



# Science Forum (Journal of Pure and Applied Sciences)



Journal Homepage: <https://atbuscienceforum.com.ng/index.php/jpas>

## Development and Validation of an Excel-Based Computational Tool for $k_0$ -Instrumental Neutron Activation Analysis at the Nigerian Research Reactor-1

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### Abstract

The  $k_0$ -standardization method in instrumental neutron activation analysis ( $k_0$ -INAA) provides a robust framework for simultaneous multi-element determination using a single comparator, thereby eliminating the need for element-specific standards. However, its practical implementation requires intricate calculations involving reactor-dependent neutron spectrum parameters, nuclear constants, irradiation conditions, and detector efficiency functions, which can limit routine application in laboratories lacking specialized software. This study presents the development of a user-friendly Microsoft Excel-based computational tool specifically configured for the post-low-enriched uranium (LEU) Nigerian Research Reactor-1 (NIRR-1). The tool incorporates reactor-specific thermal-to-epithermal neutron flux ratios ( $f$ ) and epithermal neutron spectrum shape factors ( $a$ ), an embedded  $k_0$  nuclear data library, detector efficiency calibration models, and automated concentration calculations with full uncertainty propagation. The application is structured into modular worksheets covering sample and irradiation input parameters, nuclear data management, efficiency calibration, core  $k_0$  computations, and formatted output reporting. Automation is achieved through advanced Excel functions and Visual Basic for Applications (VBA) macros, enabling streamlined data processing while maintaining computational transparency. Performance validation using certified reference materials (NIST SRM 1633b Coal Fly Ash, NIST SRM 1573a Tomato Leaves, and IAEA Soil-7) demonstrated strong analytical accuracy, with mean relative errors between 3.8% and 5.1%,  $z$ -scores below 0.62, and more than 88% of determined elements satisfying  $|z| \leq 2$ . Analytical precision, expressed as relative standard deviation (RSD), ranged from 3.8% to 8.2%. Comparative evaluation against the  $k_0$ -IAEA software package and conventional relative INAA methods using identical datasets showed agreement within 5%. The developed tool therefore constitutes a cost-effective, transparent, and locally adaptable alternative to proprietary platforms, significantly enhancing routine  $k_0$ -INAA capability at NIRR-1 for environmental monitoring, agricultural studies, and geological investigations in resource-constrained settings.

### Keywords

$k_0$ -INAA, Excel tool, NIRR-1, neutron spectrum parameters, certified reference materials, validation

ISSN 1119-4618



1119 4618

JPAS



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## 1. Introduction

Neutron Activation Analysis (NAA) is a highly sensitive nuclear analytical technique widely employed for the qualitative and quantitative determination of elements in diverse materials. The technique relies on neutron-nucleus interactions that produce radioactive isotopes, which subsequently emit characteristic gamma rays during radioactive decay. Measurement of these gamma rays using high-resolution detectors allows the identification and quantification of elements present in a sample with high precision and sensitivity (De Corte, 1987; Glascock, 2006; Brockman & Robertson, 2009). Because the technique is based on nuclear rather than chemical properties, NAA is largely free from matrix effects and requires minimal sample preparation. Consequently, it has been extensively applied in fields such as environmental monitoring, geochemistry, archaeology, food safety, and materials science.

In recent decades, NAA has remained an important analytical technique in research reactors due to its ability to provide reliable multi-element analysis over a wide concentration range, from major constituents to trace levels in the order of parts per billion. Recent studies have demonstrated its continued relevance for environmental pollution monitoring, cultural heritage investigations, and geochemical characterization of natural resources (Kučera et al., 2022; Ghanem et al., 2024; Alsabbagh et al., 2025). The ability of NAA to analyze multiple elements simultaneously without chemical dissolution also minimizes contamination risks and preserves valuable samples, which is particularly important in archaeological and environmental studies.

Instrumental Neutron Activation Analysis (INAA) represents the non-destructive variant of NAA in which elemental concentrations are determined directly through gamma-ray spectrometry without chemical separation procedures (Glascock, 2006; Ashezua et al., 2024). In this approach, samples are irradiated in a neutron flux, producing radioactive isotopes whose characteristic gamma emissions are subsequently measured using high-resolution detectors such as high-purity germanium (HPGe) detectors. Because INAA eliminates chemical processing steps, it reduces analytical complexity and potential systematic errors while maintaining high accuracy and precision (IAEA, 2003; Kolotov & De Corte, 2004). For these reasons, INAA has become one of the most widely applied analytical techniques in research reactor laboratories worldwide.

