2	Ion-exchangeable	0.5 M ammonium sulphate	2	Room
3	Weak Acid Dissociable	0.5 M acetic acid	2	Room
4	Associate with Fe (III) oxyhydroxides and Mn oxides	0.2 M oxalic acid	1	Room (dark, no light)
5	Associate with Fe (III) oxides	0.2 M oxalic acid	2	80 (water bath)
6	Organics and supergene sulphides	35% hydrogen peroxide	1	80 (water bath)
7	Primary sulphides	$KClO_3$ + HCl + 4 M HNO_3	4	150
8	Residual	HF + HNO_3 + $HClO_4$	12	185

Sequential extraction procedure

An eight-step sequential extraction, as shown in Table 1, modified from Dold (2003) and Shi et al. (2014) to suit the mineralogical and analytical conditions of the present IAC samples [[7], [8]], was applied to each sample. The solid-to-liquid ratio was 1:50 (w/v). Extraction steps and conditions were: (1) water-soluble (deionized water, 1 h, RT, 1:50); (2) ion-exchangeable (0.5 M $(NH_4)_2SO_4$, 2 h, RT); (3) acetic acid (0.5 M CH_3COOH, pH~4.5, 2 h, RT); (4) oxalic acid dark (0.2 M $H_2C_2O_4$, pH~3.0, 1 h, RT, protected from light); (5) oxalic acid heated (0.2 M $H_2C_2O_4$, 80 °C, 2 h); (6) 35% H_2O_2 (80 °C, 1 h) for organics and supergene sulphides; (7) $KClO_3$ + HCl oxidation followed by 4 M HNO_3 boil for primary sulphides; and (8) residual digestion (HF–HNO_3–$HClO_4$) for silicate-bound elements. After each step, samples were centrifuged (3000 rpm, 10 min), the supernatants filtered (0.45 µm), and the filtrates stored for analysis. The total digestion values were used as the reference basis for normalising sequential extraction recoveries and evaluating cumulative mass balance.

Analytical methods and QA/QC

Elemental analyses were conducted by ICP-OES (Agilent 51100 SVDV operating in SVDV mode) [[9], [10]]. Calibration used multi-element standards (0.1, 0.25, 0.5, 1, 2.5, 5, 10, 25, 50, 100 ppm). Method detection limits (MDLs) for the REEs and actinides were determined from replicate blanks (n = 8). Certified reference material (CRM) digests (SY-5) and laboratory spikes (n = 3) were included to monitor recovery [11]; mean recoveries for REEs were 92–106% and for Th/U 88–102%. Duplicate extractions (n = 10) returned relative standard deviations (RSD) <7% for major elements and <12% for low-abundance REEs. Blanks and procedural controls confirmed that no systematic contamination occurred.

Data processing and statistical analysis

Element concentrations from sequential steps were normalised to total digestion (complete HF-HNO_3-HCl-HClO4 digestion) and expressed as a percentage of the total [12]. Pearson correlation coefficients were calculated between phase percentages of ΣREE, Th, U, and selected major elements (Al, Fe, Mn, Ca, Na). Principal component analysis (PCA) was performed on the centred and scaled phase percentage matrix to identify major modes of covariance. All statistics were conducted in R (v4.2), using the packages stats and FactoMineR.

The overall analytical workflow comprised sample collection and preparation, sequential extraction, ICP-OES determination, normalisation to

total digestion, and statistical interpretation using Pearson correlation and PCA.

Results and Discussion

Distribution of Thorium, Uranium, and Total REE Across Extraction Phases

Sequential extraction results of the B horizon of Gemang (G3) ion-adsorption clay profile are shown in Table 2 and Figure 1. Thorium (Th), uranium (U), and total rare earth elements (ΣREEs) exhibit distinct geochemical partitioning, i.e., they are distributed in different mineral phases in different proportions. In terms of method validity and analytical precision, the total sequential recovery of each element across all samples (7.5–10 m) is at 100 ± 10%.

