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VALIDATION OF A RADIOCHEMICAL SEPARATION AND ALPHA SPECTROMETRIC METHOD FOR DETERMINATION OF ^{234}U, ^{235}U, AND ^{238}U IN ENVIRONMENTAL SAMPLES

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ABSTRACT

This study presents the validation of a radiochemical separation and alpha spectrometric method for the determination of uranium isotopes (^{234}U, ^{235}U, and ^{238}U) in environmental samples. The procedure was evaluated using two International Atomic Energy Agency (IAEA) certified reference materials (CRMs), namely IAEA-385 (Irish Sea Sediment) and IAEA-384 (Fangataufa Sediment), to assess its analytical performance. Validation parameters included selectivity, accuracy, precision, repeatability, ruggedness, and robustness. The calculated u-scores and z-scores were within acceptable limits, and relative bias values demonstrated good agreement with certified values. Inter-analyst comparison using IAEA-385 confirmed the method's ruggedness, while consistent performance across different CRMs demonstrated its robustness. The validated procedure provides a reliable and standardized approach for uranium isotope analysis in environmental matrices and is established at the Radiochemistry and Environment Laboratory, Malaysian Nuclear Agency, for routine environmental monitoring applications.

Keywords: uranium isotope, alpha spectrometry, method validation, radiochemistry

ABSTRAK

Kajian ini membentangkan penentusahan kaedah pemisahan radiokimia dan pengukuran menggunakan spektrometri alfa bagi penentuan isotop uranium (^{234}U, ^{235}U dan ^{238}U) dalam sampel alam sekitar. Prosedur ini dinilai menggunakan dua bahan rujukan diperakui (CRM) daripada Agensi Tenaga Atom Antarabangsa (IAEA), iaitu IAEA-385 (Sedimen Laut Ireland) dan IAEA-384 (Sedimen Fangataufa), bagi menilai prestasi analitik kaedah tersebut. Parameter penentusahan yang dinilai merangkumi ketertentuan, ketepatan, kejituan, kebolehulangan, kekasaran dan keteguhan. Nilai u-score dan z-score yang diperoleh adalah dalam julat penerimaan, manakala bias relatif menunjukkan persetujuan yang baik dengan nilai diperakui. Perbandingan antara penganalisis menggunakan IAEA-385 mengesahkan kekasapan kaedah, manakala prestasi yang konsisten merentasi CRM yang berbeza membuktikan keteguhannya. Prosedur yang telah ditentusahkan ini menyediakan pendekatan yang boleh dipercayai dan piawai bagi analisis isotop uranium dalam matriks alam sekitar serta telah dilaksanakan di Makmal Radiokimia dan Alam Sekitar, Agensi Nuklear Malaysia, untuk aplikasi pemantauan alam sekitar secara rutin.

Kata kunci: *isotop uranium, spektrometri alfa, penentusahan kaedah, radiokimia*

INTRODUCTION

Accurate analysis of uranium in sediment samples is crucial for environmental monitoring, pollution assessment, and regulatory compliance (IAEA 1997). Uranium, a naturally occurring radioactive element, poses significant health and ecological risks at elevated concentrations (IAEA 2005). Accurate quantification and monitoring of uranium levels in environmental samples are essential for managing these risks (EPA 2006). This study presents the validation of the developed uranium analysis procedure using radiochemical separation and alpha spectrometry, conducted at the Radiochemistry and Environment Group, Malaysian Nuclear Agency.

Method validation is critical in analytical chemistry to ensure the reliability and accuracy of analytical methods (Rambla-Alegre et al. 2012). Key parameters evaluated during validation include selectivity, accuracy, precision, repeatability, and robustness. Selectivity ensures the method accurately identifies the target analyte in the presence of other substances. Accuracy measures how closely the results agree with the true value (Magnusson & Örnemark 2014). Precision assesses the repeatability or reproducibility of results under consistent conditions.