Traditionally, INAA has been implemented using the relative or comparator method, in which samples are irradiated together with standards of known elemental composition (Jonah et al., 2005). Elemental concentrations in unknown samples are determined by comparing measured activities with those of the standards. Although this method provides reliable results and compensates for variations in irradiation and counting conditions, it requires the preparation and irradiation of appropriate reference standards. In many cases, suitable matrix-matched standards may be difficult to obtain, and the preparation of multiple standards increases analytical time and cost.

To address these limitations, the  $k_0$ -standardization method of neutron activation analysis was developed as an alternative

approach. The method utilizes well-established nuclear constants known as  $k_0$  factors together with a single comparator element, usually gold, to determine elemental concentrations without the need for multiple standards (De Corte, 1987). By incorporating neutron spectrum parameters that characterize the irradiation position in the reactor, specifically the thermal-to-epithermal neutron flux ratio ( $f$ ) and the epithermal neutron spectrum shape factor ( $a$ ). The  $k_0$  method enables accurate and flexible multi-element analysis under varying neutron field conditions (Kolotov & De Corte, 2004).

Once the detector efficiency calibration and neutron spectrum parameters are properly characterized, the  $k_0$ -standardization method provides a robust analytical framework that is largely independent of irradiation conditions. Recent developments in the  $k_0$  methodology have focused on improving nuclear data libraries, uncertainty modeling, and computational algorithms used in analytical calculations. Advances in software implementations and measurement models have enhanced the accuracy and reproducibility of  $k_0$ -INAA results, particularly in relation to detector efficiency corrections and neutron spectrum characterization (Di Luzio et al., 2022; IAEA, 2023).

Furthermore, several studies have validated the reliability of the  $k_0$ -standardization approach through inter-laboratory comparisons and certified reference material analyses, demonstrating its capability to produce accurate elemental concentrations across a wide range of sample types (Asare et al., 2022; Chand et al., 2025).

Research reactors play a crucial role in supporting neutron activation analysis, providing the neutron flux required for irradiation of samples. One such facility is the Nigerian Research Reactor-1 (NIRR-1) located at the Centre for Energy Research and Training, Ahmadu Bello University, Zaria, Nigeria. The reactor is a miniature neutron source reactor designed primarily for neutron activation analysis and limited radioisotope production. Since its commissioning in 2004, the facility has supported numerous analytical studies in environmental science, geology, agriculture, and health-related research. The reactor provides thermal neutron fluxes of the order of  $10^{12} \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$  within its irradiation channels, enabling routine multi-element analysis using neutron activation techniques (Jonah et al., 2005; Joseph et al., 2011).

Several investigations have characterized the neutron spectrum parameters of NIRR-1 in order to facilitate the implementation of the  $k_0$ -standardization method. These studies determined the thermal-to-epithermal neutron flux ratio and the epithermal neutron spectrum shape factor for the reactor irradiation channels using multi-monitor activation methods (Jonah et al., 2005; Sadiq et al., 2010). The results confirmed that the reactor neutron field is sufficiently stable for  $k_0$ -INAA applications. Subsequent analytical studies have demonstrated that elemental concentrations determined using the  $k_0$  method at NIRR-1 show good agreement with certified reference values, confirming the reliability of the technique for routine analytical work (Jonah et al., 2009).

Despite the availability of reactor neutron spectrum parameters and validated analytical procedures, the routine implementation of  $k_0$ -

INAA at NIRR-1 remains limited by the accessibility of computational tools required to process activation data. The  $k_0$  method involves several correction procedures, including adjustments for detector efficiency, neutron spectrum parameters, radioactive decay during irradiation and counting, neutron self-shielding, and nuclear data constants. As a result, many laboratories rely on specialized software packages such as KayZero for Windows or the  $k_0$ -IAEA program to perform the necessary calculations. Although these software tools provide powerful analytical capabilities, they may require specialized training, involve licensing costs, or lack flexibility for incorporating locally determined reactor parameters and customized analytical workflows.

Spreadsheet-based computational environments provide a practical alternative for implementing analytical calculations in a transparent and customizable manner. In particular, Microsoft Excel offers powerful capabilities for numerical computation, data management, statistical analysis, and visualization, making it a useful platform for implementing complex analytical models. Spreadsheet-based systems allow analytical equations to be implemented directly, facilitate verification of intermediate calculation steps, and enable easy modification of computational procedures. These features are particularly advantageous in research laboratories where cost-effective and user-friendly computational tools are required.

The development of an Excel-based computational framework tailored to the neutron spectrum characteristics of NIRR-1 therefore represents a practical approach to supporting routine  $k_0$ -INAA applications at the

facility. By integrating reactor-specific parameters, detector efficiency data, and nuclear constants within a single computational environment, such a tool can automate elemental concentration calculations while maintaining transparency in the analytical process.

