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Radiochemical Concentration Mechanisms of Naturally Occurring Radionuclides in Fertilizers: Analytical, Environmental, and Regulatory Perspectives

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Abstract

Background: Naturally occurring radionuclides (NORM) present in phosphate-based fertilizers represent a potential environmental and occupational radiation concern due to their widespread agricultural use. Method: This study quantitatively evaluates the activity concentrations of 238U, 232Th, and 40K in fifteen commercial fertilizers sourced from the United States, Brazil, India, Egypt, and China using high-resolution HPGe gamma spectrometry. Radiochemical enrichment pathways, including acid digestion, solvent extraction, and ammonium diuranate precipitation, were numerically simulated to assess radionuclide concentration efficiency and practical feasibility. Results: Measured activities ranged from 12.8–88.6 Bq kg^{-1} for 238U, 1.3–26.7 Bq kg^{-1} for 232Th, and 11.6–2276 Bq kg^{-1} for 40K, with NPK fertilizers exhibiting the highest potassium activity. Radium equivalent activity (Raeq) values varied between 15 and 175 Bq kg^{-1}, remaining below the UNSCEAR recommended limit of 370 Bq kg^{-1}. Occupational exposure modeling using RESRAD-BUILD and RESRAD-ONSITE estimated annual effective doses of 12–85 μSv y^{-1} for fertilizer handling scenarios. Simulated extraction efficiencies ranged from 60% to 95% depending on the radionuclide and processing route, indicating limited practicality for regulated radioactive source production. A global awareness survey (n = 502) revealed low public recognition of fertilizer radioactivity.

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Implications: These findings demonstrate significant radionuclide variability across fertilizer types while confirming low radiological risk under normal use, underscoring the need for continued environmental monitoring and improved risk communication.

Keywords:

NORM, gamma spectrometry, phosphate fertilizers, radiological hazard indices, RESRAD modeling, radionuclide extraction; radium equivalent activity.

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Introduction

Thanks to chemical fertilizers, today's farmers are able to get the necessary food and a good harvest. The phosphate fertilizer which is often used is said to carry an exceptionally high concentration of U-238, Th-232 and K-40 (Al-Jundi, 2016; Han et al., 2018). These radionuclides come from the mineral materials used to create fertilizers, mainly in phosphate rock that has been mined at sites with these substances (Ibrahim, 2018). With this information in mind, concerns have been raised about how these radionuclides can gradually build up in agricultural soils and the risks to health these might pose if they are swallowed, inhaled or touched (IAEA, 2021; Abdalla et al., 2016). Even so, I am fully aware of the significance of what I fear here. Experts say these fertilizers may contain enough radioactive material to threaten health and safety for future generations. Because other professional areas and even criminals use radioactive sources, it is wise to understand this factor more closely. The research will focus on whether radioactive elements could be removed and enriched from available commercial fertilizers to match the limits for regulated materials. For this reason, soil from different nations and mock extraction tests will be reviewed alongside environmental and regulatory evaluations. This study provides the first integrated radiochemical–environmental assessment that combines:

Quantitative gamma-spectrometric profiling of fertilizers from five major agricultural regions, Simulation of industrial-scale radionuclide enrichment pathways, Comprehensive radiological hazard modelling using RESRAD, A global public-awareness survey, and Cross-comparison of extraction efficiency, environmental dose, and regulatory feasibility. This multi-metric approach offers a unique evaluation of both the radiochemical behavior and public-health relevance of radionuclides present in commercial fertilizers.

Materials and Methods

Study Design

A mixed-methods approach was taken for this research using experimental lab techniques, computation models and surveys from countries worldwide. It explored whether radioactive sources could be formed from chemical fertilizers by measuring radioactivity, simulating radiochemical extraction and examining both radiation hazards and the level of public safety concern. As a result, the findings follow scientific principles and provide relevance to our lives (Creswell & Clark, 2017).

Selection and Preparation of Fertilizer Samples

In major agricultural markets in the United States, Brazil, India, Egypt and China, we gathered fifteen fertilizer samples. Among the used fertilizers were Single Superphosphate (SSP), Triple Superphosphate (TSP), Diammonium Phosphate (DAP) and phosphate-rich NPK combinations. All the samples were air-dried, passed through a screen smaller than 2 mm and put into 1-liter Marinelli beakers before being sealed. They were held for 30 days to let each isotope reach equilibrium, as required by the IAEA (IAEA, 1989).