Thorium in the collected soil samples was mainly of the primary sulphide and residual phases at 80.6%; followed by iron (III), Fe^{3+} bound phase at 16.1%; iron-manganese oxide, Fe-Mn oxides bound phase at 1.4%; and organic and supergene phases at 1.1%, whereas the ion-exchangeable phases were 0.1%, which is almost negligible. This collectively suggests that Th is primarily associated with refractory accessory minerals such as thorite, monazite, and xenotime. These minerals are most probably bound within crystalline Fe-oxyhydroxides or phosphate phases, which can only be dissolved by strong acid [[13], [14]]. Thorium thus cannot be desorbed from the surface by ion exchange.

Uranium has a similar phase partitioning pattern where U is embedded in the primary sulphide and residual phases at 86.3%; followed by Fe^{3+} bound phase at 7.6%; Fe-Mn oxides bound phase at 2.4%, and weakly acid-dissociable at 1.7%. No U has been found in the ion-exchange, organic, and supergene phases. This together suggests that uranium is also mainly associated with refractory accessory minerals such as uraninite, apatite, allanite and zircon [[15], [16]]. Only a small portion of U is liberated in the water-soluble phase as uranium (VI), U^{6+}, at 1.9%. Uranium in the form of the tetravalent ion, U^{4+}, as in the Fe-Mn oxides, primary sulphide and residual phases, is less soluble and thus immobile in the ion exchange phase. The mobility of uranium depends strongly on redox conditions and is thus convertible.

The large sulphide-association of Th (54.4%) and U (41.3%) suggests that Th and U are mainly hosted or included in the hypogene sulphide phase. Essentially, a low exchangeable fraction Th and U (<0.1%) indicates that they are not easily mobilised by simple changes in the surrounding water's ionic composition. This is a key finding for operational safety in the conventional use of ammonium sulphate, as the release of radioactive elements is thus limited and poses a low risk of immediate widespread contamination. Despite their stability in the raw soil exchangeable fraction, Th and U can be co-precipitated during processing and concentrated as beneficiation proceeds from intermediate products to tailings [17].

In contrast, the total rare earth distribution, ΣREE, was more mobile and readily leached by ammonium sulphate. 25.5% of ΣREE is of ion-exchangeable and weak-acid leachable phases. It is somewhat consistent with the ion-adsorption type lateritic clays of southern China and Malaysia [[18], [19]]. The ΣREE in the ion-exchangeable fraction at 22% affirms that the Gemang IACs are ion-adsorption systems with a significant recoverable REE pool by mild salt leaching. The residual ΣREE fraction at 15.3% likely reflects structural incorporation in aluminosilicate lattices, e.g., phyllosilicate interlayers or REE-bearing accessory minerals such as monazite/ xenotime in fine fractions [20]. The small contribution of oxalate-extractable fractions indicates limited binding to poorly crystalline Fe-oxyhydroxides [21].

The unusually high proportion of ΣREE in the sulphide fraction at 53.4% contrasts with typical IAC behaviour, where REEs are predominantly exchangeable. This suggests that REE-bearing sulphides may be present in specific samples, potentially as unique or localized mineral phases or sulphidic micro-inclusions [[22], [23]]; incomplete selectivity of the sulphide extraction step using $KClO_3$ + HCl oxidation then HNO_3 (operational overlap) may partially leach non-sulphide REE hosts e.g., poorly crystalline Fe-oxides, or loosely bound REE complexes, artificially inflating REE in the sulphide fraction or co-precipitation of REE with sulphide/Fe–Mn phases during weathering.

Table 2- Average phase distribution (%) of REE, Th, U and major elements from sequential extraction (n=6)

Element	Water-soluble	Ion-exchangeable	Acetic acid	Oxalic acid (dark)	Oxalic acid (80°C)	H_2O_2	Primary Sulphide	Residual
REE	0.2	22.0	3.5	0.9	4.3	0.4	53.4	15.3
Th	0.1	0.1	0.6	1.4	16.1	1.1	54.4	26.2
U	1.9	0.0	1.7	2.4	7.6	0.0	41.3	45.0
Al	0.0	0.3	0.0	0.6	3.1	0.3	13.3	82.5
Fe	0.0	0.0	0.0	0.1	11.7	1.0	53.5	33.7
Mn	0.0	1.9	0.5	2.6	24.6	2.0	44.9	23.5
Ca	14.4	60.9	6.9	3.0	0.7	0.1	4.7	9.3
Na	1.6	20.2	40.4	2.0	3.0	1.4	12.6	19.9