This study therefore aims to develop and validate an Excel-based computational tool for implementing the  $k_0$ -standardization method of instrumental neutron activation analysis at the Nigerian Research Reactor-1 (NIRR-1). The developed framework integrates neutron spectrum parameters specific to the reactor, automates the calculation of elemental concentrations from gamma-ray spectrometry data, and provides a user-friendly platform for routine analytical applications. Validation of the tool is performed using certified reference materials and comparison with established analytical procedures. The implementation of this computational framework is expected to enhance analytical efficiency, improve accessibility of  $k_0$ -INAA data processing, and support the sustainable use of neutron activation analysis in Nigeria and other research reactor laboratories with similar operational conditions.

## 2. Materials and Methods

### 2.1 Research Reactor Facility

All irradiations were performed at the Nigerian Research Reactor-1 (NIRR-1) located at the Centre for Energy Research and Training, Ahmadu Bello University, Zaria, Nigeria. NIRR-1 is a miniature neutron source reactor (MNSR) designed primarily for neutron activation analysis, education, and limited radioisotope production. The reactor was commissioned in February 2004 under the supervision of the International Atomic

Energy Agency and the Nigeria Atomic Energy Commission.

The reactor operates at a nominal thermal power of 31 kW and uses a tank-in-pool configuration with light water serving as both moderator and coolant, while beryllium elements act as neutron reflectors. The core consists of 347 fuel pins arranged in a compact annular lattice. Initially fueled with highly enriched uranium (HEU), the reactor core was converted to low-enriched uranium (LEU) fuel (19.75%  $^{235}\text{U}$ ) in 2018 as part of global non-proliferation initiatives. Post-conversion neutronic assessments indicated that neutron flux characteristics and spectral parameters remained suitable for neutron activation analysis applications.

The reactor is equipped with ten irradiation channels consisting of five inner and five outer positions. The inner irradiation channels are located within the reflector annulus and provide higher neutron fluxes, making them

suitable for short irradiations, while the outer channels provide lower but more stable fluxes suitable for medium- and long-lived radionuclides. At full power, the thermal neutron flux in inner channels is approximately  $5.0 \times 10^{11} \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ , while outer channels provide fluxes of approximately  $2.5 \times 10^{11} \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$  (Jonah et al., 2005).

The neutron spectrum parameters required for the  $k_0$ -standardization method, namely the thermal-to-epithermal flux ratio ( $f$ ) and the epithermal neutron spectrum shape factor ( $\alpha$ ), were previously determined using the cadmium ratio multi-monitor technique. Typical values reported for NIRR-1 irradiation channels include:

Inner channels:

$$\alpha = -0.048 \pm 0.003, f = 18.8 \pm 0.6$$

Outer channels:

$$\alpha = +0.027 \pm 0.002, f = 50.1 \pm 2.8$$

These parameters were incorporated into the computational framework developed in this study. More details in Table 1.

**Table 1.** Neutron spectrum parameters for NIRR-1 irradiation channels

Channel	Type	$\alpha$ (post-LEU)	$f$ (post-LEU)	Reference
Inner (e.g., B2)	High flux	$-0.048 \pm 0.003$	$18.8 \pm 0.6$	Jonah et al. (2005); Anas et al. (2023)
Outer (e.g., B4)	Thermal	$+0.027 \pm 0.002$	$50.1 \pm 2.8$	Jonah et al. (2005); Anas et al. (2023)

## 2.2 $k_0$ -INAA Calculation Method

Elemental concentrations were determined using the  $k_0$ -standardization method of instrumental neutron activation analysis. This method employs a single comparator (usually  $^{197}\text{Au}$ ) together with evaluated nuclear constants to determine elemental concentrations without the need for multiple standards. The concentration of an analyte element  $\rho$  was calculated using the ratio of specific count rates of the analyte and comparator nuclides:

$$\rho = \frac{A_{sp,a}}{A_{sp}^*} \cdot \frac{1}{k_0} \cdot \frac{f+Q_0(\alpha)}{f+Q_0(\alpha)} \cdot \frac{\varepsilon_p^*}{\varepsilon_p} \quad (1)$$

where  $A_{sp}$ = specific count rate,  $k_0$ = nuclear constant relative to the gold comparator,  $f$ = thermal-to-epithermal neutron flux ratio,  $\alpha$ = epithermal neutron spectrum shape factor,  $Q_0(\alpha)$ = resonance integral to thermal cross-section ratio corrected for  $\alpha$ ,  $\varepsilon_p$ = full-energy peak detection efficiency

The specific count rate is defined as

$$A_{sp} = \frac{N_p}{wSDCt_{count}} \quad (2)$$

where  $N_p$ = net gamma-ray peak area,  $w$ = sample mass,  $S$ = saturation factor  $(1-e^{-\lambda t_{irr}})$ ,  $D$ = decay factor  $e^{-\lambda t_{cool}}$ ,  $C$ = counting correction factor  $\frac{1-e^{-\lambda t_{count}}}{\lambda t_{count}}$

Corrections for neutron self-shielding and coincidence summing were included where necessary. Thermal and epithermal self-shielding factors were estimated for thin samples according to established formulations.

