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Modeling K-40 transfer from aquatic ecosystems to aquatic biota using the ERICA Tool

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Modeling K-40 transfer from aquatic ecosystems to aquatic biota using the ERICA Tool

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Abstract. The environmental radiological risk assessment following the release of naturally occurring radioactivity associated with potassium-40 (K-40) requires the quantification of activity concentrations in environmental media and reference organisms. The methodology adopted by the ERICA Integrated Approach involves the application of concentration ratios (CR values) and distribution coefficients (K_d values) for aquatic ecosystems. In this study, we describe the methodologies used to derive the experimental transfer parameters for the seawater column and marine sediments, compiled into spreadsheets with their respective units ($Bq.L^{-1}$ and $Bq.kg^{-1}$), using the ERICA Tool databases to ensure transparency and traceability throughout the documentation process. Detailed information is provided on the concentration ratio (CR) values applied to marine ecosystems, including those for the seawater column and marine sediments. A total of 16 mean CR values were derived for the marine ecosystem based on the marine water system. For aquatic system categories in which empirical data were unavailable, CR values were estimated by substituting data from taxonomically related organisms or biogeochemically analogous elements.

Keywords: Radioecology · Potassium-40 · Aquatic biota · ERICA Tool · Environmental assessment · Environmental assessment.

1 Introduction

The Sustainable Development Goals (SDGs) were established by the United Nations (UN) in 2015 as part of the 2030 Agenda, a global framework aimed at promoting sustainable development [17]. The 2030 Agenda comprises 17 Sustainable Development Goals (SDGs) and 169 targets designed to foster sustainable social, economic, and environmental development by 2030 through poverty eradication, inequality reduction, and the protection of natural resources [8, 11].

The 17 SDGs encompass global objectives related to poverty eradication (SDG 1), food security (SDG 2), health and well-being (SDG 3), quality education (SDG 4), gender equality (SDG 5), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation, and infrastructure (SDG 9), reduced inequalities (SDG 10), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), conservation of aquatic ecosystems (SDG 14), protection of terrestrial biodiversity (SDG 15), peace, justice, and strong institutions (SDG 16), and partnerships for the goals (SDG 17).

The context of this study, three SDGs are particularly relevant. SDG 7 promotes sustainable, secure, and efficient energy systems, including the modernization of energy technologies and the expansion of access to low-carbon energy sources [7, 12, 16]. SDG 13 emphasizes the integration of climate change mitigation and adaptation strategies, in which nuclear energy can contribute by reducing greenhouse gas emissions [2, 3]. SDG 14 is directly associated with the conservation and sustainable use of marine ecosystems, highlighting the importance of radioecological monitoring for assessing potential environmental impacts and supporting the sustainable management of coastal zones [4, 19].

Exposure of non-human biota to ionizing radiation has been extensively investigated within the framework of environmental radiological protection over the past decades [10, 15, 23]. Among naturally occurring radionuclides, potassium-40 (K-40) is of particular interest because of its ubiquitous distribution in natural ecosystems and its contribution as one of the principal sources of natural radiation exposure for both humans and other living organisms [1, 5, 20, 24].

The Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA Tool) is a widely adopted software platform for environmental radiological risk assessment of non-human biota inhabiting terrestrial, freshwater, and marine ecosystems [**?**, 9, 13]. The assessment methodology is structured into three successive tiers (Tier 1, Tier 2, and Tier 3), each providing an increasing level of refinement in exposure and risk assessment.

In the present study, the ERICA Tool was applied at the Tier 2 assessment level to estimate the transfer of the naturally occurring radionuclide K-40 from environmental media to marine biota in the Piraquara de Fora coastal region, Angra dos Reis, Rio de Janeiro, Brazil. Site-specific input data were incorporated

into the model, including K-40 activity concentrations measured in the seawater column and marine sediments, together with marine reference organisms and radioecological parameters available in the ERICA database.

Furthermore, the modeling approach enabled the estimation of predicted activity concentrations in marine organisms, internal, external, and total absorbed dose rates, as well as the corresponding risk quotients (RQs). The predicted dose rates were compared with the 10 μGy.h^{-1} screening dose rate adopted by the ERICA Tool to evaluate the potential radiological effects of K-40 on marine biota. The results provide scientific support for environmental radiological protection and sustainable management of coastal ecosystems influenced by nuclear activities.

2 Materials and methods

2.1 Study area

The study area comprises the Piraquara de Fora region located in the Ilha Grande Bay, Angra dos Reis, Rio de Janeiro state, Brazil. This region was selected because it represents an area potentially influenced by the discharge of cooling effluents from the Angra I and Angra II nuclear reactors of the Almirante Álvaro Alberto Nuclear Power Plant (AAANPP), operated by Eletronuclear.