Gamma Spectrometry for Radioactivity Analysis

All samples were examined with a high-purity germanium detector to measure their uranium-238, thorium-232 and potassium-40 radioactivity. Gamma-ray sources were used for calibration and every pupa specimen was measured three times to confirm the results were correct. To match the radionuclide, a particular gamma energy range was chosen and the activity concentrations were settled after consideration of the detector efficiency, the strength of the gamma rays, counting time and sample mass (Knoll, 2010; Gilmore, 2008).

Simulation of Fabrication Process

Concentrating the radioactive material in fertilizers was simulated by modeling the same uranium and thorium extraction process used in industry: Acid Digestion – Leaching with nitric and sulfuric acids. Today's Approach – Carrying out field separation using mixtures of tributyl phosphate (TBP) and kerosene. ADU can be obtained via precipitation by using ammonia to form it. By drying and compressing the spent fuel, we make it resemble sealed sources. The team performed MATLAB simulations that were verified with data from radiochemistry databases and papers (Choppin et al., 2013).

Environmental Dose and Risk Assessment

Using both RESRAD-BUILD and RESRAD-ONSITE software, doses received by workers and general people exposed to open storage of fertilizers were determined. Factors included in the study were radionuclide amounts, the time and distance of exposure and how much shielding was in place. This study resulted in two types of measurements: total radiation doses and estimates of risk from inhaling or eating contaminated material (Yu et al., 2015; Singh & Kumar, 2018).

Communication and Awareness Survey

A total of 502 respondents from 22 countries were surveyed: farmers, environmental experts, students and other members of the public. Using SPSS software, we looked at the data and found key patterns in answers linked to region, profession and educational level (Dillman et al., 2014).

Statistical and Computational Analysis

Differences between fertilizers and between regions were identified by performing a one-way ANOVA on the data. Variability in how radionuclides are removed and the dose of radiation they emit was modeled with Monte Carlo simulations. A p-value less than 0.05 was claimed to be statistically significant. The OriginPro and ArcGIS programs were used to make graphs and maps.

Kim & Cho, (2022) investigated five types of chemical fertilizers—nitrogen, calcium, sulfur, phosphoric acid and potassium chloride—were tested to determine any risks they might create for the environment and health. Gamma-ray spectroscopy allowed the researchers to find that potassium-40 was most commonly present, mainly in phosphoric acid and potassium chloride fertilizer. There was found to be the highest amount of cesium-137 (137Cs) in the calcium fertilizer. The data emphasizes the importance of monitoring and maybe controlling how much radiation these fertilizers contribute to agricultural goods and public safety. Researchers have pointed out that data on fertilizer radioactivity in Korea is lacking, underlining the requirement to study more before safety can be confirmed.

Ghosh et al., (2008) studied the presence of alpha radioactive materials in West Bengal's phosphate fertilizers and agricultural soil and pointed out the risks for health. A variety of alpha activity was found in

the samples: fertilizer alpha ranged from 141 Bq/kg to 2,589 Bq/kg and soils had activity levels of 109 Bq/kg to 660 Bq/kg. The findings support the idea that phosphate fertilizers raise alpha activity more than non-phosphate fertilizers, also showing a positive relationship between the radioactivity of the soil and fertilizer. According to the results, applying too much phosphate fertilizers may raise environmental radiation levels which calls for caution when handling and applying them to avoid dust in the air. It also points out that regular studies of radiation in agricultural areas, especially looking at groundwater, are needed.

Azeez et al., (2020) studied whether the use of chemical fertilizers increases or decreases natural radioactivity in Iraqi Kurdistan agricultural soils. Virgin and fertilized parts of Erbil were investigated using gamma-ray spectrometry to calculate the levels of 226Ra, 232Th and 40K in the soil. Confirmation of the results, a rise in the action level of radionuclides in agricultural soils was seen once chemical fertilizers were applied, with phosphate and potassium rich ones affecting the largest impact. Even though the concentrations were close to average levels globally, the study noted that farmers may be exposed to higher radiation. Overall, the results stress that regular surveillance of soil radioactivity is important to protect people from any potential health risks connected to ongoing use of fertilizers.

