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Article

Comprehensive Analysis of Contaminants in Powdered Milk Samples Using an HPGe for γ Radiation

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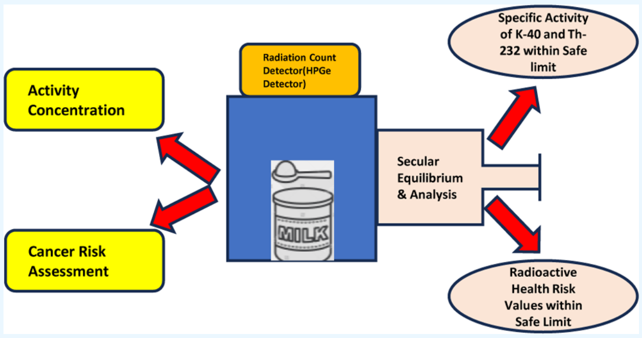

ABSTRACT: *Aims*: This study aimed to assess the activity concentrations and cancer risk assessments of ^{232}Th and ^{40}K in powdered milk samples collected from various suppliers in Pakistan, considering the increasing concern about cancer risks associated with environmental radiological effects related to food consumption. *Subjects and Methods*: Specific activity concentrations were determined using a high-resolution, high-purity germanium γ-spectroscopy system. *Results*: The specific activity levels of ^{40}K and ^{232}Th in the analyzed powdered milk samples were found to be 230.86 and 6.87 Bq/kg, respectively, well within the safe limits recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The hazard index (0.074 Bq/kg) and radium equivalent (27.58 Bq/kg) were calculated as indicators of radiation hazard, along with absorbed dose (26.26 nGy/h), annual effective dose (0.13 nGy/h), and excess lifetime cancer risk (0.45). These parameters provide insights into the potential health risks associated with powdered milk consumption. *Conclusions*: The findings collectively affirm the radiological safety of the analyzed powdered milk samples, providing valuable insights into the potential health risks associated with their consumption.

1. INTRODUCTION

Radiation exposure, emanating from both natural and artificial sources, remains a persistent concern for human health. Among the various routes of exposure, the ingestion of contaminated food and indoor exposure to γ radiation are particularly significant. Powdered milk, a staple in the Pakistani diet cherished for its convenience and nutritional value, has recently garnered attention as a potential source of radioactivity.

Contaminated milk powder may lead to radiation poisoning due to the presence of radioactive isotopes.[1] These isotopes can emit ionizing radiation, which, if ingested in sufficient quantities, can disrupt cellular processes and cause damage to tissues and organs. Chronic exposure to radioactive contaminants in milk powder can result in various health issues, including radiation sickness, which manifests as symptoms like nausea, vomiting, weakness, and in severe cases, organ failure.[2] Additionally, long-term exposure to radiation increases the risk of developing cancerous conditions, such as leukemia, thyroid cancer, or bone cancer.[3] Therefore, the consumption of milk powder contaminated with radioactive elements poses a significant health risk and underscores the importance of ensuring the safety and quality of food products to protect public health.

Natural radioactivity, primarily originating from radionuclides like ^{238}U, ^{232}Th, and ^{40}K in the earth's crust, contributes to background radiation levels. Indoor exposure to γ rays, especially when construction materials sourced from the earth are used, can surpass outdoor exposure due to changes in source geometry.[4] Additionally, the presence of radon gas, a decay product of radium (^{226}Ra) found in building materials, further accentuates indoor radiation exposure.[5]

While previous studies have explored radioactivity concentrations in foods globally, including neighboring countries, such as Iran, there remains a gap in understanding the radiation exposure associated with powdered milk consumption, specifically in Pakistan. Given the absence of specific guidelines for local foodstuffs, the need to assess radiation exposure in dietary staples like powdered milk is paramount, especially considering the significant amount of time individuals spend indoors, where exposure to γ radiation from construction materials is prevalent.[4]

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The study aims to address the existing gap in knowledge concerning radiation exposure from powdered milk consumption in Pakistan. By analysis of specific radionuclide activity levels in powdered milk samples commonly consumed in Pakistan, the research provides valuable insights into the radiological safety of these products. This investigation sheds light on the potential risks associated with powdered milk consumption and contributes to the understanding of radiation exposure in the context of dietary habits in Pakistan. Employing high-purity germanium (HPGe) for γ radiation detection, we will assess the concentrations of long-lived radionuclides, including ^{226}Ra, ^{232}Th, and ^{40}K, in powdered milk samples. By evaluating the associated radiation exposure and potential health risks, we aim to provide valuable insights into the safety of powdered milk consumption in Pakistan. Through this investigation, we hope to contribute to efforts aimed at safeguarding public health and ensuring the nutritional integrity of the Pakistani diet.