The local hydrodynamics are predominantly controlled by low-velocity tidal currents. However, the high discharge flow rate from the cooling systems, estimated at approximately 120 m^3.s^{-1}, modifies the natural water circulation patterns, promoting the resuspension and transport of fine sediments within the area [6].

2.2 Surface sediment and water sampling

Based on these environmental characteristics, eight georeferenced sampling sites (UTN01 to UTN08) were established in the Piraquara de Fora region (Fig. 1). Surface sediment samples were collected using a Van Veen grab sampler, targeting the upper 10 cm sediment layer (with approximately 3 kg of sediment collected per sampling site).

For the collection of surface water, the sampling container (a plastic bottle with an approximate volume of 1 L) was submerged with the opening facing downward before sediment collection, until reaching a depth of approximately 20 cm below the water surface.

The sediment samples (after approximately 30 days of storage to achieve secular equilibrium) and the water column samples (stored in 1 L plastic bottles) were subjected to laboratory analyses for the determination of K-40 radionuclide activity concentrations in the water column. These data were subsequently used in the transfer modeling to aquatic organisms using the ERICA Tool.

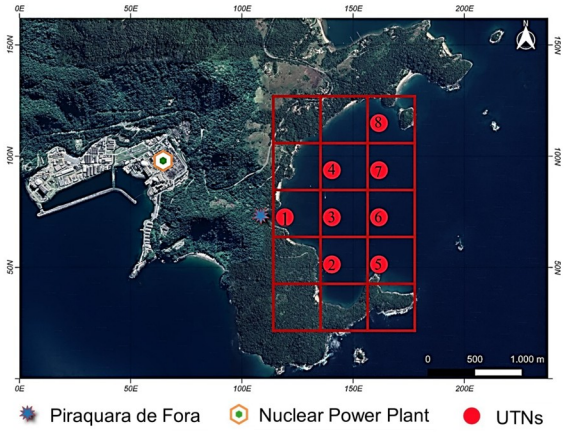


Fig. 1. Location of the Almirante Álvaro Alberto Nuclear Power Plant and the Piraquara de Fora inlet sampling points (UTN-01: S23°00'45.0", W44°26'38.4"; UTN-02: S23°01'01.4", W44°26'21.6"; UTN-03: S23°00'44.3", W44°26'21.8"; UTN-04: S23°00'27.7", W44°26'21.9"; UTN-05: S23°01'00.8", W44°26'03.8"; UTN-06: S23°00'43.9", W44°26'04.2"; UTN-07: S23°00'27.6", W44°26'04.7"; UTN-08: S23°00'11.9", W44°26'04.3"). The map was generated using the Quantum Geographic Information System (QGIS, version 3.30.2-'s-Hertogenbosch), with GIS data obtained from the Brazilian Institute of Geography and Statistics.

2.3 Analytical methods

The marine sediment samples were initially dried in an oven at 80 °C for approximately 24 h until reaching constant mass. After drying, the samples were disaggregated and ground using a mortar and pestle until complete homogenization. Subsequently, the material was transferred into 300 mL plastic containers and stored for a sufficient period to establish secular equilibrium between the radionuclides of the natural decay series [21, 22].

Seawater samples were collected and stored in 1 L plastic bottles, remaining sealed until radiometric analyses were performed. The determination of the natural radionuclide K-40 activity in sediment and aquatic matrices was carried out by high-resolution gamma-ray spectrometry at the Gamma Spectrometry Laboratory (LSG)[6] of the Institute of Radioprotection and Dosimetry (IRD/CNEN), Rio de Janeiro, Brazil.

The measurements were performed using detection systems equipped with high-purity germanium (HPGe) detectors manufactured by Canberra Industries (Meriden, CT, USA), model BE5030.

[6] The LSG regularly participates in national and international intercomparison programs, achieving satisfactory results in the Mixed Analyte Performance Evaluation Program (MAPEP) conducted by the United States Department of Energy (US-DOE), as well as in exercises organized by the LNMRI/CNEN.

The activity concentration of K-40 was determined from the net area of the photopeak corresponding to the gamma-ray energy of 1460.8 keV. The counting time for both samples and background radiation measurements was 60,000 s, aiming to minimize uncertainties associated with the spectrometric background.

Efficiency calibration was performed using a multielemental standard solution containing gamma-emitting radionuclides in an aqueous matrix acidified with nitric acid. The standard was provided by the Brazilian Laboratory of Ionizing Radiation Metrology (LNMRI/CNEN), with metrological traceability linked to the Bureau International des Poids et Mesures (BIPM), France. Energy calibration of the detection systems was routinely performed using a certified Eu-152 source.

Activity concentrations and their associated uncertainties were calculated from the areas of the spectrometric peaks using the Genie™ 2000 software (Canberra Industries, USA). The reported uncertainties correspond to the statistical uncertainties associated with the counting of detected photons.