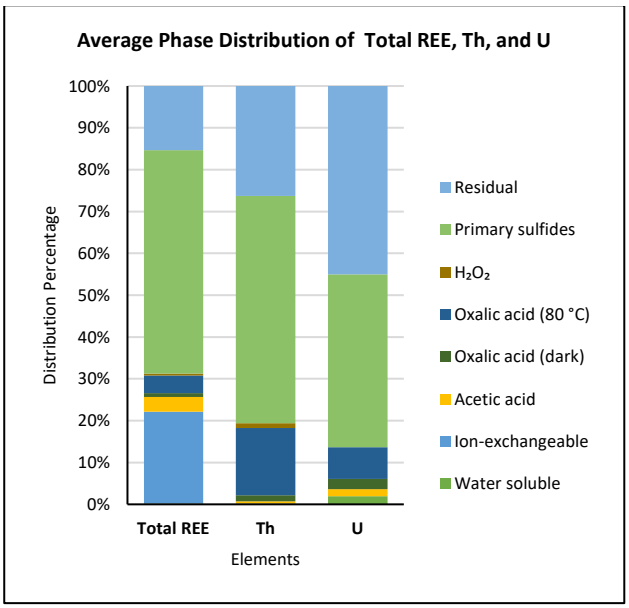

Figure 1 - Phase Distribution of Total REE, Th and U of average G3 soil profile(n=7)

Correlation Between Th, U, REE and Major Elements

Pearson correlation coefficients rounded to one decimal place (Table 3), and PCA results (Figure 2) reveal two principal geochemical associations distinct from the earlier hypothesis. Thorium and uranium are very strongly correlated (r = +0.90), confirming their common mineralogical host and co-behaviour during weathering. Both Th and U exhibit negative correlations with Fe, Mn, Ca, and Na (r≈−0.5 to −0.6), indicating that these actinides are not controlled by secondary oxide or exchangeable carbonate phases, but are instead retained in refractory mineral lattices such as monazite–xenotime or thorite-type phosphates [24]. Their weak to moderate positive correlation with Al (r ≈ +0.5 to +0.6) suggests partial structural substitution or mechanical entrapment within aluminosilicate residues [25]. Th and U remain structurally sequestered within stable mineral phases, reducing their mobility during in-situ leaching operations.

Table 3- Pearson correlation matrix (phase percentages)

Element	Th	U	∑REE	Al	Fe	Mn	Ca	Na
Th	1.0							
U	0.9	1.0						
∑REE	0.1	0.3	1.0					
Al	0.6	0.5	0.2	1.0				
Fe	-0.5	-0.6	-0.4	0.1	1.0			
Mn	-0.4	-0.3	0.2	0.1	0.7	1.0		
Ca	-0.6	-0.6	-0.5	-0.4	0.6	0.3	1.0	
Na	-0.4	-0.6	-0.3	-0.5	-0.1	-0.3	-0.2	1.0

In contrast, the ΣREE group shows a weak positive correlation with Al (r=+0.2) but a mild negative relationship with Fe (r=-0.4) and Ca (r=-0.5). This trend implies that REEs in the Gemang ion-adsorption clay are not strongly bound to Fe–Mn oxides or carbonates, but are instead associated with clay mineral surfaces through outer-sphere cation exchange. The absence of a positive ΣREE–Ca/Na correlation contradicts the behaviour observed in some South China IACs [26], highlighting local mineralogical control in which kaolinite-dominated matrices limit alkaline exchange buffering.

However, given the limited sample size (n=6), the correlation coefficients should be interpreted as indicative rather than definitive. However, the magnitude of some correlations (r > 0.7) is high enough to suggest real covariant behaviour deserving further mineralogical corroboration.

Principal Component Analysis (PCA)

Principal component analysis (PCA), as shown in Figure 2 of the phase-percentage matrix (Table 2), extracted two components that explained 70.0% of the total variance (PC1: 45.4%; PC2: 24.7%).