2. MATERIALS AND METHODS

2.1. Sample Collection. A total of 14 different samples of powdered milk were collected from different locations in Pakistan. The selection of milk for this study was based on its widespread utilization in Pakistan, where it is predominantly used in various culinary applications, such as tea-making and as a primary ingredient in numerous food preparations. Table 1 shows the collected sample types and Codes.

Table 1. Identification of Samples and Corresponding Codes Utilized in This Study

sl. no.	samples	milk type
1	NN-1	blend (skimmed milk and vegetable fat)
2	MJ-1	growing-up formula
3	NN-2	follow-up formula
4	AAJ-1	growing-up formula
5	NG-1	growing-up formula
6	SS-1	soy infant formula
7	GA-1	nutritional supplement diabetes patients
8	ORS-1	full cream milk powder
9	CG-1	follow-on formula
10	PP-1	nutritional supplement to help kids grow
11	NN-3	powder tea whitener
12	NN-4	growing-up formula
13	BF-P	specialized formula (low weight infants)
14	NN-5	nutritional formula

2.2. Sample Preparation. All milk samples were prepared in accordance with the guidelines provided by the International Atomic Energy Agency (IAEA).[6] A comprehensive sample preparation process is initiated to ensure the precise and reliable measurement of γ radiation emitted by the samples. This procedure comprises essential steps to guarantee the accuracy and reliability of γ spectroscopy analysis.

2.3. Homogenization and Removal of Moister. Homogenization is a crucial step in ensuring the uniform distribution of substances within a sample, particularly important when dealing with heterogeneous samples.[7] In this study, traditional tools, such as a mortar and pestle, were used to achieve homogeneity through thorough mixing.

Following homogenization, the samples underwent a moisture removal process to eliminate excess moisture, which could interfere with spectroscopy analysis. Excess moisture has the potential to attenuate γ rays and contribute to background radiation levels, thereby affecting the accuracy of energy measurements.[8] To address this issue, the samples were subjected to heat treatment in an oven to remove any moisture present. The sieved samples were then dried in an electric oven at 110 °C temperature for 24 h.

The removal of moisture through heat treatment is essential for ensuring an accurate γ spectroscopy analysis. By eliminating moisture, γ rays can penetrate the sample more effectively, leading to more precise energy measurements.[9] This step enhances the reliability of the data obtained from the analysis, allowing for a more accurate assessment of the radioactivity levels in the powdered milk sample.

2.4. Cooling and Weighing. After the heat treatment, the samples were allowed to cool to room temperature to achieve thermal equilibrium with the surroundings. Subsequently, each sample was carefully weighed up to 500 g.

2.5. Encapsulation in Marinelli Beakers. To safeguard against contamination and preserve the integrity of radioactive material, each sample was meticulously encapsulated within specialized sealed containers referred to as "Marinelli beakers". These beakers are characterized by their cylindrical shape, featuring a flat top for secure sealing. Crafted from high-density materials such as lead, they offer robust protection against radiation. Marinelli beakers adhere to standardized geometry, typically with a fixed volume, such as 1 L. The dimensions of Marinelli beaker consist of radius height r = 5.36 cm, cylinder height h_1 = 2.16 cm, and ring height h_2 = 6.42 cm, respectively. This standardized design facilitates accurate estimation and subtraction of background radiation during measurement processes, ensuring precise results.[10]

2.6. Secular Equilibrium. Secular equilibrium refers to a state where the rate of decay of a radioactive isotope and its decay products becomes stable over time. In the context of this study, allowing the samples to remain undisturbed in the Marinelli beakers for approximately 40 days facilitates the attainment of a secular equilibrium. During this period, the radioactive decay processes within the samples reach a stable state, ensuring that the activity measurements accurately reflect the true levels of radioactive isotopes present.[11]

Maintaining airtight conditions is crucial during this period to prevent the introduction of external contaminants that could interfere with the equilibrium process. To achieve this, the Marinelli beakers were hermetically sealed using tape, creating a barrier that prevents the entry of air and other external substances. This sealing mechanism ensures that the samples remain isolated from their surroundings, allowing for uninterrupted decay of radioactive isotopes and the establishment of a secular equilibrium.