Analytical quality control was ensured through periodic analyses of certified reference material for soil (089/ERA), traceable to the National Institute of Standards and Technology (NIST), which was analyzed as a blind sample among the measurements of environmental samples.

2.4 Radioecological model for aquatic biota

The assessment of the transfer of the natural radionuclide K-40 to aquatic organisms was performed using the software ERICA Tool.

Initially, the selected environment was the marine ecosystem, representative of the coastal region of Piraquara de Fora, located within the area influenced by the Nuclear Power Plant. The radionuclide considered in the assessment was K-40, a naturally occurring radionuclide present in aquatic and sedimentary compartments.

The modeling was conducted using Tier 2 of the ERICA Tool, in which the experimentally determined activity concentrations in seawater were introduced as model input parameters, expressed in $Bq.L^{-1}$. Based on these data, the software estimated the transfer of the radionuclide to different environmental compartments and aquatic biota.

The reference organisms selected for the simulation were benthic fish, crustaceans, pelagic fish, phytoplankton, and zooplankton, representing different trophic levels and habitats within the marine ecosystem. For each organism, the geometries recommended by the ERICA Tool were adopted and applied in the dosimetric calculations to estimate internal and external exposures.

The environmental transfer of K-40 was estimated using the tabulated values of the distribution coefficient (K_d) and concentration ratio (CR) available in the software database. The distribution coefficient was used to establish the relationship between radionuclide concentrations in water and sediment, whereas the concentration ratios allowed the estimation of radionuclide uptake by organisms based on the concentrations present in the aquatic environment.

Absorbed dose rates were calculated using the ERICA Tool dosimetric model through the Dose Conversion Coefficients (DCCs), considering both external exposure contributions from water and sediments and internal exposure resulting from radionuclide incorporation by organisms. The total absorbed dose rate was obtained by summing the internal and external components and was expressed in μGy.h^{-1}.

The interpretation of the results was performed using the Risk Quotient (RQ), defined as the ratio between the estimated total dose rate for each organism and the screening value adopted by the ERICA Tool. In this study, the reference dose rate of 10 μGy.h^{-1} was applied, which is internationally recommended as a screening level below which significant detrimental radiological effects are not expected in populations of non-human organisms.

The simulation results indicated predicted K-40 activity concentrations of 100 Bq.kg^{-1} for benthic and pelagic fish, 50 Bq.kg^{-1} for crustaceans, 1,000 Bq.kg^{-1} for zooplankton, and 5,000 Bq.kg^{-1} for phytoplankton. The model also estimated activity concentrations of 11.0 Bq L^{-1} in seawater and 476 Bq.kg^{-1} (dry weight) in sediments.

3 Results and discussions

3.1 Radiological risk assessment for marine biota

The activity concentrations of the natural radionuclide K-40 measured in the environmental compartments were used as input parameters in the ERICA Tool to estimate radionuclide transfer and radiological exposure to marine reference organisms. The model considered the experimentally determined concentration in seawater (11 Bq.L^{-1}) and the sediment concentration (476 Bq.kg^{-1} dry weight) as environmental exposure sources.

The predicted K-40 activity concentrations in marine organisms showed considerable variation among the selected reference organisms (Table 1). The highest estimated concentration was observed for phytoplankton (5,000 Bq.kg^{-1} fresh weight), followed by zooplankton (1,000 Bq.kg^{-1} fresh weight), while fish and crustaceans exhibited lower predicted concentrations.

The descriptive statistical analysis of the predicted activity concentrations showed values ranging from 50 to 5,000 Bq.kg^{-1} fresh weight, with an average concentration of 1,250 Bq.kg^{-1} and a median value of 100 Bq.kg^{-1}. The high coefficient of variation (170.5%) reflects the heterogeneous distribution of K-40 among marine organisms due to physiological and ecological differences between taxonomic groups.

The radiological risk assessment results obtained using the ERICA Tool indicated that the total absorbed dose rates for the reference organisms ranged from 3.14 $\times$ 10^{2} to 2.65 $\times$ 10^{3} μGy.h^{-1}. Phytoplankton exhibited the highest total absorbed dose rate (2.65 $\times$ 10^{3} μGy.h^{-1}), followed by crustaceans (7.39 $\times$ 10^{2} μGy.h^{-1}), zooplankton (7.21 $\times$ 10^{2} μGy.h^{-1}), benthic fish (5.15 $\times$ 10^{2} μGy.h^{-1}), and pelagic fish (3.14 $\times$ 10^{2} μGy.h^{-1}).

Table 1. Activity concentrations of ^{40}K used and estimated by the ERICA Tool for environmental compartments and reference organisms of the marine ecosystem.