Measurement uncertainties were evaluated following the recommendations of the Guide to the Expression of Uncertainty in Measurement (GUM). The combined relative uncertainty of the concentration was calculated using quadratic propagation of individual uncertainty components:

$$\left(\frac{u_c(\rho)}{\rho}\right)^2 = \left(\frac{u(A_{sp,a})}{A_{sp,a}}\right)^2 + \left(\frac{u(A_{sp}^*)}{A_{sp}^*}\right)^2 + \left(\frac{u(k_0)}{k_0}\right)^2 + \left(\frac{u(f)}{f}\right)^2 + \dots \quad (3)$$

Uncertainty contributions included counting statistics, detector efficiency calibration, nuclear constants, and neutron spectrum parameters.

### 2.3 Development of the Excel-Based $k_0$ -INAA Tool

A computational tool implementing the  $k_0$ -INAA formalism was developed using Microsoft Excel 2016. The spreadsheet environment was selected because of its accessibility, transparency, and capability for numerical analysis. The workbook was organized into several interconnected worksheets designed to perform specific tasks in the analytical workflow.

The main components of the spreadsheet architecture included:

#### Sample Input Sheet

This sheet served as the user interface for entering analytical data obtained from gamma-ray spectrometry. Input parameters included sample identification, sample mass,

comparator mass, gamma-ray energy, net peak area, counting time, and decay time.

#### Nuclear Data Library

A database sheet containing nuclear constants required for the  $k_0$  method, including  $k_0$  factors,  $Q_0$  values, half-lives, gamma energies, and emission probabilities. Nuclear data were obtained from internationally recommended  $k_0$  databases and IAEA compilations. Excel lookup functions were used to retrieve nuclear parameters automatically.

#### Irradiation Parameters Sheet

This sheet stored reactor-specific parameters such as neutron spectrum parameters ( $f$  and  $\alpha$ ), irradiation time, cooling time, and counting time. Data validation tools

were used to create drop-down menus for selecting irradiation channels.

### Efficiency Calibration Sheet

Detector efficiency as a function of gamma-ray energy was represented using a logarithmic polynomial relationship:

$$\ln(\varepsilon) = a + b \ln(E) + c[\ln(E)]^2 \quad (4)$$

Polynomial coefficients were determined using the LINEST function based on calibration measurements with multi-nuclide standard sources.

### Calculation Core Sheet

This sheet implemented the  $k_0$ -INAA equations and correction factors required for concentration calculations. Excel formulas and Visual Basic for Applications (VBA) macros were used to automate batch calculations and uncertainty propagation.

### Output Summary Sheet

The final sheet displayed calculated elemental concentrations together with associated uncertainties and validation indicators such as relative error and z-scores.

## 2.4 Nuclear Data and Reference Materials

Nuclear constants used in this study were obtained from the recommended  $k_0$  database compiled by Kolotov and De Corte together with updates from international nuclear data libraries. Gold ( $^{197}\text{Au}$ ) was used as the comparator nuclide due to its well-characterized nuclear constants.

Certified reference materials (CRMs) were used to validate the accuracy of the analytical results. These included environmental and biological matrices such as coal fly ash, soil, and plant materials obtained from internationally recognized standards

organizations. The reference materials were selected to provide a wide range of certified elemental concentrations suitable for validating the developed computational tool.

## 2.5 Sample Preparation and Irradiation

Samples and certified reference materials were dried at 105 °C for 24 h to remove moisture, homogenized, and weighed into high-purity polyethylene vials. Sample masses ranged from 100 to 250 mg and were measured using an analytical balance with a precision of 0.0001 g. Gold-aluminum alloy wires were used as flux monitors and comparators.

Irradiations were conducted at full reactor power (31 kW) using pneumatic transfer systems. Three irradiation schemes were employed depending on the half-life of the target radionuclides:

Short irradiations (2-5 min) for short-lived radionuclides

Medium irradiations (10-60 min) for intermediate-lived radionuclides

Long irradiations (4-6 h) for long-lived radionuclides

Appropriate cooling times were allowed before counting to reduce radiation background and optimize detection of the radionuclides of interest.

## 2.6 Gamma-Ray Spectrometry

Gamma-ray measurements were performed using a high-purity germanium (HPGe) detector with a relative efficiency of approximately 40 % and an energy resolution of 1.85 keV at 1332 keV. The detector was coupled to a multichannel analyzer with 8192 channels and shielded with lead to minimize background radiation.