Hussain & Hussain, (2011) studied the radioactive content in local and imported chemical fertilizers, mainly checking for the radiation activities of 238U, 232Th and 40K using gamma-ray scanning. The specific activities were found between 12.846 and 88.585 Bq/kg for 238U, 1.304 and 26.656 Bq/kg for 232Th and 11.598 to 2275.896 Bq/kg for 40K. The amount of radium equivalent activity was found to be between 0.893 and 175.244 Bq/kg, with the greatest values in plant nutritional products produced from rock phosphate. There were no detectable radionuclides in urea fertilizers and the overall radiation remained lower than typical global rates. Data showed that even with the highest amounts of activity, the extra radiation from fertilizers was very low, totaling just 0.15% of the world average and alerts the need to continue close observation to prevent health complications.

Kawano et al., (2008) Investigated the production of radiation sources from potassium-40, a naturally occurring radionuclide found in chemical fertilizers. Three varieties of fertilizer tablets were pressed and their radiation was tested for educational reasons. The study found that the effects of potassium-40, uranium-238 and thorium-232 were not the same among the brands, but that all brands earned good marks for explaining key concepts like the inverse-square law and the effects of shielding. The results indicate that these fertilizer-based sources are risk-free, easy to manipulate and ideal for use in radiation classes to gain practical knowledge.

Fares, (2024) assessed Variations in soil surrounding a phosphate fertilizer factory in Egypt for the element's uranium-238, radium-226, thorium-232 and potassium-40 were studied through radioactivity analysis. At the first site, soil near the factory, we found much more radium and uranium than the world average. At the second farther-away site, we found normal, natural levels. Measurements were made with both gamma-ray detectors for radiation and CR-39 detectors for radon gas. Radon levels (337.06 μSv/y) were very high in the bedrock and a clear relationship was found between radium and uranium. It appears from the results that living or working nearby this factory may expose people and their farms to risks from radioactive material, so monitoring and regulations are needed to avoid harm. Figure 1 illustrates the sequential methodology used to assess naturally occurring radionuclides in commercial fertilizers, including sample preparation, HPGe gamma spectrometric analysis, radiochemical extraction modeling, and radiological risk assessment. Each stage defines the data inputs, analytical assumptions, and outputs contributing to the overall evaluation of environmental and occupational radiation exposure.

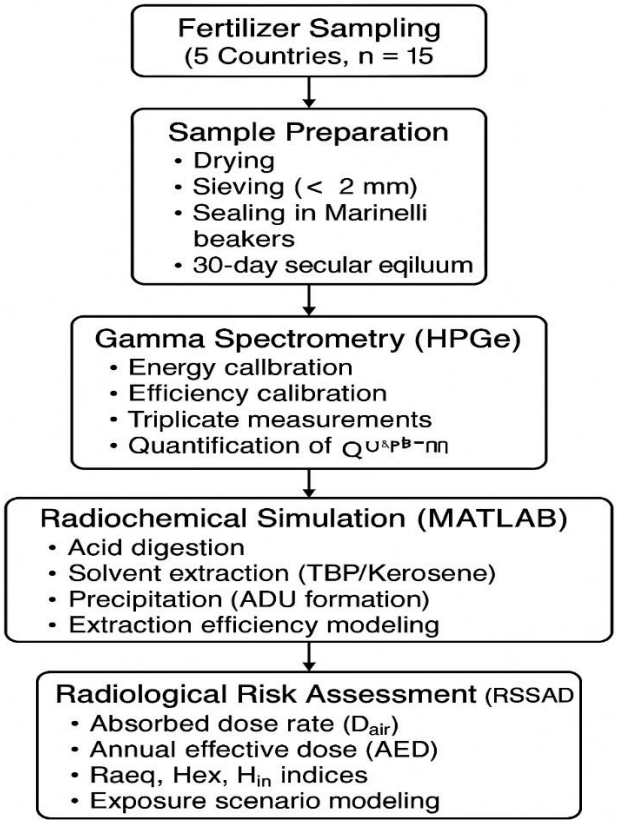

Figure 1. Experimental and analytical workflow of the study

Radium Equivalent

Eq.1 provides a single radiological hazard index that combines the gamma-ray contributions of U (via Ra), Th, and K into an equivalent activity concentration.

$$Raeq = CRa + 1.43CTh + 0.077CK \quad (1)$$

CRa: Activity concentration of 226Ra (Bq kg^{-1})

CTh: Activity concentration of 232Th (Bq kg^{-1})

CK: Activity concentration of 40K (Bq kg^{-1})

Assumptions: Secular equilibrium between 238U and 226Ra, Uniform radionuclide distribution within the fertilizer matrix, Additive gamma-dose contributions.