Compartment/Organism	AC (Bq.L^{-1})	AC (Bq.kg^{-1} fresh weight)	AC (Bq kg^{-1} dry weight)
Seawater	11	–	–
Sediment	–	–	476
Benthic fish	–	100	–
Crustacean	–	50	–
Pelagic fish	–	100	–
Phytoplankton	–	5,000	–
Zooplankton	–	1,000	–
Minimum	–	50	–
Maximum	–	5,000	–
Mean	–	1,250	–
Median	–	100	–
Standard deviation	–	2,131	–
Coefficient of variation (%)	–	170.5	–

AC = Activity Concentration.

The Risk Quotients (RQ), calculated as the ratio between the estimated dose rate and the screening value adopted by the model (10 μGy.h^{-1}), ranged from 3.14×10^{1} to 2.65×10^{2}. The highest value was observed for phytoplankton (RQ = 2.65×10^{2}), whereas the lowest value was recorded for pelagic fish (RQ = 3.14×10^{1}).

All evaluated organisms presented RQ values above 1, indicating that the estimated dose rates exceeded the screening benchmark of 10 μGy.h^{-1} adopted by the ERICA Tool for the protection of non-human biota.

The higher exposure estimated for phytoplankton is associated with its high capacity for the direct uptake and incorporation of dissolved K-40 from seawater due to its physiological functions related to cellular metabolic processes.

However, the estimated dose rate for phytoplankton corresponds to approximately 265% of the screening value adopted by the model, indicating that the contribution of naturally occurring K-40 represents a relevant exposure pathway within this compartment.

3.2 Comparison of dose rates with natural background radiation levels

The estimated dose rates remained below the natural background radiation levels reported for marine ecosystems [13, 14, 18]. Benthic fish exhibited an estimated dose rate of 5.15×10^{-2} μGy.h^{-1}, compared with the ERICA reference value of 1.90 μGy.h^{-1} (range: 0.68–31 μGy.h^{-1}). Similarly, pelagic fish showed a dose rate of 3.14×10^{-2} µμGy.h^{-1}, which is below the typical background value of 0.48 μGy.h^{-1} (range: 0.18–1.10 μGy.h^{-1}).

Phytoplankton exhibited the highest estimated dose rate (2.65×10^{-1} μGy.h^{-1}), which remained well below the typical natural background level of 2.50 μGy.h^{-1} (range: 0.94–30 μGy.h^{-1}). These results indicate that K-40 contributes only to natural background radiation and does not represent a significant radiological risk to marine biota.

3.3 Statistical analysis

Shapiro–Wilk normality test The Shapiro–Wilk normality test was performed using BioEstat 5.0 to evaluate the distribution of K-40 activity concentrations in seawater, marine sediments, and the dose rates estimated by the ERICA Tool. The histograms shown in Fig. 2 indicate a relatively homogeneous distribution of K-40 concentrations in the water column during 2022 and 2023, with low variability among the sampling sites. The natural radionuclide K-40

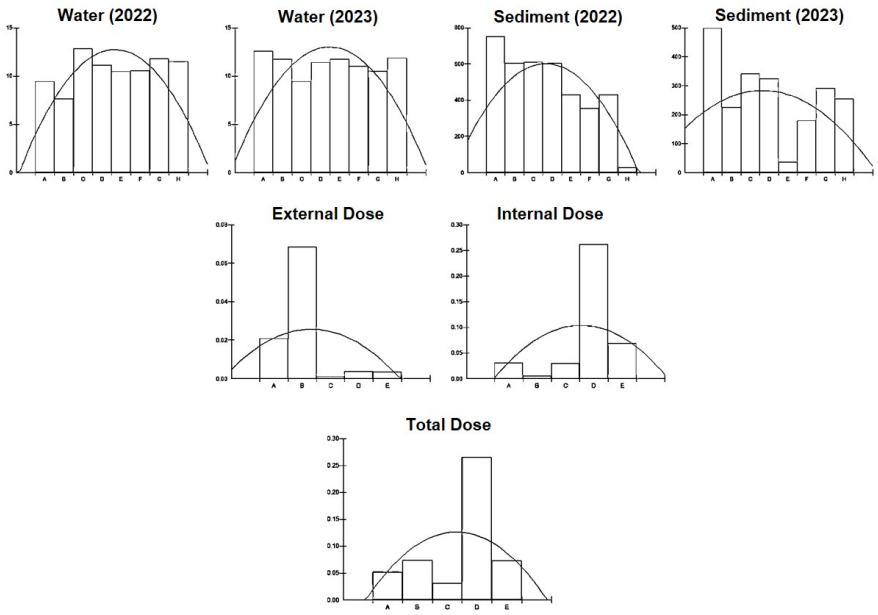


Fig. 2. Distribution of K-40 activity concentrations in seawater and marine sediments, and of the estimated radiological dose rates (external, internal, and total) for marine reference organisms used in the Shapiro–Wilk normality analysis.

exhibited the highest activity concentrations, with mean values of 10.66 $Bq.L^{-1}$ (2022) and 11.28 $Bq.L^{-1}$ (2023) in seawater. Higher activity concentrations were observed in marine sediments (476.20 and 268.38 $Bq.kg^{-1}$, respectively), consistent with the preferential accumulation of radionuclides in the particulate phase.