Repeatability examines the consistency of results under the same conditions, while ruggedness tests the method's reliability across variations such as different operators or equipment settings. Robustness evaluates the method's reliability when deliberately introducing minor variations in experimental conditions. Linearity demonstrates how well the method generates results that are directly proportional to the analyte's concentration. Limits of detection (LOD) and quantitation (LOQ) are crucial, with LOD being the lowest detectable concentration and LOQ the lowest concentration that can be quantitatively determined with acceptable accuracy and precision.

This study aims to evaluate key aspects of analytical methods to ensure their reliability and accuracy. The focus is on accuracy, precision, repeatability, specificity, and specific aspects of robustness and ruggedness. Other important factors are still being investigated and will be discussed in future study. This ongoing research aims to enhance the analytical capability of the laboratory, ensure the generation of reliable and traceable results, and strengthen laboratory quality management practices in alignment with ISO/IEC 17025 principles.

METHODOLOGY

Reagents and Materials

All reagents were of analytical grade. Concentrated nitric acid (HNO_3, 65%), hydrochloric acid (HCl, 37%), hydrofluoric acid (HF, 40%), perchloric acid ($HClO_4$, 70%), sulfuric acid (H_2SO_4, 95%), hydrogen peroxide (H_2O_2, 30%), and ammonium hydroxide (NH_4OH, 28%) were used for digestion and chemical separation. Diluted acid solutions of defined molarity were prepared from the concentrated stock solutions using distilled water for subsequent ion-exchange and extraction chromatography steps. A NIST-traceable ^{232}U solution was employed as a tracer to monitor chemical recovery throughout the procedure. Anion exchange resin AG 1-X2 (chloride form, 100–200 mesh) and TRU-Spec extraction chromatography resin were used for uranium separation and purification. Polished stainless steel discs were used for electrodeposition prior to alpha

spectrometric measurement. Certified reference materials IAEA-385 and IAEA-384 were used for performance evaluation.

Radiochemical Separation and Source Preparation

Approximately 0.5 g of sediment CRM was accurately weighed into a 250 mL Teflon beaker and moistened with a small volume of dilute nitric acid (~1–2 M HNO_3) to form a homogeneous slurry. Approximately 0.5 Bq of ^{232}U tracer was then added prior to digestion to monitor chemical recovery and assess the efficiency of the separation procedure. The sample was digested using a mixed-acid consisting of hydrofluoric acid, nitric acid, perchloric acid, and hydrogen peroxide. The beaker was heated on a controlled hot plate until dryness to ensure complete dissolution of silicate and refractory components. Repeated evaporation with concentrated nitric acid was performed to eliminate residual fluoride complexes and convert uranium into a nitrate medium suitable for anion exchange separation. Mixed-acid digestion using $HF–HNO_3–HClO_4$ is widely applied for the decomposition of environmental matrices containing silicate minerals (IAEA 1997).

The dried residue was dissolved in 8 M nitric acid and loaded onto a pre-conditioned AG 1-X2 anion exchange column. In concentrated nitric acid medium, uranium forms stable anionic nitrate complexes (e.g., $UO_2(NO_3)_3^-$) that are selectively retained on the resin, while most matrix elements pass through. The column was washed with additional 8 M nitric acid to remove residual matrix constituents. The uranium fraction was subsequently eluted and evaporated to dryness. Anion exchange in strong nitric acid medium is a well-established method for uranium separation from complex environmental matrices, as described by Horwitz et al. (1992, 1993) and further applied in environmental uranium determination by Jia et al. (2002).

For further purification, the residue was dissolved in 2 M nitric acid and loaded onto a TRU-Spec extraction chromatography column that had been preconditioned with distilled water followed by 2 M nitric acid. The column was sequentially washed with nitric acid solutions of decreasing molarity to remove interfering actinides and residual matrix components. Uranium was eluted using ammonium bioxalate solution, and the eluate was evaporated to dryness. TRU-Spec resin provides enhanced selectivity for actinides and improves alpha spectral quality by minimizing co-eluting species (Horwitz et al. 1993; Jia et al. 2002)

The purified uranium fraction was subjected to electrodeposition to produce a thin, uniform source suitable for alpha spectrometry. The residue was treated with perchloric and sulfuric acids to convert the uranium into a sulfate medium, followed by controlled evaporation. The final solution was adjusted to pH 2.0–2.2 using dilute sulfuric acid, and a small amount of sodium dodecyl sulfate was added to improve deposition quality. The solution was transferred to an electrodeposition cell fitted with a polished stainless steel disc. Electrodeposition was carried out for one hour under controlled current conditions to obtain a thin and homogeneous uranium layer. After deposition, the disc was rinsed, dried, and briefly flamed to ensure adherence of the deposit. Electrodeposition is widely employed in alpha spectrometric analysis to minimize self-absorption and achieve optimal peak resolution (Gaburo et al. 2006).

