

Determination of Radioisotopes in Atmospheric Particles (2023 and 2024), Santo Domingo, Dominican Republic

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Abstract

The presence of radioactive particles in aerosols makes them a greater health concern than their size (PM₁₀ or PM_{2.5}), as they can cause lung diseases, cancer, and birth defects, in addition to allergies and respiratory conditions. Radioisotopes in aerosols can originate naturally as a result of the interaction of cosmic radiation with elements dispersed in the air, such as ¹⁴C, ²²Na, ³H, and ⁷Be, and from windblown dust residues from the natural decay processes of ²³⁸U and ²³⁵U and their decay products, such as ²³²Th, ²²⁶Ra, ²²²Rn, ⁴⁰K and ²¹⁰Pb, which are frequently found in urban aerosols. Aerosols can also contain artificially produced radioisotopes such as ⁹⁰Sr, ¹³⁷Cs, ¹³¹I, and ³H. Additionally, ⁶⁰Co, ⁹⁹Tc, ¹⁸F, ¹³³Ba, ⁶⁷Ga, and ²²Na are present as waste products from nuclear activities, industry, and nuclear medicine, which have been improperly handled and exposed to the environment. Nineteen samples were taken in Santo Domingo using the ASTM D1739 sampling technique to determine the presence of radioisotopes in the particulate matter. Gamma-emitting radioisotopes were detected using gamma spectroscopy with a hyper pure germanium detector (Barba-Lobo & Bolivar, 2023). The average Bq·Kg⁻¹ content in particulate matter of ²³⁵U (3.08), ²³²Th (0.40), ²²⁶Ra (5.05), ²¹⁴Bi (2.44), ²¹⁰Pb (2.33), ⁷Be (0.72), and ⁴⁰K (2.56) indicates that the concentrations of these radioisotopes are typically higher in soils. Levels of ¹³⁷Cs and ⁶⁰Co were negligible. These levels were relatively low compared to European standards for radioisotopes in aerosols and soils. The artificial radioisotopes found in the particulate matter with concentrations in Bq·Kg⁻¹ were ¹³¹I (3.94), ⁹⁹Tc (2.51), ¹³³Ba (3.10), ⁶⁷Ga (2.13) and ²²Na (1.95). The latter, although it may be of natural origin, like the others, is used in industrial applications and Nuclear Medicine.

Keywords

Aerosols, Radioisotopes, Radio Diagnostics, Particulate Matter, Pollution

1. Introduction

The presence of solid, liquid, and gaseous particles that can remain suspended in the atmosphere is commonly referred to as aerosols. Atmospheric aerosols result from the action of wind lifting dust from the ground, water vapor, waste from industrial and domestic activities, transportation (Friedlander, 2000), and chemical compounds produced by the combustion of organic and inorganic materials of fossil origin. The period between 1950 and 1960 saw the greatest release of ^{137}Cs into the atmosphere by countries conducting nuclear tests. Between 1960 and 1974, France carried out 14 nuclear tests in the Algerian desert, leaving radioactive residue from the explosions scattered in the soil and atmosphere (McKendry et al., 2007). The average ^{137}Cs radioactivity in the Sahara Desert of Algeria is $14 \text{ Bq}\cdot\text{Kg}^{-1}$ of soil (Menut et al., 2009). Meanwhile, the $^{239}\text{Pu}+^{240}\text{Pu}$ radioactivity has been found to range between 0.57 and $0.82 \text{ Bq}\cdot\text{Kg}^{-1}$ (Moreno et al., 2006). The atmosphere over the Dominican Republic is blanketed each year by dust from the Sahara Desert, causing serious lung problems, allergies, general malaise, and triggering allergies and asthma (UNSCEAR, 1982). As we know, this dust, which is lifted by the wind during desert storms, is laden with heavy metals (Matos-Espinosa et al., 2025) as well as natural radioisotopes, in addition to artificial ones resulting from nuclear tests conducted in Algeria by France starting in 1960 (Gbadebo, 2011). Besides the dust originating from the Sahara (Zivuku et al., 2023), there is also dust stirred up by industrial, mining, and domestic activities. According to some experts, the levels that reached Europe in 2024 (Basart et al., 2012; Xu-Yang et al., 2025) did not pose a serious health problem and were found to be below these values. Comparing the 2004 value of ^{137}Cs , which was $14 \text{ Bq}\cdot\text{Kg}^{-1}$, with the values measured of $20 - 28 \text{ Bq}\cdot\text{Kg}^{-1}$ in 2024, it was observed that there is a contribution from Saharan dust (Perry et al., 1997). Sometimes these emissions contain radioactive material residue from nuclear power plants, which is released into the atmosphere and carried great distances by wind, water, and clouds, as happened in the 1986 Chernobyl disaster in Russia, the worst radioactive disaster in history; or as when the 2011 earthquake in Japan, which generated a tsunami and affected the Fukushima nuclear plant, released some radioactive material into the water. Before these tests, dust storms from the Sahara reached all of the Americas, carrying large quantities of particulate matter that clouded the atmosphere in the Caribbean, including the Dominican Republic. The large quantities of particulate matter composed of naturally occurring radioactive materials and heavy metals in soils today also contain residues from nuclear tests, such as ^{90}Sr , ^{230}Pu , ^{14}C , and ^{137}Cs (Alvarado et al., 2014). Many soils contain ^{40}K , ^{235}U , ^{226}Ra , ^{214}Pb , ^{214}Bi , among others, which, through natural decay, decay into other radioactive elements. Due to their new characteristics, ^{222}Rn , which is a gas, rises into the atmos-