Statistical analysis began with the Shapiro–Wilk test to assess data normality. The K-40 activity concentrations in seawater did not reject the null hypothesis of normality ($W = 0.96$, $p = 0.74$; $W = 0.94$, $p = 0.56$), and the same pattern was observed for sediment concentrations ($W = 0.90$, $p = 0.36$; $W = 0.98$, $p = 0.93$).

In contrast, the estimated external, internal, and total dose rates deviated significantly from a normal distribution ($p = 0.037$, 0.035, and 0.025, respec-

tively), indicating that non-parametric statistical methods are more appropriate for these variables.

The results confirm that K-40 is the dominant natural contributor to radioactivity in seawater with activity concentrations within typical environmental background levels while the normal distribution of the seawater data supports the application of parametric statistical analyses for exposure assessment.

Pearson correlation analysis The Pearson correlation analysis ($n = 5$ paired observations) in Fig. 3, showed that the only statistically significant association was between the K-40 activity concentrations in seawater (2022) and the external dose rate, exhibiting a strong negative correlation (r = -0.88; 95% CI: -0.99 to -0.02; $p = 0.05$).

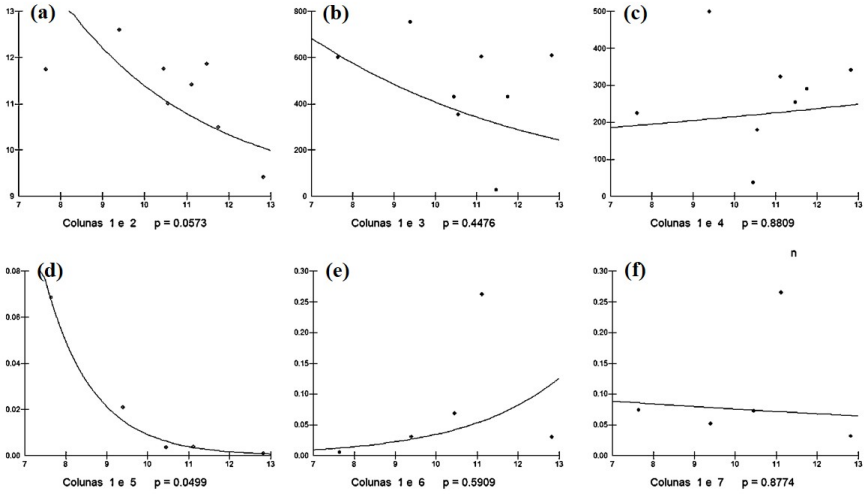


Fig. 3. Pearson linear correlation between the K-40 activity concentrations in seawater (2022) and the absorbed dose rates estimated by the ERICA Tool for marine reference organisms: (a) Column 1, Seawater (2022) vs. Column 2, Seawater (2023); (b) Column 1, Seawater (2022) vs. Column 3, Sediment (2022); (c) Column 1, Seawater (2022) vs. Column 4, Sediment (2023); (d) Column 1, Seawater (2022) vs. Column 5, External Dose Rate; (e) Column 1, Seawater (2022) vs. Column 6, Internal Dose Rate; and (f) Column 1, Seawater (2022) vs. Column 7, Total Dose Rate.

The coefficient of determination ($R = 0.77$) indicates that approximately 77% of the variability in the external dose rate can be explained by the K-40 activity concentration in seawater (2022).

All other correlations were not statistically significant ($p > 0.05$). The relationship between seawater activity concentrations measured in the two consecu-

tive sampling years showed a negative but non-significant correlation (r= -0.76; $p = 0.14$).

The correlations between seawater (2022) and sediment activity concentrations for both years were negligible ($p = 0.8$ and 0.9, respectively), as were those between seawater activity and the internal dose rate ($p = 0.6$) and the total dose rate ($p = 0.9$). In all cases, the confidence intervals were wide and included zero confirming the absence of significant linear associations.

The low statistical power (≤ 0.6 for $\alpha = 0.05$) reflects the limited sample size and reduces the ability to detect moderate correlations. Therefore, the results suggest that dissolved K-40 is not a consistent linear predictor of internal or total absorbed dose rates.

In Fig. 4, the Pearson correlation analysis using K-40 activity concentrations in seawater measured in 2023 ($n = 5$ paired observations) did not identify any statistically significant linear association with the other investigated variables ($p > 0.05$ for all comparisons).