2.7. Sample Analysis. The analysis of activity concentrations for ^{226}Ra, ^{232}Th, and ^{40}K in the milk samples was conducted using a high-purity germanium γ-ray spectrometer (HPGe). This involved the utilization of a personal-computer-based multichannel analyzer (MCA) along with a spectroscopic amplifier. The γ-ray spectrometer employed in this study featured a unique vertical dipstick design and was equipped with a liquid nitrogen cooling system. The HPGe crystal used in the measurements has dimensions of 59 mm in diameter and 53.4 mm in length, and exhibited a photopeak efficiency of approximately 52.3%.[12] For a cobalt (^{60}Co) point source's 1.33 MeV γ transition, the system displayed an energy resolution of 1.85 keV (full width half-maximum [fwhm]). In this study, the minimum detectable activity is 1.5 Bq/kg.[12]

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To mitigate potential interference from external radiation, an HPGe detector was positioned securely within a cylindrical cavity shielded by a substantial 10 cm thick layer of lead. This protective shield was further reinforced with an inner lining of 2 mm copper and an outer lining of 2 mm aluminum. Energy calibration of the system was accomplished using point sources emitting γ rays at specific energies, including ^{137}Cs (661.61 keV), ^{241}Am (59.53 keV), ^{57}Co (122.04 and 136.46 keV), ^{60}Co (1173, 1332, and 508 keV), ^{22}Na (1274.55 keV), and additional ^{57}Co (122.04 and 136.46 keV) sources. The calibration process adhered to established procedures outlined by Knoll (2000).

For calibration and detection, the Reference Material Uranium Ore, IAEA (RGU-1), was utilized. The calibration and the efficiency of the detectors are described in our last paper.[20] This reference material contains standards for uranium, thium, and potassium radioactivity measurements. Each milk sample underwent analysis through the acquisition of its γ-ray spectrum, with recording times ranging from 15,000 to 20,000 s. Background radiation levels recorded during inactive periods were documented to ensure the accuracy of activity concentration measurements and were subsequently subtracted from the spectra of the milk samples.

The determination of ^{226}Ra activity concentrations relied on the activities of ^{214}Pb and 214 Bi, while the assessment of ^{232}Th activity involved the calculation of radioactive progeny, including ^{228}Ac, ^{212}Pb, and ^{208}Ti. Additionally, the activity mass concentration of 40K was ascertained by measuring the γ transition at 1460.8 keV. Equation 1 was used for activity concentration.[11]

$$\text{activity concentration (Bq/kg) [A]\_ct} = (A - C\_b)/(P.\ \varepsilon.\ t.\ m) \quad (1)$$

where A represents the total area beneath the peak in the γ-ray spectrum, Cb represents the background area beneath the same peak, P represents the likelihood of γ radiation being emitted at the specific energy of interest, ε represents the detector's efficiency at the photopeak energy, t represents the duration of sample measurement, and m represents the mass of the milk sample in kilograms.

These parameters and calculations enable the determination of the activity concentration for natural radionuclides, including ^{226}Ra, ^{232}Th, and ^{40}K, in milk samples. This information plays a crucial role in assessing the safety and quality of milk products.

3. RESULTS AND DISCUSSION

The specific radionuclide activity of various powdered milk samples used in Pakistan was examined to assess their safety for consumption. The results, as presented in Table 2, indicate that NG-1 and ORS-1 have the highest thorium (^{232}Th) activity levels among the samples, with values of 7.75 ± 0.48 and 7.53 ± 0.51 Bq/kg, respectively. These higher concentrations indicate regional variations in soil composition and agricultural practices, influencing the presence of thorium in milk. However, it is important to note that all thorium activity concentrations remain well below the regulatory limit of 30 Bq/kg set by the UNSEAR standard. Similarly, elevated concentrations of 40K were detected in NN-1, NN-5, and ORS-1 samples, with values of 366.57 ± 6.13, 338.25 ± 6.13, and 312.23 ± 5.87 Bq/kg, respectively. This observation suggests potential differences in soil potassium content and dietary intake by dairy animals, contributing to higher potassium levels in certain milk samples. Overall, while variations in activity concentrations were observed among the powdered milk samples, all values remained within acceptable limits established by UNSCEAR. These findings underscore the safety of powdered milk products for consumption, with no significant radiological risks identified. Continued monitoring and adherence to safety protocols are essential to ensure the ongoing safety and quality of powdered milk products.