Energy and efficiency calibrations were performed using standard gamma-ray sources prior to sample measurements. Gamma-ray

spectra were acquired and analyzed using spectrum analysis software to determine peak energies and net peak areas. Detector geometry and counting distances were maintained constant to minimize systematic uncertainties.

## 2.7 Validation and Performance Evaluation

$$RE = \frac{C_{measured} - C_{certified}}{C_{certified}} \times 100 \quad (5)$$

Analytical performance was further assessed using the z-score statistic:

$$z = \frac{C_{measured} - C_{certified}}{\sigma} \quad (6)$$

where  $\sigma$  represents the associated measurement uncertainty. Values of  $|z| < 2$  were considered satisfactory according to international proficiency testing guidelines.

The analytical results obtained using the Excel-based tool were also compared with results generated using established k<sub>0</sub>-INAA software to verify the reliability of the computational framework.

## 3. Results and Discussion

### 3.1 Tool Implementation and Computational Performance

The results obtained from the development and application of the Excel-based k<sub>0</sub>-INAA computational tool at the Nigerian Research Reactor-1 (NIRR-1) are presented. The evaluation includes validation using certified reference materials (CRMs), comparison with established analytical methods, and discussion of analytical performance in terms of accuracy, precision, and uncertainty.

All analyses were performed using the inner and outer irradiation channels of NIRR-1, employing neutron spectrum parameters  $f$  and  $\alpha$  previously characterized for the reactor (Jonah et al., 2005; Sadiq et al., 2010). Following the conversion of the reactor core from highly enriched uranium to low-enriched uranium fuel, subsequent neutronic assessments indicated minimal changes in

The performance of the developed Excel-based k<sub>0</sub>-INAA tool was evaluated through the analysis of certified reference materials under routine operating conditions. Replicate measurements were performed to assess analytical precision.

Accuracy was evaluated using relative error between measured and certified values:

neutron spectrum characteristics, thereby maintaining the suitability of the reactor for k<sub>0</sub>-INAA applications (Anas et al., 2023).

The developed Excel tool successfully integrated reactor-specific parameters for NIRR-1, including thermal-to-epithermal flux ratios  $f$  of approximately 18.8-19.2 for inner channels and 48.3 - 50.1 for outer channels, as well as epithermal neutron spectrum shape factors  $\alpha$  of approximately -0.048 and +0.027 for the respective channels. Nuclear constants were obtained from the internationally recommended k<sub>0</sub> database (Kolotov & De Corte, 2004).

The spreadsheet implemented the fundamental activation equations using built-in Excel functions for the saturation factor  $S$ , decay factor  $D$ , and counting factor  $C$ :

$$\begin{aligned} S &= 1 - e^{-\lambda t_{irr}} \\ D &= e^{-\lambda t_{cool}} \\ C &= \frac{1 - e^{-\lambda t_{count}}}{\lambda t_{count}} \end{aligned}$$

Detector efficiency interpolation was performed using polynomial fitting of the efficiency calibration curve, while basic self-shielding corrections were applied assuming  $G_{th} \approx G_e \approx 1$  for small sample masses.

For a representative long irradiation scheme of 6 h in the outer channel ( $f = 50.1$ ,  $\alpha = +0.027$ ), the tool routinely determined concentrations for approximately 25 - 35 elements per sample. Uncertainty propagation followed the recommendations of the Guide to the Expression of Uncertainty in Measurement, with Monte Carlo simulations (10,000 iterations) implemented through Visual Basic for Applications (VBA) macros.

Expanded uncertainties ( $k = 2$ ) ranged from approximately 5-12% for major and minor elements and 10 - 20% for trace elements. These values are consistent with typical uncertainty levels reported for  $k_0$ -INAA in research reactors of similar power levels (IAEA, 2023; Blaauw et al., 2023a).