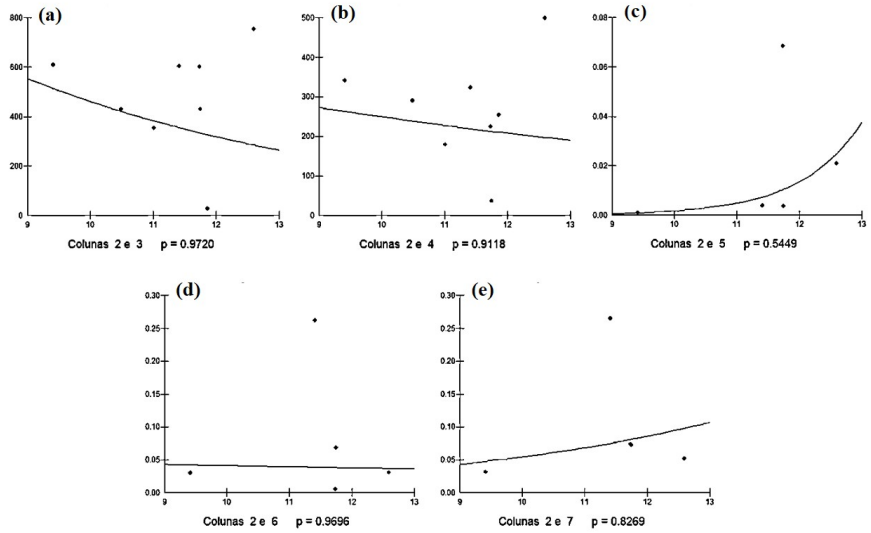


Fig. 4. Pearson linear correlation between the K-40 activity concentrations in seawater (2023) and the absorbed dose rates estimated by the ERICA Tool for marine reference organisms: (a) Column 2, Seawater (2023) vs. Column 3, Sediment (2022); (b) Column 2, Seawater (2023) vs. Column 4, Sediment (2023); (c) Column 2, Seawater (2023) vs. Column 5, External Dose Rate; (d) Column 2, Seawater (2023) vs. Column 6, Internal Dose Rate; and (e) Column 2, Seawater (2023) vs. Column 7, Total Dose Rate.

The correlation coefficients were consistently low: $r = 0.19$ (95% CI: -0.83 to 0.92; $p = 0.7$) for seawater (2023) versus sediment (2022); $r = 0.04$ (95% CI: -0.87 to 0.89; $p = 0.9$) versus sediment (2023); $r = 0.4$ (95% CI: -0.76 to 0.94;

$p = 0.5$) versus the external dose rate; $r = 0.02$ ($p = 0.97$) versus the internal dose rate; and $r = 0.14$ ($p = 0.8$) versus the total dose rate.

The corresponding coefficients of determination were very low ($R \leq 0.13$), while the 95% and 99% confidence intervals were broad and consistently included zero, confirming the absence of statistically significant linear relationships. The statistical power calculated for $\alpha = 0.05$ ranged from 0.05 to 0.13 and was even lower for $\alpha = 0.01$, reflecting the limited sample size (df = 3).

These results indicate that K-40 activity concentrations in seawater (2023) are not reliable linear predictors of external, internal, or total absorbed dose rates, nor of contemporary or previous sediment activity concentrations.

The significant negative correlation previously observed between seawater (2022) and the external dose rate (r = -0.879; p = 0.050) was not reproduced in the 2023 dataset, suggesting that the relationship between dissolved K-40 activity and external exposure is not temporally consistent.

Fig. 5, the Pearson correlation analysis involving K-40 activity concentrations in marine sediments collected in 2022 (n = 5 paired observations) identified only one statistically significant linear association: the correlation between sediment activity concentrations measured in 2022 and 2023 with $r = 0.97$ (95% CI: 0.60–1.00), $R = 0.94$, and $p = 0.0063$.

Approximately 94% of the variability in K-40 activity concentrations measured in marine sediments in 2023 was explained by the spatial distribution observed in 2022 ($R = 0.94$), indicating a high degree of temporal stability of K-40 in the sediment compartment.

99% confidence interval (0.25–1.00) was relatively wide due to the limited sample size confirming a strong positive relationship. The statistical power was high (0.90 for $\alpha = 0.05$ and 0.73 for $\alpha = 0.01$), supporting the robustness of this correlation.

In contrast, no statistically significant correlations were observed between 2022 sediment activity concentrations and the estimated dose rates. Correlation coefficients were $r = 0.21$ ($p = 0.7$) for the external dose rate, r = -0.11 ($p = 0.8$) for the internal dose rate, and r = -0.06 ($p = 0.9$) for the total dose rate.

Coefficients of determination were low ($R \leq 0.05$), and the confidence intervals included zero, indicating the absence of meaningful linear relationships between sediment K-40 activity and radiological dose rates.