Table 2. Comprehensive Analysis of Specific Activity Levels Detected in the Collected Milk Samples

sl. no.	sample name	milk type	specific activity ^{232}Th (Bq/kg)	specific activity ^{40}K (Bq/kg)
1	NN-1	blend (skimmed milk and vegetable fat)	5.71 ± 0.53	366.57 ± 6.13
2	MJ-1	growing-up formula	6.04 ± 0.46	191.52 ± 4.46
3	NN-2	follow-up formula	7.13 ± 0.51	180.03 ± 4.34
4	AAJ-1	growing-up formula	6.64 ± 0.53	256.84 ± 5.23
5	NG-1	growing-up formula	7.75 ± 0.48	191.64 ± 4.46
6	SS-1	soy infant formula	7.28 ± 0.53	188.84 ± 4.46
7	GA-1	nutritional supplement diabetes patients	7.26 ± 0.53	194.19 ± 4.59
8	ORS-1	full cream milk powder	7.53 ± 0.51	312.23 ± 5.87
9	CG-1	follow-on formula	6.31 ± 0.48	188.71 ± 4.46
10	PP-1	nutritional supplement to help kids grow	6.93 ± 0.46	200.32 ± 4.59
11	NN-3	powder tea whitener	6.37 ± 0.46	201.85 ± 4.59
12	NN-4	growing-up formula	7.13 ± 0.51	260.03 ± 5.36
13	BF-P	specialized formula(low weight infants)	7.13 ± 0.46	161.02 ± 4.08
14	NN-5	nutritional formula	7.04 ± 0.51	338.25 ± 6.13

Table 3 provides a total specific activity of radionuclides, including ^{232}Th and ^{40}K, along with their concentrations for each powdered milk sample. The total activity is expressed in Bq/kg, and the concentrations of ^{232}Th and ^{40}K are given in ppm and percent, respectively. The last row of the table

Table 3. Overview of Radionuclide Activity in Powdered Milk Samples (Bq/kg), with Concentrations of ^{232}Th (ppm) and ^{40}K (%)

sl. no.	sample code	total activity (Bq/kg)	^{232}Th (ppm)	^{40}K (%)
1	NN-1	6.657	1.41	1.17
2	MJ-1	4.93	1.48	0.61
3	NN-2	4.85	1.76	0.57
4	AAJ-1	5.76	1.65	0.82
5	NG-1	4.95	1.91	0.61
6	SS-1	4.99	1.79	0.61
7	GA-1	5.13	1.789	0.62
8	ORS-1	6.38	1.85	0.99
9	CG-1	4.95	1.55	0.61
10	PP-1	5.059	1.707	0.64
11	NN-3	5.059	1.57	0.645
12	NN-4	5.869	1.76	0.83
13	BF-P	4.549	1.76	0.52
14	NN-5	6.635	1.74	1.08
UNSCEAR		450	30	40

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indicates the UNSCEAR-established safe limit for the total activity, set at 450 Bq/kg.[13] The total activity represents the combined influence of thorium and potassium levels within each milk powder sample. Notably, all samples exhibit total specific activity values well within the UNSCEAR-acceptable range, reinforcing the safety of these powdered milk products for consumption. Specifically, NN-1, NN-4, and NN-5 show slightly higher total activity values of 6.657, 5.869, and 6.635 Bq/kg, respectively. However, these values remain comfortably below the established safety threshold of 450 Bq/kg.

Figure 1 visually represents the specific activity values of thorium (^{232}Th) in milk powder samples. These values were

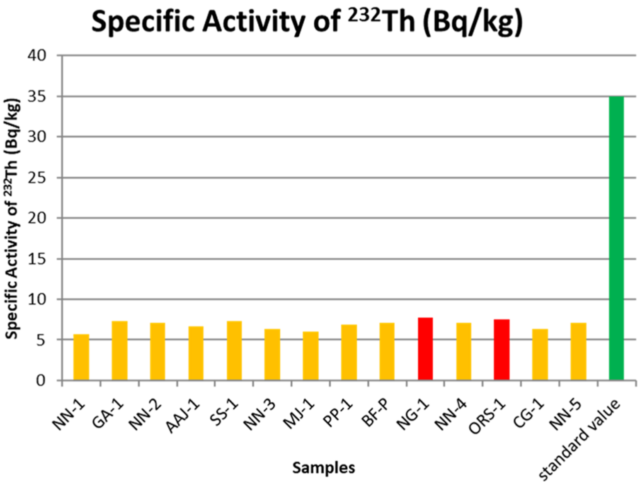

Figure 1. Visualization demonstrating the specific activity of thorium (^{232}Th) in milk powder samples.

determined using high-purity germanium (HPGe) analysis, a precise method for detecting radioactive isotopes. In the graph, each bar corresponds to the thorium-specific activity level of a specific milk powder sample. The height of each bar indicates the magnitude of the thorium activity concentration, measured in Becquerels per kilogram (Bq/kg).