PC1 separates phases associated with exchangeable /leachable pools from lithogenic /oxidative pools, i.e., strong positive loadings on Ion-exchangeable and Water-soluble contrast with negative loadings on Primary sulphide, Residual, H_2O_2, and Oxalic acid at 80 °C. PC2 contrasts Residual (positive) with H_2O_2 and Oxalic acid at 80 °C (negative), distinguishing more refractory host control from oxide- and organic-bound contributions.

In score space, Ca and Na plot toward the Ion-exchangeable /Water-soluble quadrant, consistent with the readily leachable REE association, while Th, Fe and Mn align with Primary sulphide and oxidative phases, and Al is aligned toward Residual, reflecting its clay-framework affinity. REE and U sit intermediate but trend toward Ion-exchangeable vs Residual, respectively, supporting the selective exchangeability of REE under mild ammonium leaching with limited co-mobilisation of Th/U.

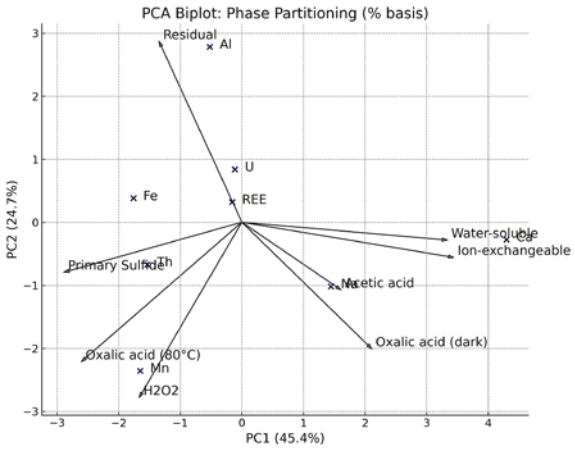

Figure 2- PCA Biplot of Phase Partitioning

Samples at 8.0 - 9.0 m depth plot as shown in Figure 3, toward the REE-enriched quadrant, reflecting zones of higher weathering and greater ion-exchange potential, whereas deeper samples (≥9.5 m) cluster in Th-U-Fe-rich domains, suggesting lithogenic enrichment and incomplete alteration. The PCA plot demonstrates that the 8.0–9.0 m depth is the most favourable for REE leaching using ion-exchange ammonium sulphate, as a high proportion of the ion-exchangeable phase characterises this zone. In contrast, in the deeper depths, particularly those ≥ 9.5 m, REE recovery is less favourable. This is because the REEs in these depths are more strongly associated with refractory phases, i.e., residual or primary sulphide phases. Stronger acids are needed to break down and release the REEs if these phases are intended for extraction. This geochemical differentiation illustrates the natural zonation of the soil profile, which can be utilised as a selective in-situ leaching strategy. The processing zone can thus be divided into two: the shallow zones using milder, more cost-effective, and environmentally friendlier leaching agents, while the deeper zones use stronger, more potent acid–complexant combinations to mobilise the refractory-bound REEs [[26], [27]].

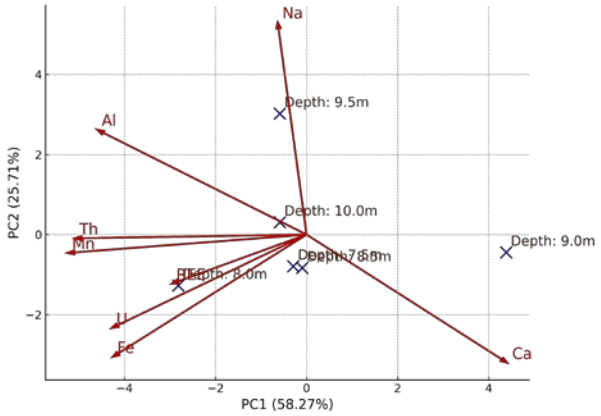

Figure 3- PCA Biplot of Elements Partitioning in Depths

Implications for the process design of selective in-situ leaching

The clear geochemical separation between exchangeable ΣREE and refractory Th/U implies that mild ammonium-salt leaching can preferentially mobilise REEs while leaving Th and U immobile, provided leaching remains non-oxidative and pH is controlled above 4. To reduce the risk of releasing Th/U due to sulphide/oxide dissolution, the leaching solution should not contain strong oxidants and should be maintained near-neutral to mildly acidic conditions.