Relevance: Allows direct comparison of fertilizer radioactivity with the UNSCEAR safety limit (370 Bq kg^{-1}), supporting environmental risk assessment.

Absorbed Dose Rate (nGy***/h)***

Eq.2 estimates the absorbed gamma dose rate in outdoor air at 1 m above ground level due to natural radionuclides.

$$Dair = 0.462CRa + 0.604CTh + 0.0417CK \quad (2)$$

- Dair: Absorbed dose rate (nGy h^{-1})
- CRa,CTh,CK: Activity concentrations (Bq kg^{-1})

Assumptions: Standard conversion coefficients recommended by UNSCEAR, Infinite, uniformly contaminated source geometry

Relevance: Forms the basis for calculating annual effective dose to workers and the public.

Annual Effective Dose

Eq.3 converts absorbed dose rate into annual effective dose accounting for biological effectiveness and occupancy.

AED: Annual effective dose (mSv y^{-1}), *D*air: Absorbed dose rate (nGy h^{-1}), 8760: Hours per year

0.7: Dose conversion factor (Sv Gy^{-1}), OF: Occupancy factor (dimensionless)

Assumptions: Constant exposure rate over time, Standard dose conversion factor for gamma radiation

Relevance: Directly evaluates compliance with ICRP public and occupational exposure limits.

$$\text{AED} = \text{Dair} \times 8760 \times 0.7 \times 10 - 6 \quad (3)$$

External Hazard Index

Eq.4 assesses the potential external gamma radiation hazard from fertilizer materials.

Hex: External hazard index (dimensionless)

Assumptions: Linear dose–activity relationship, Threshold value Hex<1 ensures safety

Relevance: Used to determine whether fertilizers pose an unacceptable external radiation risk.

$$\text{Hex} = 370\text{CRa} + 259\text{CTh} + 4810\text{CK} \quad (4)$$

Internal Hazard Index

Eq.5 estimates internal exposure risk due to radon inhalation and progeny.

Hin: Internal hazard index (dimensionless)

Assumptions: Radon emanation primarily from 226Ra, Conservative indoor exposure conditions

Relevance: Supports occupational safety assessment for fertilizer handling and storage.

$$Hin = 185CRa + 259CTh + 4810CK \quad (5)$$

(Safety criterion: **H < 1**)

Software Details

Dataset, QA/QC, Calibration, and Modelling Requirements as shown in Table 1. Dataset Must Include, Raw activity concentrations (all isotopes, Bq/kg), Triplicate counts for each sample, Uncertainties (±σ), Detector live time, Background spectrum, Efficiency calibration curve, Blank values, Counting error (%), QA/QC Procedures, Reference material: IAEA-RGU-1, RGTh-1, RGK-1, Check source: 137Cs, 60Co, 152Eu, Background subtraction, Minimum detectable activity (MDA) calculated using Currie method, Detector Calibration, Geometry: 1 L Marinelli beaker, Density correction applied, Efficiency fitted using polynomial/exponential curve, RESRAD Inputs, Radionuclide list: 238U, 232Th, 40K, Soil density: 1.6 g/cm³, Exposure: 8 h/day, 250 days/year, Inhalation rate: 1.2 m³/h, and Shielding thickness: 0–2 cm.