The bars in the graph are color-coded, with red bars highlighting samples that have higher thorium-specific activity levels. Notably, the samples labeled ORS-1 and NG-1 stand out for exhibiting a higher concentration of thorium activity compared to that of the other samples.

This graphical representation provides a clear overview of the variability in the thorium concentration across different milk powder products. Identifying samples with higher activity levels, such as ORS-1 and NG-1, is essential for further investigation of potential sources of contamination or variability in manufacturing processes. Understanding these factors is crucial for ensuring compliance with safety regulations and maintaining the quality of milk powder products for consumers.

Figure 2 presents the average specific activity of radionuclide potassium-40 (^{40}K) across all samples. Despite samples NN-1, NN-5, and ORS-1 displaying the highest average specific activity values, it is important to note that these concentrations remain below the UNSCEAR-acceptable limit of 450 Bq/kg for a total specific activity. This underscores the overall compliance of the studied milk powder samples with international safety standards, assuring consumers that even samples with comparatively higher 40K activity levels do not pose a radiological risk within established safety limits.

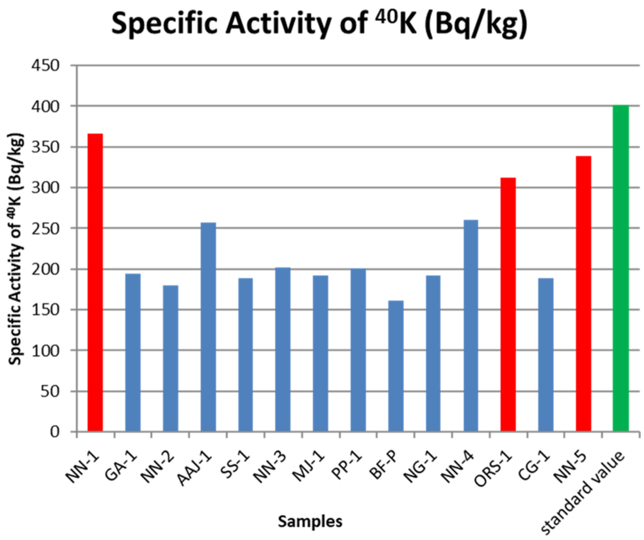

Figure 2. Visualization of (^{40}K) specific activity across milk powder samples.

3.1. Radium Equivalent. The radium equivalent activity (Ra_{eq}) is a crucial parameter used to evaluate the consistency of radiation exposure.[14] It is calculated based on the specific activities of ^{232}Th and ^{40}K within milk powder samples. Table 4 provides a comprehensive overview of the Ra_{eq} values for each sample, encapsulating the combined radiological impact of these radionuclides.

The data in Table 4 reveal that all samples exhibit Ra_{eq} values well below the radium restriction value set by UNSCEAR, which stands at 127 Bq/kg. This indicates that the milk powder samples comply with established safety standards regarding radium content. Notably, none of the samples showed a radium peak, further confirming their adherence to safety regulations.

Despite certain samples, such as NN-1, NN-5, and ORS-1, demonstrating relatively higher Ra_{eq} values compared to others, with NN-1 recording the highest value at 36.356 Bq/kg, it is important to emphasize that all observed values fall within the safe range. This highlights the overall safety of the milk powder samples analyzed in this study, reassuring consumers of their suitability for consumption.

Figure 3 illustrates the radiation equivalent (Ra_{eq}) in milk powder samples. Samples NN-1, NN-5, and ORS-1 exhibit relatively higher Ra_{eq} values compared to others, with NN-1 reaching the highest value at 36.356 Bq/kg. However, it is crucial to emphasize that all Ra_{eq} values, even in these cases, fall within the safe range. This indicates compliance with established safety standards, assuring consumers that the milk powder samples do not pose a radiological risk within acceptable limits.

3.2. Indoor Absorbed Dose. The term "absorbed dose" signifies the amount of radioactive energy absorbed by a unit mass.[15] According to the guidelines established by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the recommended limit for indoor absorbed dose (D_{in}) is 112.80 nanogray per hour (nGy/h).[16] Upon meticulous examination of the data within the table, it is noteworthy that sample NN-1 displays an indoor absorbed dose of 35.97 nGy/h; this value falls below the UNSCEAR-prescribed threshold of 112.80 nGy/h, indicating compliance with the specified safety standards.