The natural zonation and vertical variation in exchangeable ΣREE and major element concentrations, as indicated by PCA sample spread, suggest that in-situ leaching designs should also consider stratigraphic variability. Early-stage exploration should prioritise mapping vertical heterogeneity within the exchangeable fraction of the deposit to delineate the high-value zones accurately. This spatial understanding enables the application of selective leaching techniques, such as targeted well placement or confined percolation, to preferentially recover exchangeable rare earth elements (REEs). This targeted approach optimises efficiency by minimising overall reagent consumption, thereby reducing the operation's environmental footprint.

A robust monitoring strategy is also important during leaching operations. Dissolved iron (Fe) and manganese (Mn) concentrations, and the redox potential, should be included as key monitoring parameters. These measures serve as critical indicators of incipient sulphide oxidation, an event that could lead to the unintended mobilisation of thorium (Th) and uranium (U) into the leachate pool.

Limitations and recommendations for future research

Data derived from sequential extraction procedures have some inherent limitations. The methods are operationally defined to ensure accuracy and repeatability. However, the results are consequently dependent on the specific extraction procedure and matrix. Furthermore, in this study, only a small sample size was used (n=6), which limits statistical power and thus does not reflect regional conditions.

To overcome the limitations and enhance understanding of the deposits, more samples from the spatial lateral and vertical profiles should be collected and data included to produce a more statistically significant data set [28].

Other mineralogical and geochemical methods should also be included to minimise ambiguities. X-ray diffraction (XRD) can be used to analyse the removal or persistence of mineral phases before and after leaching [29]. Scanning electron microscopy with energy-dispersive X-ray spectrometry (SEM-EDS) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA–ICP–MS) can be employed to visually identify the elements hosted in the mineral matrix [30].

To bridge the gap from laboratory data to operational reality, pilot leach tests, such as small columns, are needed to simulate in-situ conditions and thus allow further optimisation.

Conclusions

The sequential extraction results show that rare earth elements (ΣREE), thorium (Th), and uranium (U) in the Gemang ion-adsorption clay do not share the same geochemical behaviour. ΣREE display a meaningful exchangeable component, with an average of 22.0% occurring in the ion-exchangeable fraction, confirming that part of the REE inventory remains potentially recoverable by mild ammonium-salt leaching. In contrast, Th and U are concentrated mainly in the primary sulphide and residual fractions, indicating stronger retention in less labile phases and lower susceptibility to release under simple ion-exchange conditions.

The correlation and PCA results support this distinction. ΣREE show closer association with Ca and Na, consistent with exchangeable or weakly bound occurrence, whereas Th and U are more closely associated with Fe- and Mn-bearing phases and refractory mineral hosts. This separation in geochemical behaviour suggests that selective mobilisation of REEs is more feasible than co-mobilisation of radionuclides under mild leaching conditions. However, the unusually high ΣREE proportion in the primary sulphide step indicates that some overlap between operational fractions remains possible, and that the extraction sequence should be interpreted as an operational partitioning tool rather than a direct mineralogical determination.

From a process perspective, the results support the view that ammonium-sulphate leaching can preferentially target the exchangeable REE pool while limiting Th and U release, provided that the leaching system remains non-oxidative and chemically controlled. This is important for the design of safer and more selective REE recovery routes from Malaysian ion-adsorption clays, where minimising radionuclide mobilisation is a key environmental and operational requirement.

At the same time, the present work should be treated as a geochemical and operational baseline rather than a complete process validation. Future work should include direct mineralogical verification of host phases by XRD, SEM-EDS, and LA-ICP-MS, together with dynamic column or pilot leaching tests to confirm whether the selective behaviour inferred from sequential extraction is maintained under realistic in-situ leaching conditions.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

CRediT author statement.