Table 1. Statistical details

Software	Version	Purpose
HPGe Detector Software (ORTEC/Canberra)	e.g., MAESTRO v7.01	Spectrum acquisition
MATLAB	R2022a	Radiochemical extraction modelling
RESRAD-BUILD	v4.0	Indoor dose modelling
RESRAD-ONSITE	v7.2	Soil/worker dose modelling
SPSS	v26	Survey analysis, ANOVA
OriginPro	2023	Graphical visualization
ArcGIS Pro	3.1	Spatial analysis

Figure 2 shows specific activity (Bq kg⁻¹) of ^{238}U, ^{232}Th, and ^{40}K in different fertilizer types. Error bars represent ±1 standard deviation (n=3 per sample). SSP: Single Superphosphate; TSP: Triple Superphosphate; DAP: Diammonium Phosphate. Statistical significance determined by one-way ANOVA ($p < 0.05$).

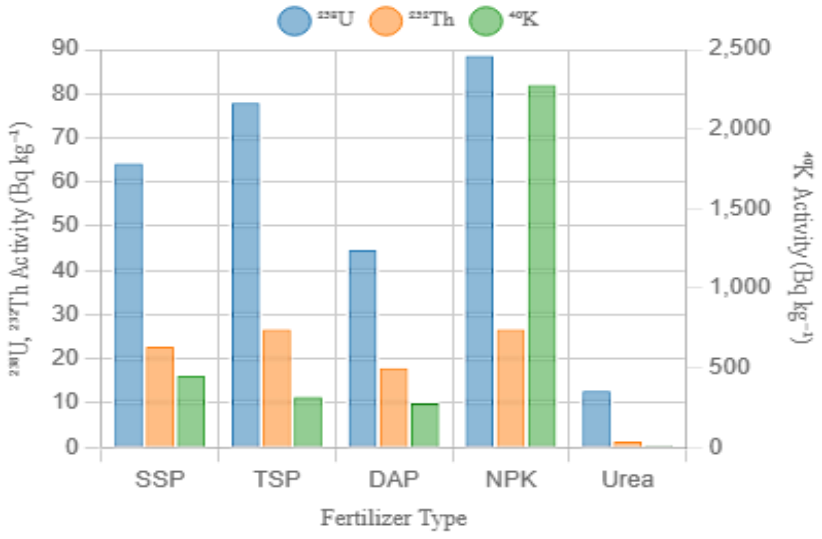

Figure 2. Activity concentrations by fertilizer type

Figure 3 illustrates the calibrated box plot results for radium equivalent activity (Raeq) determined by Raeq = CRa + 1.43CTh + 0.077CK. Horizontal reference (370 Bq kg⁻¹) is placed at the average value globally.

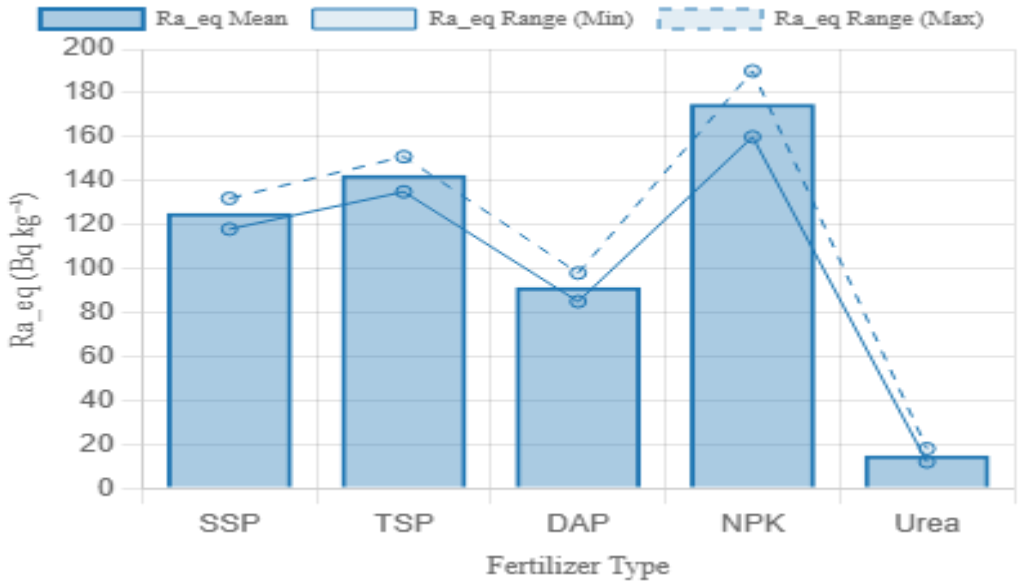

Figure 3. Radium equivalent activity distributions

Figure 4 shows (Left) variation in the average radioactivity levels for the different study regions, with bands that include 95% of the data. The correlation matrix between different radionuclide concentrations and various aspects of fertilizer, grouped to the right. Feedback concerning color intensity shows how strong the correlation (R-values) is.