The Pearson correlation analysis (Fig. 6) between K-40 activity concentrations in marine sediments (2023) ($n = 5$) and the dosimetric variables likewise revealed no statistically significant linear associations.

External dose rate Pearson correlation coefficient was r = -0.02 (95% CI: -0.89 to 0.88; $p = 0.98$), while values of $r = 0.01$ (95% CI: -0.88 to 0.88; $p = 0.98$) and $r = 0.01$ (95% CI: -0.88 to 0.88; $p = 0.99$) were obtained for the internal and total dose rates, respectively.

Coefficients of determination were negligible ($R \leq 0.0003$), confirming the absence of linear relationships between recent sediment K-40 activity and the estimated dose rates.

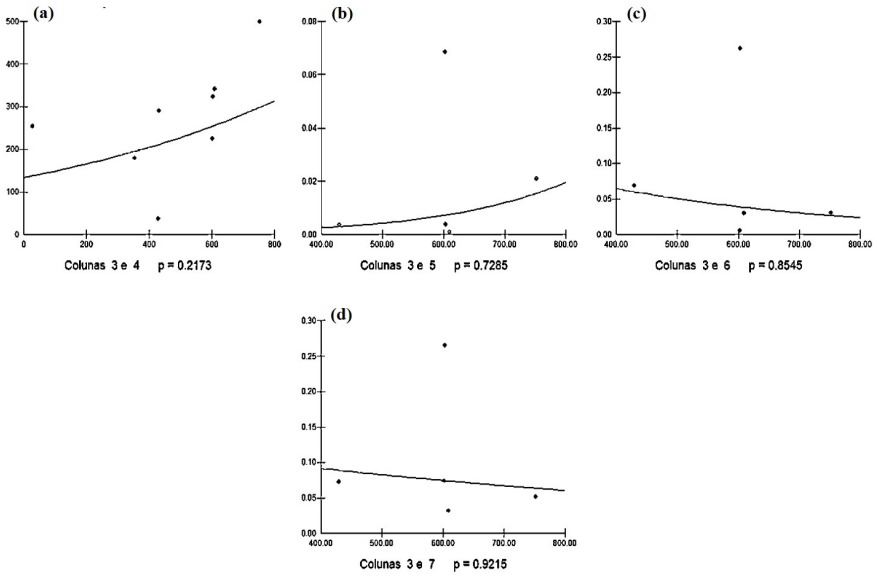


Fig. 5. Pearson linear correlation between the K-40 activity concentrations in marine sediments (2022) and the absorbed dose rates estimated by the ERICA Tool for marine reference organisms: (a) Column 3, Sediment (2022) vs. Column 4, Sediment (2023); (b) Column 3, Sediment (2022) vs. Column 5, External Dose Rate; (c) Column 3, Sediment (2022) vs. Column 6, Internal Dose Rate; and (d) Column 3, Sediment (2022) vs. Column 7, Total Dose Rate.

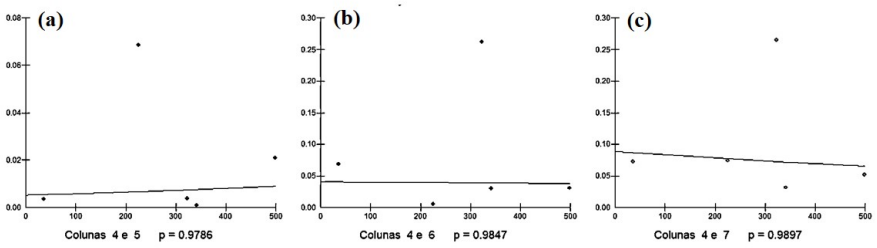


Fig. 6. Pearson linear correlation between the K-40 activity concentrations in marine sediments (2023) and the absorbed dose rates estimated by the ERICA Tool for marine reference organisms: (a) Column 4, Sediment (2023) vs. Column 5, External Dose Rate; (b) Column 4, Sediment (2023) vs. Column 6, Internal Dose Rate; and (c) Column 4, Sediment (2023) vs. Column 7, Total Dose Rate.

The limited sample size (df = 3) and low statistical power, the near-zero correlation coefficients and high p-values indicate that the lack of association is unlikely to be solely a consequence of insufficient statistical power.

Although a strong interannual correlation was observed between sediment K-40 activity in 2022 and 2023 (r = 0.97; p = 0.01), sediment activity was not a reliable linear predictor of radiological dose rates.

Pearson correlation analysis (Fig. 7) among the different absorbed dose components (n = 5) revealed no statistically significant linear relationships. The correlation between the external and internal dose rates was moderate and negative (r = -0.461; R = 0.2; p = 0.4), but it was not statistically significant.