S. Chang: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft. **N. Fendy:** Investigation, Validation, Writing – review&editing; **N. Shoparwe:** Supervision, Project administration, Resources; **A. Yusoff**: Conceptualization, Supervision, Project administration, Writing– review&editing.

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Chang S.C., Fendy N.A., Shoparwe N.F., Yusoff A.H.

Келантан Малайзия университеті, Малайзия

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Сараптамадан өтті: *30 қараша 2025*
Қабылданды: *13 шілде 2026*

ТҮЙІНДЕМЕ

Бұл зерттеу Малайзияның Батыс Келантан қаласындағы Геманг аймағынан алынған иондық-адсорбциялық саздардағы (ИАС) жалпы сирек кездесетін жер элементтерінің (ΣREE), торийдің (Th) және уранның (U) геохимиялық бөлінуін анықтауға және бұл бөлінудің шектеулі радионуклидті мобилизациямен ИАС-ты селективті қалпына келтіруге қалай әсер етуі мүмкін екенін бағалауға бағытталған. Өкілетті сапролиттік ИАС үлгілеріне сегіз сатылы тізбекті экстракция процедурасы қолданылды, ал алынған фракциялар ICP-OES арқылы талданды. Пирсон корреляциялық талдауы және негізгі компоненттік талдау (PCA) ΣREE, Th, U және таңдалған негізгі элементтер арасындағы байланысты зерттеу үшін қолданылды. Тізбекті экстракция нәтижелері ΣREE негізінен ион алмастырылатын фракцияда (орташа 22,0%) шоғырланғанын, қалдық фракциядан (15,3%) қосымша үлестер қосылғанын және бастапқы сульфид сатысында айтарлықтай жоғары үлеске ие болғанын (53,4%) көрсетті. Керісінше, Th және U негізінен бастапқы сульфид фракциясында (сәйкесінше 54,4% және 41,3%) және қалдық фракцияда (сәйкесінше 26,2% және 45,0%) шоғырланған. Al, Fe, Mn, Ca және Na сияқты негізгі элементтер саз, оксид және отқа төзімді минералды иелермен сәйкес таралуды көрсетті. Статистикалық талдау ΣREE және Ca-Na арасындағы оң байланысты көрсетті, ал Th және U Fe-Mn бар фракциялармен тығыз байланысты болды, бұл әртүрлі ие бақылаулары мен әртүрлі мобилизация мінез-құлқын көрсетеді. Бұл нәтижелер алмасатын фракцияда қалпына келтірілетін сирек кездесетін жердегі элменттер пулының бар екенін, ал Th және U-ның көпшілігі тексерілген пайдалану схемасы бойынша онша тұрақсыз фазаларда қалатынын көрсетеді. Сондықтан зерттеу аммоний-тұзды жұмсақ шаймалау табиғи радиоактивті материалдардың шығарылуын шектей отырып, Геманг ИАС-тан сирек кездесетін жердегі элменттерді селективті түрде қалпына келтіруге ықпал етуі мүмкін екендігінің геохимиялық дәлелдерін ұсынады, дегенмен минералогиялық валидация және динамикалық шаймалау сынақтары әлі де қажет.

Түйін сөздер: сирек кездесетін жер элементтері, торий, уран, тізбектей экстракция, ион-адсорбциялық саз, батыс Келантан, корреляциялық талдау.

Авторлар туралы ақпарат:

Chang S.C. *PhD докторант, ғылыми қызметкер, Биоинженерия және технология факультеті, Алтын, сирек жер және материалдық технологиялар орталығы, Келантан Малайзия университеті, 17600 Джели, Келантан, Малайзия. Email: chang.shenchang@yahoo.com*

Fendy N.A. *Ғылыми қызметкер, Алтын, сирек жер және материалдар технологиялары орталығы, Малайзия университеті Келантан, 17600 Джели, Келантан, Малайзия. Email: nurafikahfendy@gmail.com*

Shoparwe N.F. *Доцент, директор, Биоинженерия және технологиялар факультеті, Алтын, сирек жер және материалдық технологиялар орталығы, Малайзия университеті Келантан, 17600 Джели, Келантан, Малайзия. Email: fazliani.s@umk.edu.my*

Yusoff A.H. *Доцент, техникалық кеңесші, Биоинженерия және технология факультеті, Алтын, сирек жер және материалдық технологиялар орталығы, Келантан Малайзия университеті, 17600 Джели, Келантан, Малайзия. Email: hafidz.y@umk.edu.my*

Геохимическое распределение и корреляция редкоземельных элементов, тория и урана в ионно-адсорбционных глинах района Геманг, Западный Келантан, Малайзия

Chang S.C., Fendy N.A., Shoparwe N.F., Yusoff A.H.