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Table 4. Radium Equivalent Activity, H_{in}, Absorbed Dose, Annual Effective Dose Rate, and Excessive Lifetime Cancer Risk in Powder Milk

sl. no.	sample codes	Ra_{eq} (Bq/kg)	H_{in} (Bq/kg)	D_{in} (nGy/h)	E_{in} (nGy/h)	ELCRin (%)
1	NN-1	36.356	0.098	35.97	0.17	0.62
2	GA-1	25.319	0.068	23.73	0.116	0.407
3	NN-2	24.039	0.065	22.429	0.11	0.38
4	AAJ-1	29.249	0.079	28.113	0.138	0.48
5	SS-1	24.938	0.067	23.314	0.114	0.4
6	NN-3	24.638	0.066	23.36	0.114	0.4
7	MJ-1	23.367	0.063	22.162	0.108	0.38
8	PP-1	25.314	0.068	23.85	0.117	0.409
9	BF-P	22.576	0.061	20.889	0.103	0.358
10	NG-1	25.821	0.069	24.054	0.118	0.413
11	NN-4	30.193	0.08	28.909	0.142	0.49
12	ORS-1	34.778	0.09	33.576	0.165	0.57
13	CG-1	23.532	0.064	22.227	0.109	0.38
14	NN-5	36.083	0.097	35.147	0.17	0.6
UNSCEAR	0.46	0.45	112.80	0.346	1.45	

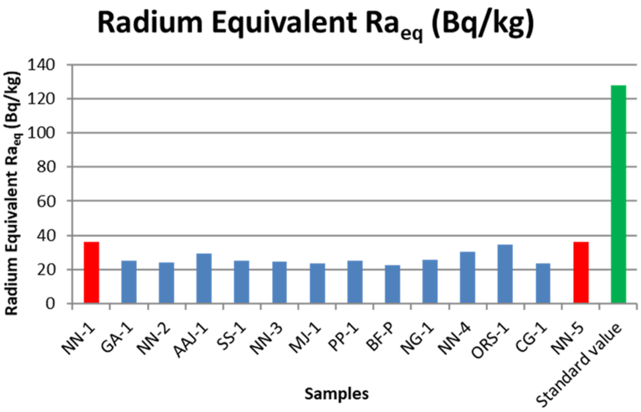

Figure 3. Visual representation of radium equivalent levels in milk powder samples.

In considering the remaining samples, their respective indoor absorbed dose values are all below the UNSCEAR-prescribed threshold of 112.80 nGy/h. For instance, GA-1, NN-2, AAJ-1, SS-1, NN-3, MJ-1, PP-1, BF-P, NG-1, NN-4, ORS-1, CG-1, and NN-5 exhibit indoor absorbed dose values that are within the safe range.

Figure 4 illustrates the Absorbed Dose in milk powder samples. Consistent with earlier findings, all samples, including NN-1, demonstrated absorbed dose values below the UNSCEAR-prescribed threshold of 112.80 nGy/h. This reaffirms compliance with international safety standards, indicating that the milk powder samples pose no significant radiological risks and are suitable for consumption.

3.3. Indoor Hazard Index (H_{in}). The highest value observed in sample NN-1 corresponds to the maximum indoor hazard index, as depicted in Table 4, which exhibits a range from a minimum of 0.061 Bq/kg to a maximum of 0.098 Bq/kg. The indoor hazard index is a crucial parameter in radiological risk assessment, representing the potential radiological hazard associated with indoor exposure to specific radionuclides.[17] In the case of sample NN-1, its maximum indoor hazard index value of 0.098 Bq/kg, as indicated by the graph, signifies the upper limit of radiological risk attributed to this particular sample. The observed range in the graph provides a comprehensive view of the variability in indoor hazard index values, with NN-1 standing out as having the highest value within the data set. This information aids in understanding the radiological safety profile of NN-1 in comparison to other samples and contributes valuable insights into the overall assessment of radiological risk associated with the examined milk powder samples.

In Figure 5, the blue line represents the indoor hazard index, depicting the radiological risk associated with exposure to specific radionuclides. The orange line corresponds to sample

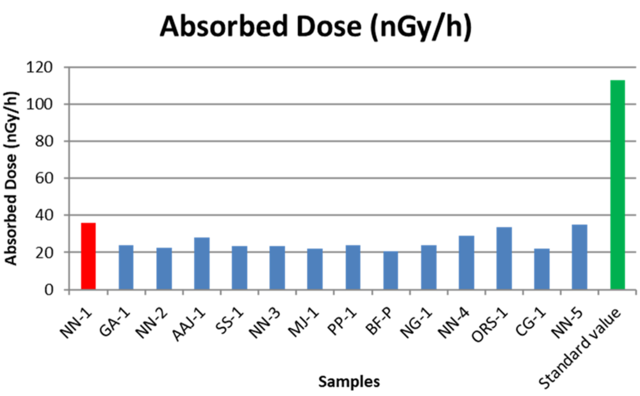

Figure 4. Visual representation of absorbed dose levels in milk powder samples.