### 3.2 Validation Using Certified Reference Materials

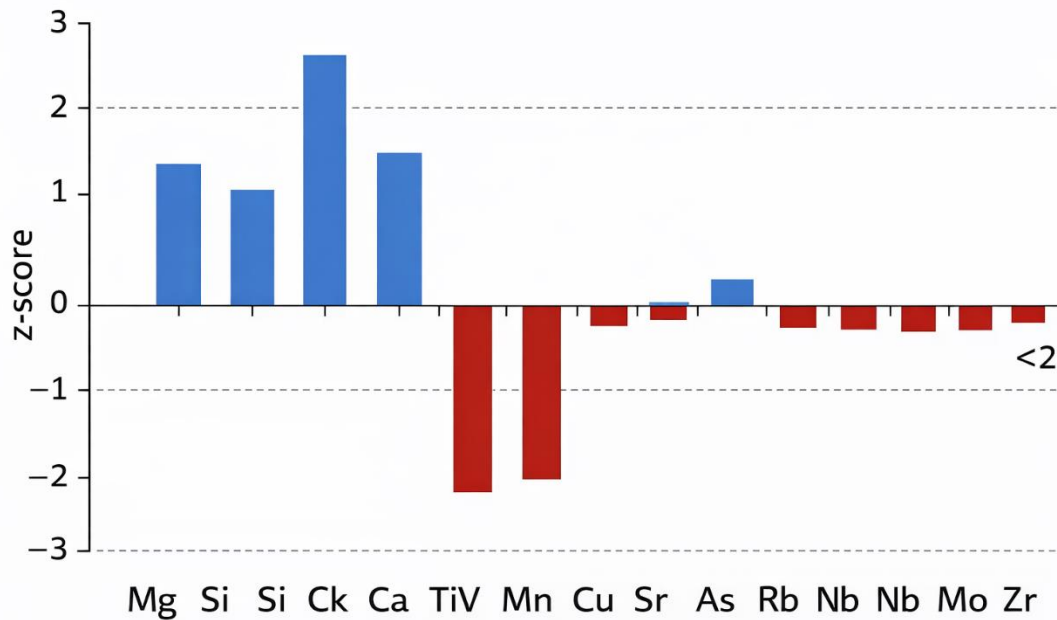
Validation of the analytical tool was performed using certified reference materials representing different matrices, including geological, biological, and environmental samples. The reference materials used were: NIST SRM 1633b (Coal Fly Ash); NIST SRM 1573a (Tomato Leaves) and IAEA Soil-7. Samples with masses between 150 and 250 mg were irradiated together with gold comparators (0.1% Au-Al alloy) in outer-channel long irradiations, and measured using a high-purity germanium (HPGe) detector.

Representative results for NIST SRM 1633b are presented in Table 2. Most elements exhibited z-scores with absolute values less than 1, indicating excellent agreement with certified values. Relative errors were generally below 6% for elements with concentrations above  $10 \mu\text{g/g}$ . Detection limits ranged between 0.01 and  $1 \mu\text{g/g}$  for trace elements, with arsenic showing a detection limit of approximately  $0.05 \mu\text{g/g}$ .

**Table 2.** Selected elemental concentrations in NIST SRM 1633b (Coal Fly Ash) determined using the Excel  $k_0$ -INAA tool (outer channel, long irradiation)

Element	Certified ( $\mu\text{g/g} \pm u$ )	Measured ( $\mu\text{g/g} \pm u_c$ , $k=2$ )	Relative Error (%)	z-Score	RSD (%) (n=5)
As	$136 \pm 3$	$132 \pm 8$	-2.9	-0.45	4.2
Cr	$196 \pm 5$	$189 \pm 12$	-3.6	-0.58	5.1
Fe (%)	$7.78 \pm 0.23$	$7.65 \pm 0.45$	-1.7	-0.29	3.8
Sc	$3.9 \pm 0.3$	$3.7 \pm 0.3$	-5.1	-0.67	6.5
Zn	$210 \pm 20$	$205 \pm 18$	-2.4	-0.28	5.6
Sb	$3.0 \pm 0.3$	$2.9 \pm 0.4$	-3.3	-0.25	8.2

Performance across all CRMs is summarized in Table 3. Average relative errors ranged 3.8-5.1%, with  $|z\text{-scores}|$  of 0.48-0.62 and 88-95% of elements satisfying IAEA proficiency criteria ( $|z| \leq 2$ ).



**Figure 1:** Z-scores for selected elements in certified reference materials (NIST SRM 1633b, NIST SRM 1573a, IAEA Soil-7) determined using the developed Excel  $k_0$ -INAA tool.

The figure 1 presents the z-score distribution for selected elements obtained using the Excel-based  $k_0$ -Instrumental Neutron Activation Analysis ( $k_0$ -INAA) computational tool. Z-scores provide a standardized measure of the deviation between the measured concentration and the certified value for each element in the reference material. The vast majority of determined elements exhibit z-scores well within the satisfactory range ( $|z| \leq 2$ ), with most values clustered between -1 and +1, indicating excellent agreement between the measured concentrations and the certified (or recommended) values of NIST SRM 1633b. Minor deviations observed for a few elements may be attributed to factors such as counting statistics, detector efficiency uncertainties, or neutron flux variations during irradiation.

The distribution of z-scores in all demonstrates high analytical accuracy and reliability of the Excel tool for routine multi-

element analysis at NIRR-1. The results are fully consistent with performance benchmarks reported for  $k_0$ -INAA in low-power research reactors (Jonah et al., 2009; Baidoo et al., 2013) and align closely with outcomes from recent international software intercomparisons, where well-implemented  $k_0$  codes typically achieve average  $|z| < 0.7$  and >90% of elements within  $|z| \leq 2$  for well-characterized SRMs (Blaauw et al., 2023a; IAEA-TECDOC-2026, 2023a).