Alpha Spectrometric Measurement

The prepared discs were measured using an ORTEC Octete Plus alpha spectrometer equipped with silicon surface barrier detectors. Energy calibration was performed using multi-alpha reference standards prior to sample analysis. Counting times were selected to achieve adequate statistical precision, particularly for the low-abundance isotope ^{235}U.

Activity concentrations were calculated using a tracer-based isotope dilution approach. The activity of each uranium isotope was determined from the ratio of net analyte count rate to net tracer count rate, multiplied by the certified activity of the ^{232}U tracer and normalized to sample mass, as expressed in Eq. 1. Blank corrections were applied to both analyte and tracer count rates, and decay correction factors were incorporated to account for time differences between reference, separation, and measurement dates. This approach inherently corrects for chemical recovery and counting efficiency variations.

$$A_A = \frac{A_{tracer} \cdot W_t \frac{(R_{S1} - R_{B1})}{(R_{S2} - R_{B2})}}{W_s} \cdot f_1 \cdot f_2 \ldots \text{Eq. 1}$$

Where:

A_A = activity concentration of analyte
A_{tracer}= certified activity concentration of tracer at reference date
W_t = mass of tracer added (kg)
W_s = mass of sample (kg)
R_{S1} = gross count rate of analyte (counts s^{-1})
R_{B1}= blank count rate of analyte (counts s^{-1})
R_{S2} = gross count rate of tracer (counts s^{-1})
R_{B2}= blank count rate of tracer (counts s^{-1})
f_1 = decay correction factor for tracer
f_2 = decay correction factor for analyte

Method Performance Evaluation and Validation Criteria

Selectivity was determined by evaluating the energy spectrum produced, ensuring the method could accurately identify uranium isotopes in the presence of other components (NATA 2006). Accuracy was assessed by comparing measured values to known CRM values, calculated using the u-score using Eq. 2 below:

$$U - score = \frac{|x_{lab} - x_{ref}|}{\sqrt{Unc_{ref}^2 + Unc_{lab}^2}} \ldots \text{Eq. 2}$$

Where X_{lab} is the mean value from measurement; X_{ref} is the reference value, Unc_{ref} is the standard deviation of the reference value, and Unc_{lab} is the standard deviation of the analytical value. In addition to the u-score, the z-score was calculated for accuracy evaluation, defined by Eq. 3 below:

$$Z - score = \frac{|X_{lab} - X_{ref}|}{Std} \text{ ...Eq. 3}$$

Where X_{ref} is the expected activity, and std is the standard deviation. The z-score measures how many standard deviations an observed value is from the expected value, providing a standardized way to compare results.

For interpretation, the u-score was evaluated using critical values based on statistical significance. A u-score < 1.64 indicates that the results do not differ significantly, 1.64 ≤ u-score < 2.58 suggests that the results may not differ significantly, and u-score ≥ 2.58 indicates that the results are probably significantly different. For the z-score, interpretation follows commonly applied proficiency testing thresholds (Thompson et al. 2006; ISO 13528:2015), where $|z| \leq 2$ is satisfactory, $2 < |z| < 3$ is questionable, and $|z| \geq 3$ is unsatisfactory.