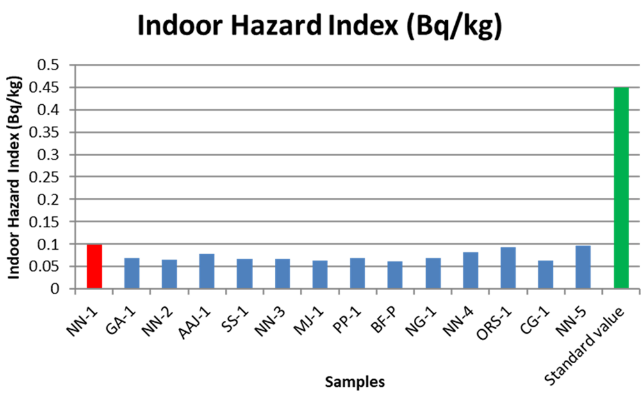

Figure 5. Visual representation of hazard index levels in milk powder samples.

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NN-1, highlighting its hazard index value in comparison to the standard indicated by the green bar graph. The comparison between the blue line and the green bar provides insight into whether the hazard index values for samples are within or exceed the acceptable standard.

3.4. Indoor Annual Effective Dose. The observation that samples NN-1, NN-5, and ORS-1 exhibit the highest values for annual effective dosage indoors, measured at 0.17 and 0.165 mSv/y, respectively, holds significance in the context of radiological risk assessment. The annual effective dosage indoors represents the estimated radiation dose received by individuals over a year due to indoor exposure to specific radionuclides.[18] In this context, the elevated values for NN-1, NN-5, and ORS-1 indicate that individuals consuming these specific milk powder samples may potentially receive a higher annual effective radiation dose compared with other samples. This finding underscores the importance of assessing and monitoring the radiological safety of these particular samples, especially in terms of their impact on overall human exposure to ionizing radiation.

Figure 6 depicts the indoor annual effective dose in milk powder samples. The green bar represents the standard value,

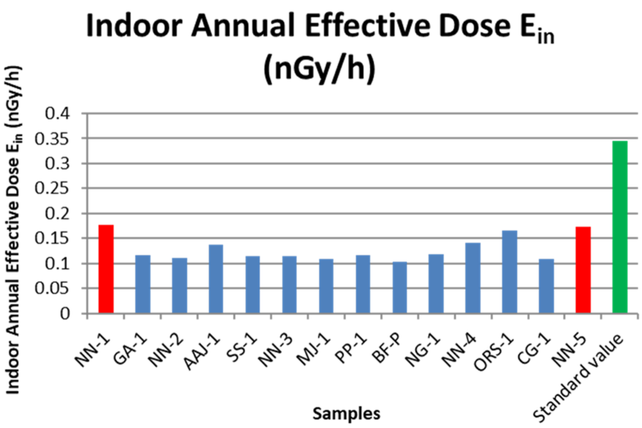

Figure 6. Visual representation of indoor annual effective dosing levels in milk powder samples.

while the orange bar indicates samples NN-1, NN-5, and ORS-1, which show higher values compared to the other samples represented by the blue bars.

3.5. Excessive Lifetime Cancer Risk. Lifetime cancer risk represents the probability of developing cancer over a lifetime due to radiation exposure.[19] In Figure 4, samples NN-1, NN-5, and ORS-1 are shown to have the highest indoor cancer risk among all samples. The Estimated Lifetime Cancer Risk (ELCRin) levels, peaking at 0.62 for NN-1, are significant indicators. Although these values exceed the UNSCEAR-recommended safe threshold of 0.45, it is noteworthy that they fall within the realm of reduced indoor cancer risk estimates.

This finding suggests that while these samples may have higher cancer risk estimates compared with others, they remain within acceptable limits. It is important to recognize that the increased cancer risk associated with these samples may involve various types of cancer, depending on factors such as the specific radionuclides present and the duration of exposure.[20] Therefore, a nuanced interpretation is needed in the overall evaluation of the radiological safety of the analyzed milk powder samples, taking into account the complexity of assessing cancer risk based on radiological parameters.