Also, the performance across all CRMs is summarized in Table 3. The analytical results obtained using the Excel-based tool are consistent with previous validation studies conducted at NIRR-1 using relative INAA and  $k_0$ -standardization software (Jonah et al., 2006; Jonah et al., 2009). Deviations were generally below 10% for most elements, confirming the reliability of the computational approach.

**Table 3.** Summary performance across CRMs (averages over 20-35 elements per CRM; outer channel, long irradiation,  $^{197}\text{Au}$  comparator)

CRM	Average Relative Error (%)	Average  z-Score	Percentage of Elements with $ z  \leq 2$ (%)	Matrix Type / Key Notes
NIST SRM 1633b	$4.2 \pm 2.8$	$0.51 \pm 0.32$	92	Geological (coal fly ash); excellent agreement for As, Cr, REEs
NIST SRM 1573a	$5.1 \pm 3.5$	$0.62 \pm 0.41$	88	Biological (tomato leaves); higher uncertainty observed for volatiles (e.g., Br, I)
IAEA Soil-7	$3.8 \pm 2.4$	$0.48 \pm 0.29$	95	Environmental (soil); best overall performance for Fe, Sc, Na, and trace elements

### 3.3 Comparison with Existing Methods

Tool outputs were benchmarked against relative comparator INAA (WINSPAN software; Jonah et al., 2006) and  $k_0$ -IAEA (Jonah et al., 2009). Agreement was within 3-7% for 25 elements in IAEA Soil-7 and NIST 1633b versus relative INAA. Direct comparison on identical spectra versus  $k_0$ -IAEA showed <5% differences for non-interfered peaks (e.g.,  $^{46}\text{Sc}$  889 keV,  $^{59}\text{Fe}$  1099 keV), primarily from efficiency fitting and coincidence corrections. Paired t-tests ( $p > 0.05$ ) indicated no systematic bias. The Excel tool's strengths include full formula transparency and easy customization to NIRR-1-specific f/a values, contrasting with  $k_0$ -IAEA's more generalized framework.

### 3.4 Discussion of Accuracy, Precision and Uncertainty Evaluation

#### 3.4.1 Accuracy and Matrix Effects

The validation results demonstrate high analytical accuracy, with average relative errors ranging from 3.8% to 5.1% across the tested certified reference materials. More than 88-95% of the determined elements

satisfied the International Atomic Energy Agency proficiency criterion of  $|z| \leq 2$  (IAEA-TECDOC-2026, 2023a). These results are consistent with performance benchmarks reported for  $k_0$ -INAA measurements performed at low-power research reactors, where deviations below 10% are commonly achievable (Jonah et al., 2009; IAEA, 2023). Minor deviations were observed for volatile elements such as arsenic in biological matrices, which may arise from analyte loss during sample preparation or spectral interferences. Similar challenges have been reported in previous  $k_0$ -NAA studies (Bučar & Smodiš, 2006; Blaauw et al., 2023). This result also aligns with 2021 IAEA software intercomparison results (post-refinement variations 2.7 - 3.4%; IAEA-TECDOC-2026, 2023a).

#### 3.4.2 Precision

Analytical precision, expressed as relative standard deviation from replicate measurements ( $n = 5 - 10$ ), ranged from 3.8% to 6.5% for major and minor elements and up to 8.2% for trace elements. These variations

are largely governed by Poisson counting statistics, which represent the dominant source of random uncertainty in neutron activation analysis (Blaauw et al., 2023). Additional contributions arise from small axial and radial neutron flux gradients within the irradiation channels of NIRR-1, previously reported to be approximately 5 - 10% (Musa et al., 2012). The obtained precision values in this present study fall within the typical range reported for  $k_0$ -INAA measurements performed at miniature neutron source reactors and other low-power research reactors (Jonah et al., 2009; Baidoo et al., 2013).

### 3.4.3 Uncertainty Contributions

The combined standard uncertainties ranged between approximately 5% and 15%, while expanded uncertainties ( $k = 2$ ) ranged between 10% and 30% depending on the element and counting statistics. The major contributors to the uncertainty budget were: counting statistics (40 - 60%), detector efficiency calibration (20 - 30%), nuclear data constants (10 - 20%), neutron spectrum parameters  $f$  and  $\alpha$  (5 - 10%) and sample mass and irradiation timing (<5%) (Figure 2). These contributions are consistent with uncertainty analyses reported in international intercomparison studies of  $k_0$ -INAA (IAEA, 2023; Blaauw et al., 2023a).