Relative bias, b (%) was also calculated to measure deviation from true values, using Eq.4 below (Eurachem 1998; Guérin & Dai 2015):

$$b(\%) = \frac{X_{lab} - X_{ref}}{X_{ref}} x100 \text{ ...Eq. 4}$$

The relative standard deviation (RSD) is calculated by multiplying the standard deviation of the sample set by 100% and then dividing it by the sample set average. The RSD is expressed as a percentage. Typically, the acceptance criterion for accuracy, precision, and repeatability of data is expressed in % RSD (Sushila Dagadu Chavan & Deepa Mahendra Desai 2022):

$$\%RSD = \frac{S}{\bar{x}} x100 \ldots \text{Eq. 5}$$

Repeatability was assessed by the closeness of agreement between successive measurements of the same sample under the same conditions, including the same radiochemical method, measuring instrument, and location, with measurements repeated over a short period. Ruggedness was demonstrated by obtaining consistent results from three different analysts using IAEA-385, while robustness was highlighted by the method's consistent performance across various CRMs. Additionally, the efficiency of the radiochemical separation process was confirmed by calculating the recovery of the ^{232}U tracer, comparing the measured activity to the known spiked activity, with high recovery rates indicating effective separation and reliable quantification of uranium isotopes in sediment samples. This comprehensive validation ensured the developed procedure was reliable and suitable for routine uranium analysis in sediment samples.

RESULTS AND DISCUSSION

Selectivity

Selectivity was evaluated by comparing the measured alpha peak energies with the evaluated nuclear decay data for uranium isotopes. According to the NuDat 3.0 database (National Nuclear Data Center, 2023). The principal alpha energies are 4196 keV for ^{238}U, 4678–4679 keV for ^{235}U, 4774 keV for ^{234}U, and approximately 5320 keV for the ^{232}U tracer.

The measured regions of interest (ROI) summarized in Table 1 were centered around these expected energies. The observed peak centroids fell within the detector resolution limits and showed deviations of less than ±1% relative to the theoretical energies. Such deviations are within the acceptable energy calibration tolerance for alpha spectrometry and are consistent with typical detector full width at half maximum (FWHM) performance (Knoll 2010).

Furthermore, no overlapping peaks or spectral interferences from other alpha-emitting radionuclides were detected in the spectrum (Figure 1). The energy separation between adjacent uranium peaks substantially exceeded the typical detector resolution of silicon surface barrier detectors, ensuring adequate spectral discrimination. These results confirm adequate spectral resolution and demonstrate that the developed method provides sufficient selectivity for uranium isotope determination in sediment samples.

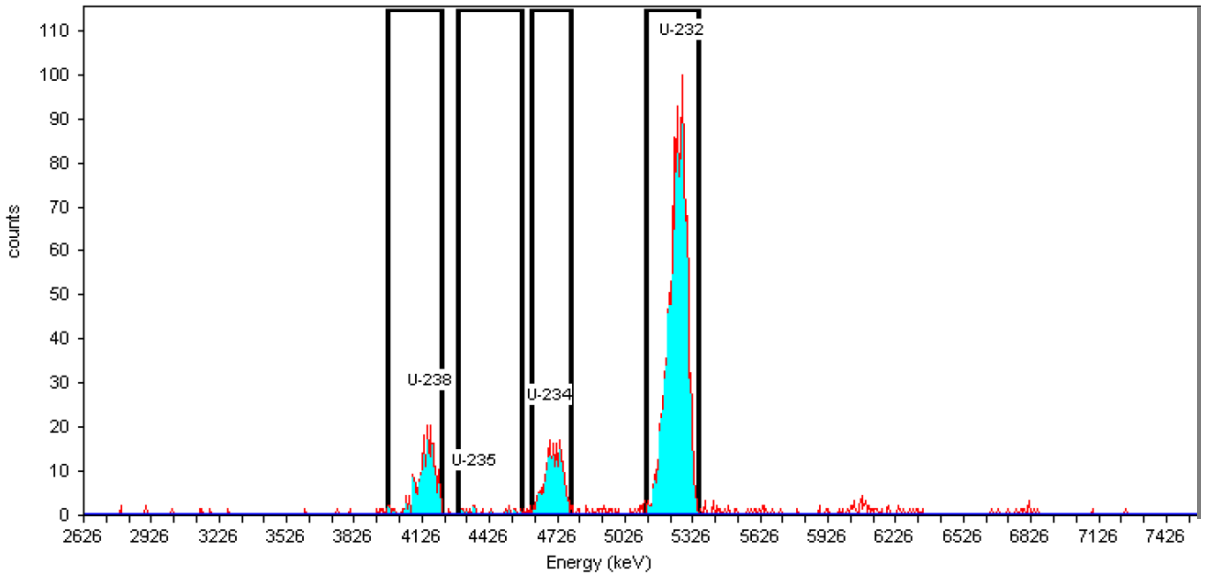

Figure 1 Uranium isotopes peak spectrum

Table 1 ^{234}U, ^{235}U, and ^{238}U energy range of interest (ROI) analysed for IAEA-385