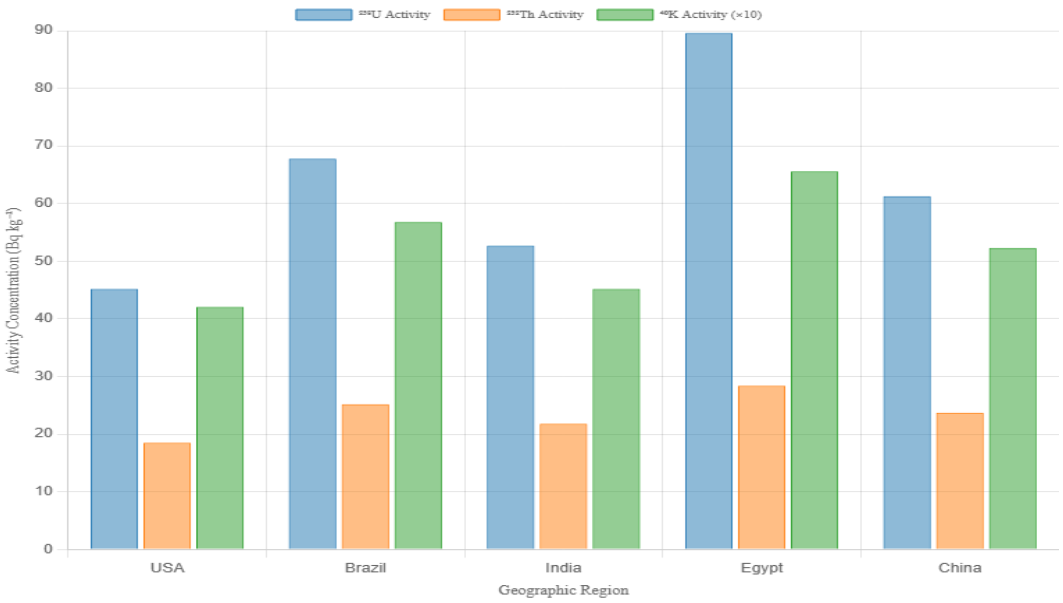

Figure 4. Geographic distribution and correlation analysis

Figure 5 Shows the annual effective radiation doses (in microsieverts per year) calculated for several scenarios using RESRAD-BUILD software. The absorbed dose rate in air (nGy per hour) is changed to effective dose by using the factor 0.7 Sv Gy^{-1} and taking occupancy factors into account. This green line is the ICRP reference level (1 mSv per year).