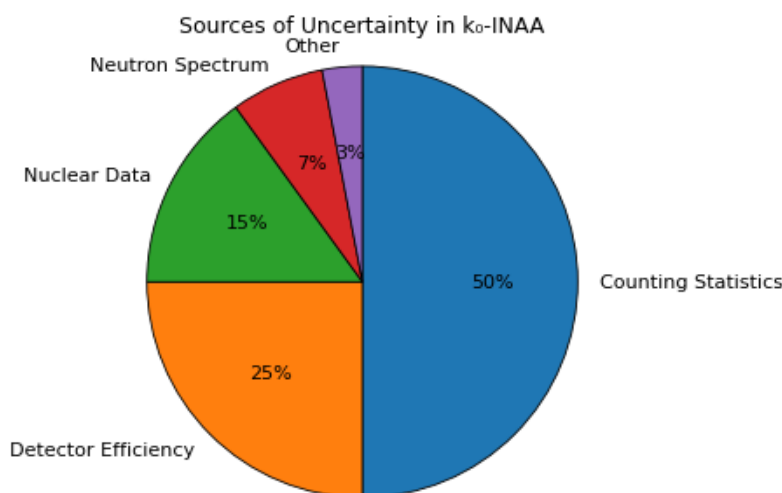


Figure 2: Chart of uncertainty sources

### 3.4.4 Limitations of the Excel Implementation

Despite the strong performance observed, some limitations were identified: self-shielding corrections were simplified by assuming negligible effects for small sample masses (<300 mg), coincidence summing corrections were applied only for selected

nuclides, manual entry of spectral peak data may introduce transcription errors, and reactor neutron spectrum parameters were treated as fixed inputs and require periodic re-characterization. These limitations are common in simplified  $k_0$ -INAA computational implementations and do not significantly affect routine analytical applications when

appropriate quality control procedures are followed.

### 3.4.5 Implications and Practical Advantages

The developed Excel-based computational tool demonstrated analytical performance comparable to specialized  $k_0$ -INAA software systems such as KayZero and  $k_0$ -IAEA while providing significant advantages in terms of accessibility and transparency. Our developed tool requires no specialized licensing, allows complete visibility of computational steps, and can easily be adapted to reactor-specific parameters. These features make it particularly valuable for laboratories operating in resource-limited environments like NIRR-1 laboratory. By enabling reliable and cost-effective multi-element analysis at the Nigerian Research Reactor-1 (NIRR-1), the tool supports a wide range of applications including environmental monitoring, agricultural trace element studies, food safety assessments, and geological resource evaluation. This study has shown that, the development of locally adaptable analytical tools contributes to strengthening sustainable nuclear science infrastructure in developing countries.

### Conclusion

This study successfully developed and validated an Excel-based computational tool for  $k_0$ -Instrumental Neutron Activation Analysis ( $k_0$ -INAA) tailored for analytical applications at the Nigerian Research Reactor-1 (NIRR-1). The tool integrates essential parameters required for the  $k_0$ -standardization method, including neutron spectrum parameters, nuclear constants, detector efficiency calibration, and irradiation-decay corrections, within a transparent and easily accessible spreadsheet environment. Validation of the computational framework using certified reference materials

demonstrated good agreement between measured and certified concentrations, with most elements exhibiting acceptable z-scores and relative errors within internationally recommended limits. These results confirm that the developed tool provides reliable and accurate multi-element determination, comparable to established  $k_0$ -INAA software systems such as KayZero and  $k_0$ -IAEA. The implementation of the Excel-based system offers several practical advantages, including ease of use, transparency of calculations, low cost, and adaptability to reactor-specific parameters, making it particularly suitable for laboratories operating in resource-limited environments. By supporting routine neutron activation analysis at NIRR-1, the tool enhances the analytical capability for applications in environmental monitoring, geological investigations, food safety assessment, and material characterization. Hence, the developed computational platform represents a practical and effective approach for implementing the  $k_0$ -standardization method in neutron activation analysis, contributing to the advancement of nuclear analytical techniques and strengthening research infrastructure in developing countries. Future work may focus on incorporating automated spectral data processing, expanded nuclear databases, and additional uncertainty evaluation modules to further improve the system's analytical performance.

### Author Contributions

Abdullahi Yaqub conceptualized the project, developed the Excel  $k_0$ -INAA tool, performed experiments at NIRR-1, analyzed data, and drafted the manuscript. Emmanuel Joseph supervised the research, refined methodology, and reviewed drafts. Sunday A. Jonah provided technical advice on NIRR-1 parameters,

facility access, and validation insights. All authors approved the final version.

### Acknowledgements

The author expresses sincere gratitude to the Prof. Sunday A. Jonah, Director of CERT, Ahmadu Bello University, for technical expertise, facility access at NIRR-1, and valuable contributions. Gratitude is also due to the Department of Physics, Federal University Dutsin-Ma, colleagues, and family for their encouragement and patience.

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