Sample no.	^{234}U		^{235}U		^{238}U		^{232}U	
	Min keV	Max keV	Min keV	Max keV	Min keV	Max keV	Min keV	Max keV
1	4577.82	4790.66	4322.42	4498.06	4012.55	4211.21	5146.29	5343.08
2	4577.63	4795.23	4300.28	4510.36	4031.14	4214.92	5162.58	5341
3	4587.77	4790.57	4307.29	4498.06	4012.55	4211.21	5170.04	5371.7
4	4564	4790	4286.43	4416.76	4004.53	4196	5099	5370
5	4572.49	4814.57	4277.94	4495.15	4008.28	4210.46	5125.27	5344.301
6	4561.7	4770.83	4271.37	4466.79	4024.72	4185.94	5117.322	5323.98

Accuracy and Precision

The measured activity concentrations, recoveries, u-scores, z-scores, and RSD values for IAEA-385 and IAEA-384 are summarized in Table 2. These parameters were used to evaluate method accuracy, precision, and robustness.

The calculated u-scores for ^{234}U, ^{235}U, and ^{238}U in both certified reference materials were below the critical value of 1.64, indicating that the measured results did not differ significantly from the certified values. The corresponding z-scores remained within the satisfactory performance range ($|z| \leq 2$), further confirming the trueness of the method.

Relative bias values for IAEA-385 were 2.01%, 7.14%, and 0.54% for ^{234}U, ^{235}U, and ^{238}U, respectively, reflecting minimal deviation from certified values. Similar agreement was observed for IAEA-384, confirming method reliability across different environmental matrices.

Table 2 Measurement data, u-score, z-score, and recovery for ^{234}U, ^{235}U, and ^{238}U in IAEA-385 and IAEA-384

IAEA-385 Certified value	**^{234}U (27.2±1.2 Bq/kg)**	**^{235}U (1.36±0.11 Bq/kg)**	**^{238}U (29.4±1.2 Bq/kg)**	**Recovery**
Sample no.	**Lab value (Bq/kg)**	**Lab value (Bq/kg)**	**Lab value (Bq/kg)**	
1	28.96±4.4	2.57±1.2	29.27±4.4	93.07
2	24.64±3.85	2.62±1.17	25.02±3.85	95.65
3	26.8±4.43	2.01±1.2	32.9±5.07	82.2
4	30.8±4.74	2.55±1.25	33.54±5	85.75
5	28.49±4.49	2.66±1.27	29.1±4.51	92.23
6	26.72±4.4	1.13±1.03	30.41±4.76	81.93
Mean	27.75±3.75	1.26±1.25	29.24±3.90	88.47
U-score	0.14	0.08	0.04	
Relative bias, %	2.01	7.14	0.54	
RSD, %	7.72	47.63	10.51	
Z-Score	0.25	0.16	0.05	
IAEA 384 Certified value	**^{234}U (40.3±2.2 Bq/kg)**	**^{235}U (1.76±0.12 Bq/kg)**	**^{238}U (36.4±1.2 Bq/kg)**	**Recovery**
Sample no.	**Lab value (Bq/kg)**	**Lab value (Bq/kg)**	**Lab value (Bq/kg)**	
1	35.34±4.71	3.03±1.19	42.61±5.38	96.79
2	40.51±5.00	2.95±1.12	33.95±4.35	110.02
3	39.16±5.50	2.80±1.32	36.24±5.15	78.27
4	38.11±4.63	2.82±1.05	32.97±4.13	110.82
5	35.86±4.65	1.61±0.94	31.56±4.20	103.97
Mean	37.80±4.90	2.64±1.12	35.47±4.64	
U-score	0.38	0.78	0.72	
Relative bias, %	6.21	50.11	10.40	
RSD, %	5.78	22.13	12.24	
Z-Score	1.15	1.51	0.22	