Figure 7 illustrates the Excessive Lifetime Cancer Risk (ELCRin) in milk powder samples. The orange bars represent

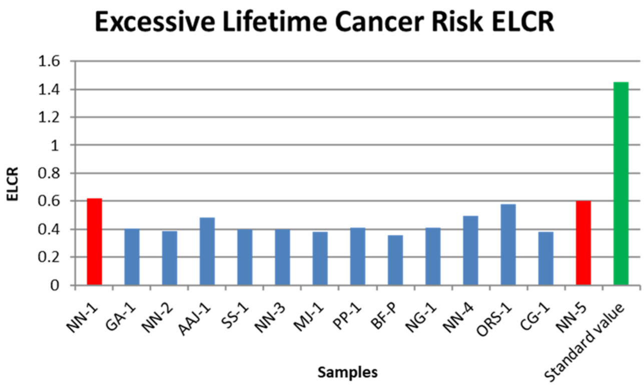

Figure 7. Visual representation of excessive lifetime cancer risk levels in milk powder samples.

the ELCRin values for specific samples, with NN-1, NN-5, and ORS-1 showing the highest values. These elevated ELCRin levels indicate a higher probability of developing cancer over a lifetime due to radiation exposure from the consumption of these specific milk powder samples.

4. CONCLUSIONS

Milk powders, fundamental to our dietary habits, may contain radioactive elements with extended half-lives, significantly contributing to natural radioactivity.[21] Elements like those in the decay series of ^{235}U, ^{226}Ra, ^{232}Th, and nonseries ^{40}K are prevalent in our environment and dietary intake. While dry milk serves as a valuable nutritional source, ensuring its purity from harmful contaminants or radionuclides is paramount.[22] These elements constitute a significant portion of background radiation and may pose potential health risks when present at elevated concentrations. Ingestion of contaminated dry milk could result in radiation poisoning, manifesting symptoms ranging from nausea and vomiting to severe organ failure.

This research aimed to identify and quantify radiation content specifically in milk powders to mitigate the risk of consuming products tainted with radionuclides. Adhering to quality control standards and regulatory guidelines, such as those established by national and international bodies such as the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), ensures the safe consumption of these products.

Analysis of the milk powder samples revealed activity and radioactive health risk values within the safe limits set by UNSCEAR. Specifically, NN-1 (a blend of skimmed milk and vegetable fat), NN-5 (a nutritional formula), and ORS-1 (full cream milk powder) exhibited higher activity concentrations of potassium (40K), as confirmed by γ spectrometry. Specific activity levels for ^{232}Th and 40K, assessed by a high-purity germanium (HPGe) analysis, also remained within safe limits, indicating the absence of radium, strontium, or other concerning peaks.

Radiological health risks, including the highest Indoor Excessive Lifetime Cancer Risk (ELCRin) value of 0.62 observed in NN-1, remained below the safe limits defined by UNSCEAR. This comprehensive analysis affirms the overall radiological safety of the studied milk powder samples,

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reinforcing their suitability for consumption within established safety thresholds. Recognizing the study's constraints is essential for a thorough understanding of the outcomes. Despite the valuable insights gained from analyzing milk powder samples, the study's limited sample size may restrict the broader applicability of the results to other populations or regions. Additionally, environmental differences across various geographic areas can impact the natural radioactivity levels found in milk powder.[23] Thus, future investigations with larger sample sizes and attention to geographical variations are necessary to strengthen the reliability and relevance of the conclusions.

4.1. Limitations. While this study provides valuable insights into the radiological safety of milk powder samples, several limitations should be acknowledged. First, the sample size was relatively small, which may limit the generalizability of the findings to a broader population. Additionally, the study focused solely on specific radionuclides, such as thorium and potassium-40, while other potentially relevant radionuclides were not assessed. Furthermore, the analysis was conducted using γ spectroscopy, which may not detect certain radionuclides present at lower concentrations or those emitting radiation at energies outside the detection range of the detector. Lastly, geographical variations in radionuclide concentrations and production processes were not accounted for, which could affect the overall radiological safety of milk powder samples.

4.2. Suggestions for Future Research. To address these limitations and further enhance our understanding of radiation exposure from powdered milk consumption, future research should consider expanding the sample size to include a more diverse range of milk powder products from various regions. Additionally, comprehensive analysis incorporating a wider range of radionuclides, including radium-226, cesium-137, iodine-131, and strontium-90, should be conducted using advanced analytical techniques, such as high-resolution γ spectroscopy or mass spectrometry. Moreover, studies investigating the impact of geographical factors and production processes on radionuclide concentrations in milk powder would provide valuable insights into potential sources of contamination and strategies for mitigating risks. Overall, addressing these aspects in future research endeavors would contribute to a more comprehensive understanding of the radiological safety of milk powder products and facilitate evidence-based regulatory measures to protect public health.

■ ASSOCIATED CONTENT

Data Availability Statement

The utilized data has been comprehensively included within the manuscript.

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