Университет Малайзии Келантан, Малайзия

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АННОТАЦИЯ

Целью данного исследования было определение геохимического распределения общего количества редкоземельных элементов (ΣREE), тория (Th) и урана (U) в ионно-адсорбционных глинах (ИАГ) из района Геманг, Западный Келантан, Малайзия, а также оценка того, как это распределение может влиять на селективное извлечение РЗЭ при ограниченной мобилизации радионуклидов. К репрезентативным образцам сапролитовых ИАГ была применена восьмиступенчатая процедура последовательной экстракции, а извлеченные фракции были проанализированы методом ICP-OES. Для изучения взаимосвязей между ΣREE, Th, U и некоторыми основными элементами были дополнительно использованы корреляционный анализ Пирсона и анализ главных компонентов (PCA). Результаты последовательной экстракции показали, что ΣREE в основном сконцентрированы в ионообменной фракции (в среднем 22,0%), с дополнительным вкладом остаточной фракции (15,3%) и заметно высокой долей в первичной сульфидной стадии (53,4%). Напротив, Th и U были сконцентрированы в основном в первичной сульфидной фракции (54,4% и 41,3% соответственно) и остаточной фракции (26,2% и 45,0% соответственно). Основные элементы, такие как Al, Fe, Mn, Ca и Na, показали распределение, соответствующее глинистым, оксидным и тугоплавким минеральным вмещающим породам. Статистический анализ показал положительную корреляцию между ΣREE и Ca-Na,

	тогда как Th и U были более тесно связаны с Fe-Mn-содержащими фракциями, что указывает на различные факторы, влияющие на вмещающую породу, и различное поведение при мобилизации. Эти результаты предполагают, что в обменной фракции присутствует восстанавливаемый пул REE, в то время как большая часть Th и U остается в менее лабильных фазах при протестированной схеме эксплуатации. Таким образом, исследование предоставляет геохимические доказательства того, что мягкое выщелачивание аммонийными солями может способствовать селективному извлечению REE из рудных месторождений Геманг, ограничивая при этом выброс природных радиоактивных материалов, хотя для подтверждения этого необходимы дальнейшие минералогические исследования и динамические испытания на выщелачивание.
	Ключевые слова: редкоземельные элементы, торий, уран, последовательная экстракция, ионно-адсорбционная глина, Западный Келантан, корреляционный анализ.
Chang S.C.	***Информация об авторах:*** *Аспирант факультета биоинженерии и технологий и аспирант-исследователь Центра технопредпринимательства по золоту, редкоземельным металлам и материалам Университета Малайзии Келантан 17600 Джели, Келантан, Малайзия. Email: chang.shenchang@yahoo.com*
Fendy N.A.	*Аспирант-исследователь Центра технологического предпринимательства по золоту, редкоземельным металлам и материалам, Университет Малайзии, Келантан, 17600 Джели, Келантан, Малайзия. Email: nurafikahfendy@gmail.com*
Shoparwe N.F.	*Доцент факультета биоинженерии и технологий и директор Центра технологического предпринимательства в области золота, редких земель и материалов (GREAT), Университет Малайзии Келантан, 17600 Джели, Келантан, Малайзия. Email: fazliani.s@umk.edu.my*
Yusoff A.H.	*Доцент факультета биоинженерии и технологий и технический консультант Центра технологического предпринимательства в области золота, редких земель и материалов (GREAT), Университет Малайзии Келантан, 17600, Келантан, Малайзия. Email: hafidz.y@umk.edu.my*

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