Precision

The RSD values further support the method's precision. For ^{234}U and ^{238}U, the RSD values were 7.72% and 10.51% for IAEA-385, and 5.78% and 12.24% for IAEA-384, respectively, demonstrating acceptable repeatability under the same analytical conditions. RSD values below 20% are generally considered acceptable for radiochemical methods at environmental activity levels, particularly where counting statistics influence measurement uncertainty (Magnusson & Örnemark 2014). In contrast, the higher RSD observed for ^{235}U (47.63% in IAEA-385 and 22.13% in IAEA-384) is attributable to its lower activity concentration and reduced counting statistics, which increase relative variability in alpha spectrometric measurements, and this behaviour is consistent with Poisson counting statistics rather than systematic analytical bias.

Recovery

The recovery values for ^{234}U, ^{235}U, and ^{238}U obtained for IAEA-385 and IAEA-384 are presented in Table 2 and were used to evaluate the efficiency of the radiochemical separation. For IAEA-385, individual recoveries ranged from 81.93% to 95.65%, with a mean value of 88.47%. For IAEA-384, recoveries ranged from 78.27% to 110.82%, yielding a mean of 99.98%.

In alpha spectrometric radiochemical analysis of environmental samples, recoveries within approximately 70–120% are generally considered acceptable, particularly when measurement uncertainty and counting statistics are taken into account. In the present study, the majority of recovery values fall within the narrower range of 80–110%, with overall mean recoveries close to 100%, indicating satisfactory chemical separation efficiency. Although one sample exhibited slightly lower recovery and two samples marginally exceeded 110%, no systematic trend of under- or over-recovery was observed. The overall distribution of recovery values therefore demonstrates adequate radiochemical control and supports the robustness of the analytical method.

Repeatability

Repeatability was evaluated through repeated measurements of IAEA-385 under identical analytical conditions. The control charts presented in Figures 2, 3, and 4 show the measured activities of ^{234}U, ^{235}U, and ^{238}U, respectively. The close agreement of successive measurements confirms method repeatability.

Although several measurements appear below the mean, all results remain within $\pm 2\sigma$ control limits and none exceed $\pm 3\sigma$ limits. For low-activity isotopes such as ^{235}U, measurement variability is strongly influenced by Poisson counting statistics, where the variance is equal to the mean count rate (Knoll 2010). Under low-count conditions, relative uncertainty increases as $1/\sqrt{N}$, which may

produce apparent clustering or wider dispersion without indicating systematic bias. The data therefore satisfy statistical control criteria.