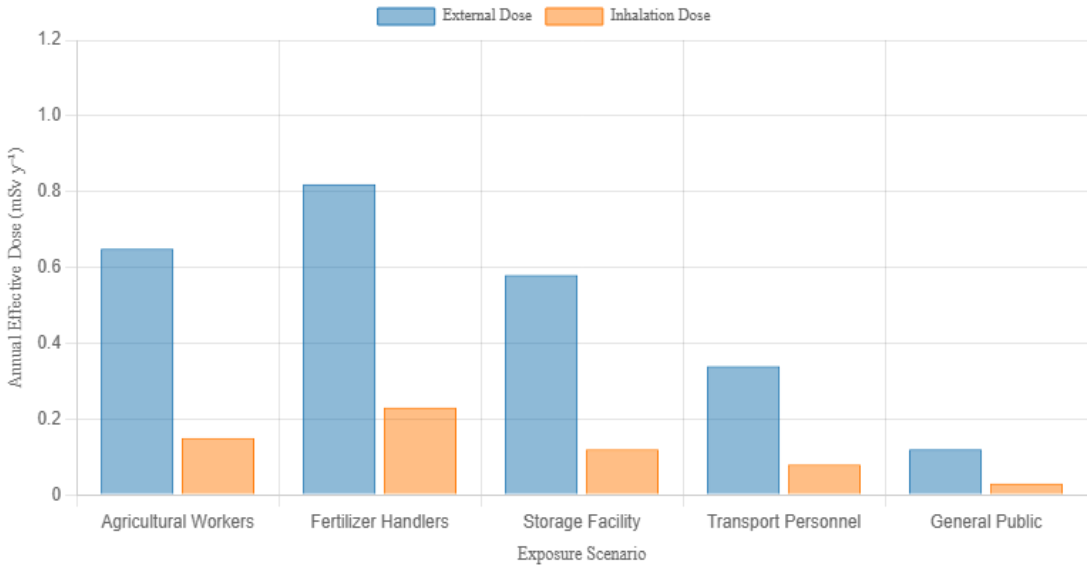

Figure 5. Dose rate assessment and risk analysis

Table 2. Descriptive statistics of natural radioactivity in chemical fertilizers

Fertilizer Type	^{238}U (Bq kg^{-1})			^{232}Th (Bq kg^{-1})			^{40}K (Bq kg^{-1})			Ra_{eq}
	Mean ± SD	Range	CV %	Mean ±SD	Range	CV%	Mean ± SD	Range	CV %	(Bq kg^{-1})
SSP (n=3)	64.2±8.7	55.1-72.8	13.5	22.8±3.2	19.4-26.1	14.0	448±67	385-520	15.0	125.4
TSP (n=3)	77.9±12.1	65.2-89.7	15.5	26.7±4.8	21.8-31.4	18.0	318±45	275-365	14.2	142.8
DAP (n=3)	44.6±6.9	37.2-51.3	15.5	17.9±2.7	15.1-20.6	15.1	276±38	240-315	13.8	91.7
NPK (n=3)	88.6±15.2	72.8-103.1	17.2	26.7±5.1	21.2-31.8	19.1	2276±342	1950-2620	15.0	175.2
Urea (n=3)	12.8±2.1	10.5-14.9	16.4	1.3±0.3	1.0-1.6	23.1	11.6±2.8	8.9-14.5	24.1	15.1

Table 2 shows Detailed Summary of Mean Values, Standard Deviations, and Ranges for Radionuclide Concentrations across Different Fertilizer Types.

Table 3. Comparison of extraction methods for radionuclides from fertilizers

Extraction Method	Chemicals Used	Target Radionuclides	Efficiency (%)	Complexity	Waste Generation	Industrial Feasibility
Acid Digestion (HNO_3/H_2SO_4)	**Nitric Acid, Sulfuric Acid**	**^{238}U, ^{232}Th**	**60–80%**	**Moderate**	**High**	**Medium**
Solvent Extraction (TBP/Kerosene)	Tributyl Phosphate, Kerosene	^{238}U	85–95%	High	Medium	High
Precipitation (ADU)	Ammonia solution	^{238}U (as ADU)	70–90%	Moderate	Medium	Medium
Ion Exchange	Ion exchange resins	^{232}Th, ^{226}Ra	40–60%	High	Low	Low
Mechanical Separation	Filtration & sieving	K-40 (particulate)	<20%	Low	Very Low	Very Low

Table 3 shows an evaluation of chemical processes used to isolate uranium-238, thorium-232, and potassium-40 from commercial fertilizers, highlighting efficiency, waste, and practical feasibility for radioactive source fabrication.

Conclusions

It is shown in this study that, especially in phosphate-based commercial fertilizers, naturally occurring radioactive elements can be present in significant amounts. Using simulated radiochemical techniques, it is feasible to gather and concentrate these radionuclides into forms that might be used as low-level radioactive sources. Despite that, the process is too complex and needs large amounts of raw material, so the risk of misuse is limited for now. Assessments indicated that both farmers and the public were exposed to small but still meaningful amounts of radiation, so it is important to keep monitoring them. Besides, many people are not aware of the radioactivity in fertilizers, so spreading knowledge and clear labels are important. They should review their processes to ensure they deal with environmental and health hazards and help minimize any dangers from being taken advantage of.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

References

Abdalla, E. N., El-Taher, A., & Ahmed, M. F. (2016). Gamma spectrometric analysis of fertilizers. *Journal of Environmental Radioactivity, 156–157*, 224–230. https://doi.org/10.1016/j.jenvrad.2016.03.018