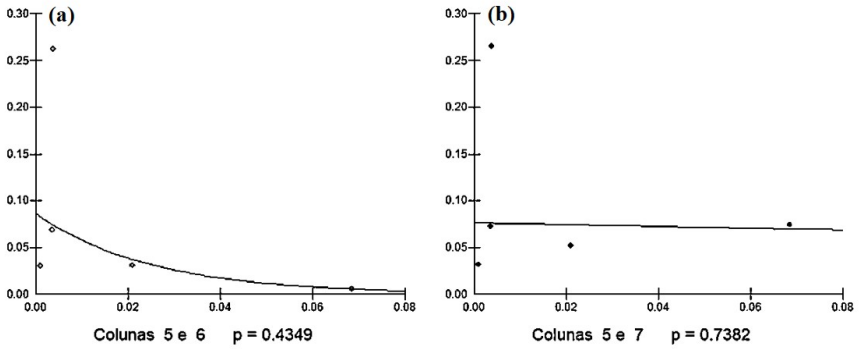


Fig. 7. Pearson linear correlation between the absorbed dose rates estimated by the ERICA Tool for marine reference organisms: (a) Column 5, External Dose Rate vs. Column 6, Internal Dose Rate; and (b) Column 5, External Dose Rate vs. Column 7, Total Dose Rate.

The wide confidence intervals, including zero, reflect the uncertainty associated with the limited sample size (df = 3) and do not support a robust inference of an inverse relationship. Correlation between the external and total dose rates was also weak (r = -0.2; R = 0.04; p = 0.7), indicating no significant linear association.

In contrast, the Pearson correlation between the internal and total dose rates (Fig. 8) revealed a very strong positive association (r = 0.96; 95% CI: 0.54–1.00; p = 0.01). The coefficient of determination (R = 0.93) indicates that approximately 93% of the variability in the total absorbed dose is explained by the internal dose rate demonstrating that internal exposure is the primary contributor to total radiological dose under the evaluated conditions.

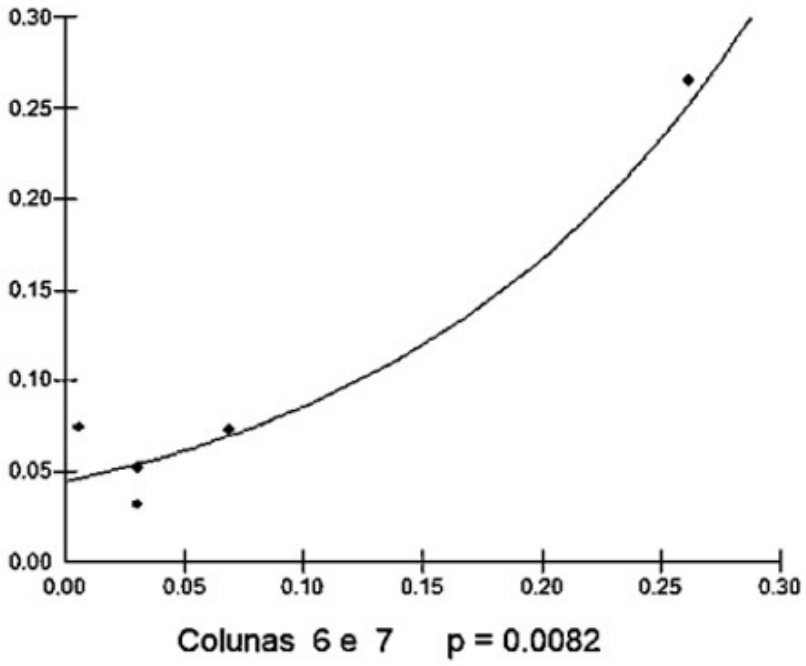


Fig. 8. Pearson linear correlation between the internal absorbed dose rate (Column 6) and the total absorbed dose rate (Column 7) estimated by the ERICA Tool for marine reference organisms.

4 Conclusion

The results demonstrate the temporal stability of sedimentary K-40 activity ($r = 0.97$; $p = 0.01$). A strong correlation between the internal and total absorbed dose rates ($r = 0.96$; $p = 0.01$; $R = 0.9$) indicates that internal exposure is the dominant contributor to total dose.

The absence of significant correlations between environmental K-40 activity and dose rates suggests that seawater and sediment concentrations are not direct linear predictors of radiological exposure. Future studies should expand the temporal and spatial sampling coverage, investigate seasonal variability, and apply multivariate and non-linear models to improve the understanding of radionuclide transfer processes in marine ecosystems.

Declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Clinical trial

Not applicable. This study is not a clinical trial and does not involve human participants or clinical interventions. Therefore, trial registration is not required.

Consent to Publish

All authors have reviewed and approved the final version of the manuscript and consent to its publication.

Ethics and Consent to Participate

Not applicable. This study did not involve human participants or procedures requiring ethical approval or informed consent.

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