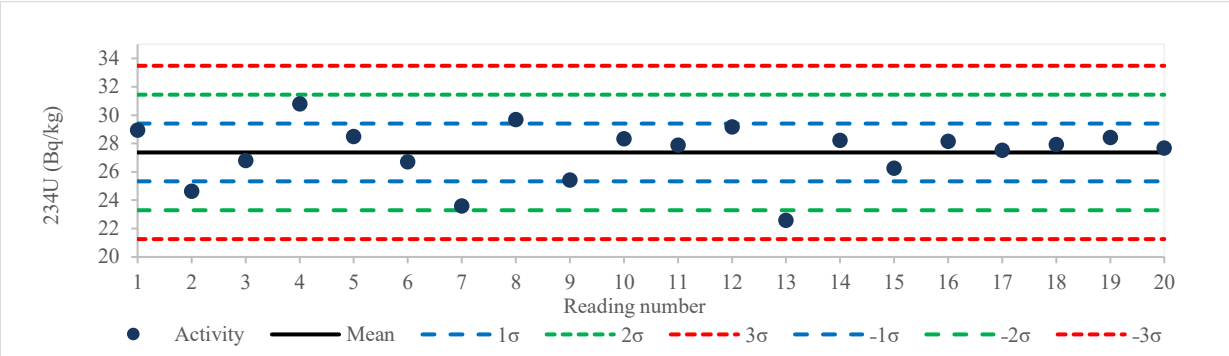

Figure 2 ^{234}U Radioactivity (Bq/kg) measured in IAEA-385

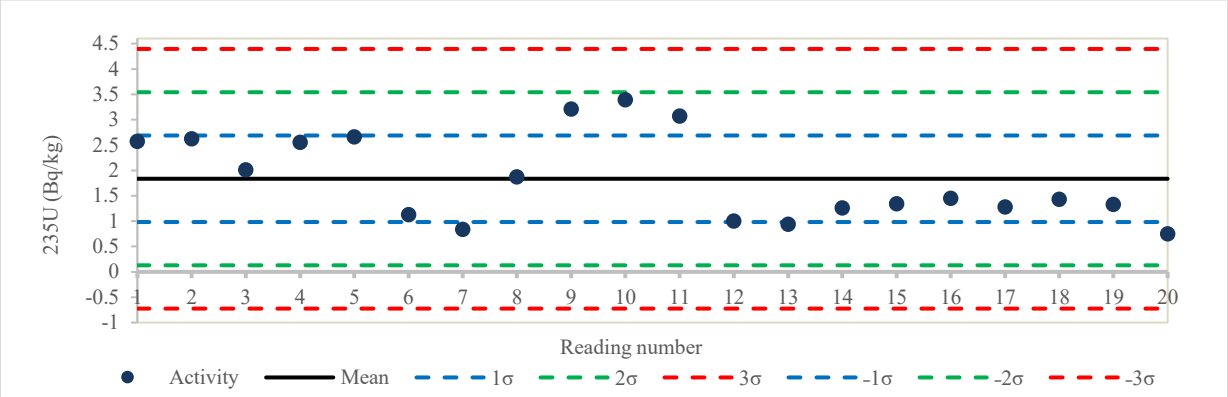

Figure 3 ^{235}U Radioactivity (Bq/kg) measured in IAEA-385

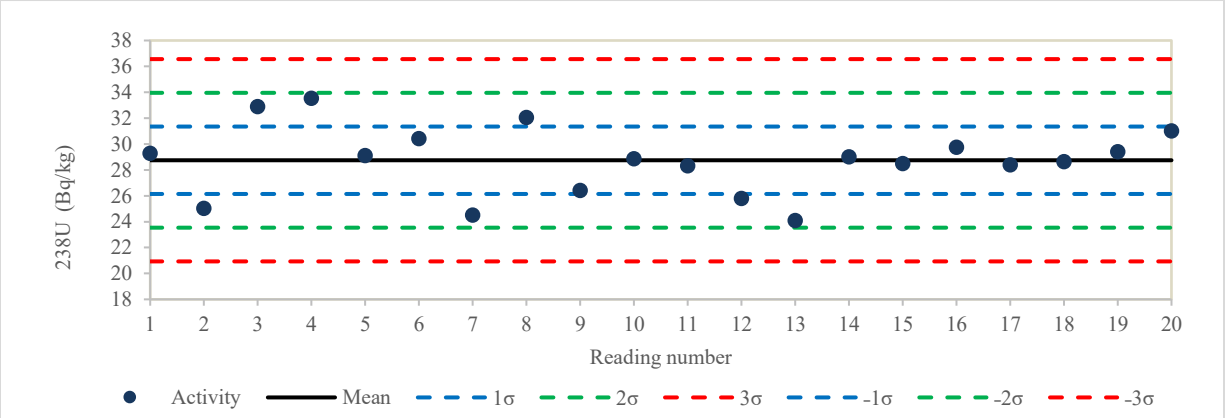

Figure 4 ^{238}U Radioactivity (Bq/kg) measured in IAEA-385

Robustness

The method's robustness was demonstrated through consistent performance across different CRMs. The performance of this method using IAEA-385 has been discussed under the accuracy parameter. The u-scores obtained for IAEA-384, as shown in Table 2, were 0.38, 0.78, and 0.72 for ^{234}U, ^{235}U, and ^{238}U, respectively, demonstrating statistically acceptable agreement with certified values and confirming the reliability of the radiochemical separation procedure across different environmental matrices.