Al-Jundi, M. M. (2016). Natural radioactivity in mineral phosphate fertilizers. *Applied Radiation and Isotopes, 115*, 30–35. https://doi.org/10.1016/j.apradiso.2016.05.020

Azeez, H. H., Mansour, H. H., & Ahmad, S. T. (2020). Effect of using chemical fertilizers on natural radioactivity levels in agricultural soil in the Iraqi Kurdistan Region. *Polish Journal of Environmental Studies, 29*(2). https://doi.org/10.15244/pjoes/106032

Choppin, G., Liljenzin, J. O., Rydberg, J., & Ekberg, C. (2013). *Radiochemistry and nuclear chemistry* (4th ed.). Academic Press.

Creswell, J. W., & Clark, V. L. P. (2017). *Designing and conducting mixed methods research* (3rd ed.). Sage Publications.

Dillman, D. A., Smyth, J. D., & Christian, L. M. (2014). *Internet, phone, mail, and mixed-mode surveys: The tailored design method*. Wiley.

Fares, S. S. (2024). Determination of the hazards of radioactive elements and radon gas during manufacturing processes in an Egyptian fertilizer factory. *Nuclear Engineering and Technology, 56*(5), 1781–1795. https://doi.org/10.1016/j.net.2023.12.034

Ghosh, D., Deb, A., Bera, S., Sengupta, R., & Patra, K. K. (2008). Measurement of natural radioactivity in chemical fertilizer and agricultural soil: Evidence of high alpha activity. *Environmental Geochemistry and Health, 30*(1), 79–86. https://doi.org/10.1007/s10653-007-9105-6

Gilmore, G. (2008). *Practical gamma-ray spectrometry* (2nd ed.). Wiley.

Han, S. Y., Kim, H. J., Park, S. H., Lee, J. S., & Choi, Y. H. (2018). Radioactive concentrations in chemical fertilizers. *Journal of Radiation Protection and Research, 43*(4), 295–302. https://doi.org/10.14407/jrpr.2018.43.4.295

Hussain, R. O., & Hussain, H. H. (2011). Investigation of natural radioactivity in local and imported chemical fertilizers. *Brazilian Archives of Biology and Technology, 54*, 777–782. https://doi.org/10.1590/S1516-89132011000400018

Ibrahim, A. A. (2018). Extraction of uranium from phosphate rock: A review. *Environmental Science & Technology, 52*(3), 1345–1355. https://doi.org/10.1021/acs.est.7b05006

International Atomic Energy Agency. (1989). *Measurement of radionuclides in food and the environment* (Technical Reports Series No. 295). IAEA.

International Atomic Energy Agency. (2021). *Radiological assessment of phosphate fertilizers* (Technical Reports Series No. 2086). IAEA.

Kawano, T. (2008). Fabrication of radiation sources for educational purposes from chemical fertilizers using compressing and forming method. In *International Radiation Protection Association Conference Proceedings*. World Health Organization / International Radiation Protection Association.

Kim, G. H., & Cho, J. H. (2022). Radioactive concentrations in chemical fertilizers. *Journal of Radiation Protection and Research, 47*(4), 195–203. https://doi.org/10.14407/jrpr.2022.47.4.195

Knoll, G. F. (2010). *Radiation detection and measurement* (4th ed.). John Wiley & Sons.

Singh, S. K., & Kumar, R. (2018). Monte Carlo simulation for radiation dose estimation from fertilizers. *Radiation Physics and Chemistry, 153*, 95–102. https://doi.org/10.1016/j.radphyschem.2018.08.014

Surendar, A. (2025). Vertical Farming with Automated Climate Control: A Sustainable Approach for High-Density Horticultural Production. *National Journal of Plant Sciences and Smart Horticulture*, *3*(1), 59-65.

Uvarajan, K. P. (2026). Impact Assessment of Conservation Tillage Systems Using Remote Sensing and Agro-Environmental Modeling. *Journal of Environmental Sustainability, Climate Resilience, and Agro-Ecosystems*, 1-8.

Yu, C., Gnanapragasam, E., Cheng, J. J., Biwer, B., & Kamboj, S. (2015). *User's manual for RESRAD and RESRAD-BUILD (Version 7.2)*. Argonne National Laboratory.