Ruggedness

While robustness focuses on internal factors (such as sample composition) that affect method performance, ruggedness assesses how well a method performs across variations introduced by external factors. These conditions can include different laboratories, different analysts, different instruments, reagent lots, elapsed assay times, temperatures, and days.

The ruggedness of the method was assessed using CRM IAEA-385 by comparing results obtained independently by three analysts (TMZ, NAZ, and FTN). The detailed inter analyst results are presented in Table 3. The calculated u-scores for all analysts were below 1.64, demonstrating agreement within acceptable limits and confirming the method's reproducibility across operators.

Table 3 Uranium radioactivity value reported by different analysts

No of replicates	**^{234}U lab value (Bq/kg)**		
	Analyst TMZ	**Analyst NAZ**	**Analyst FTN**
1	28.23±3.62	28.96±4.4	32.28±3.93
2	26.26±3.16	24.64±3.85	32.25±4.12
3	28.16±3.29	28.49±4.49	31.82±3.93
4	27.52±3.85	26.8±4.43	32.1±3.81
5	27.93±3.99	28.35±5.31	31.68±3.83
6	28.44±4.26	29.18±5.25	25.68±3.71
7	27.68±4.11	25.42±4.79	
Mean (Bq/kg)	**27.75±3.75**	**27.41±4.65**	**30.97±3.89**
U score	**0.14**	**0.04**	**0.93**
Z score	**0.75**	**0.11**	**1.45**

No of replicates	**^{235}U lab value (Bq/kg)**		
	Analyst TMZ	**Analyst NAZ**	**Analyst FTN**
1	1.26±0.96	2.57±1.2	2.38±0.91
2	1.34±1.01	2.62±1.17	2.03±0.94
3	1.45±0.77	2.66±1.27	2.17±0.9
4	1.28±1.7	2.01±1.2	2.06±0.79
5	1.43±1.55	3.39±1.94	1.29±0.73
6	1.33±1.69	1±1.42	1.06±0.89
7	0.75±1.08	3.21±1.79	

Mean (Bq/kg)	**1.26±1.25**	**2.49±1.43**	**1.83±0.86**
U score	**0.08**	**0.79**	**0.54**
Z score	**0.41**	**1.42**	**0.89**

No of replicates	**^{238}U lab value (Bq/kg)**		
	Analyst TMZ	**Analyst NAZ**	**Analyst FTN**
1	29±3.73	29.27±4.4	33.36±4.04
2	28.5±3.27	25.02±3.85	24.93±3.47
3	29.74±3.49	29.1±4.51	25.19±3.35
4	28.38±3.91	32.9±5.07	25.25±3.2
5	28.65±4.1	28.85±5.29	25.38±3.29
6	29.41±4.4	25.8±4.76	25.15±3.63
7	31.01±4.37	26.41±4.84	
Mean (Bq/kg)	**29.24±3.90**	**28.19±4.67**	**26.54±3.50**
U-score	**0.04**	**0.25**	**0.77**
Z score	**0.17**	**0.45**	**0.85**

CONCLUSION

The developed method for the determination of ^{234}U, ^{235}U, and ^{238}U in environmental samples demonstrated satisfactory performance with respect to the evaluated validation parameters. Evaluation using IAEA-certified reference materials (IAEA-385 and IAEA-384) confirmed acceptable selectivity, accuracy, precision, repeatability, and robustness under the applied conditions. The calculated u-scores and z-scores met the established acceptance criteria, indicating no statistically significant deviation from the certified values and confirming the method's accuracy and reliability. Precision assessment based on RSD values demonstrated consistent performance, with variability for ^{235}U attributable to counting statistics associated with its lower activity concentration. The method's ruggedness was further verified through consistent results obtained by different analysts. Although the present validation demonstrates strong analytical performance, additional studies are recommended to further evaluate parameters such as LOD, LOQ, and extended robustness testing. Overall, the validated method provides a reliable and standardized approach for uranium isotope determination in environmental matrices, supporting environmental monitoring and radiological assessment.

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