phere and decays into ^{210}Po , ^{210}Tl , and ^{210}Pb radioisotopes that become part of the atmospheric particulate matter; as well as ^{22}Na , ^3H , ^{14}C , and ^7Be of cosmogenic origin (Balco & Shuster, 2009). Therefore, by breathing this aerosol, we are incorporating radioactive material into our bodies through this route. This could seriously affect health. Epidemiological studies have determined that populations exposed to aerosols (Boucher, 2015) with high levels of radioactive particles are affected by cancer and other lung conditions, as well as congenital malformations during pregnancy due to chromosomal aberrations during fetal development. According to the World Health Organization, the presence of air pollutants, particularly particulate matter ($\text{PM}_{2.5}$), was the cause of 3.7 million deaths in 2012. In the Americas alone, there were approximately 58,000 deaths; 11% of these were due to chronic lung diseases, 6% to lung cancer, 3% to respiratory infections, and the remainder indirectly due to heart and brain conditions. The presence of radioisotopes in samples taken in Santo Domingo, National District, Dominican Republic, during 2023 and 2024 and analyzed using gamma spectroscopy with a sodium iodide detector and a hyper pure germanium detector, indicates that radioisotopes are somehow reaching the atmosphere of Santo Domingo from the soil (USEPA, 2007) or from other regions, including via Saharan dust; some of these could be from exposed medical waste used in nuclear medicine. According to the WHO, levels of ^{222}Rn should not exceed $100 \text{ Bq}\cdot\text{m}^3$ to be considered low risk. The problem isn't radon itself (Guevara Rojas, 2024), but its decay products, such as ^{210}Po and ^{210}Pb , which remain and bioaccumulate in the body. The average activity at ground level is $0.95 \text{ mBq}\cdot\text{kg}^{-3}$ in aerosol form and $370 \text{ Bq}\cdot\text{kg}^{-1}$ in soil (UNSCEAR, 2000a). According to a study conducted by Guevara Rojas in Peru in 2024, the maximum value obtained was $150 \text{ mBq}\cdot\text{kg}^{-3}$ in aerosols form, while in Costa Rica it was $140 \text{ mBq}\cdot\text{kg}^{-3}$. In rocks, for example, in an abandoned granite mining area in Nigeria, ^{40}K values ranged from 0.201 to 0.301 $\text{Bq}\cdot\text{kg}^{-1}$ (Gbadebo, 2011). Granite, an igneous rock, and other metamorphic rocks are generally gamma emitters due to ^{40}K present (Verdoya et al., 2001).

2. Study Sites

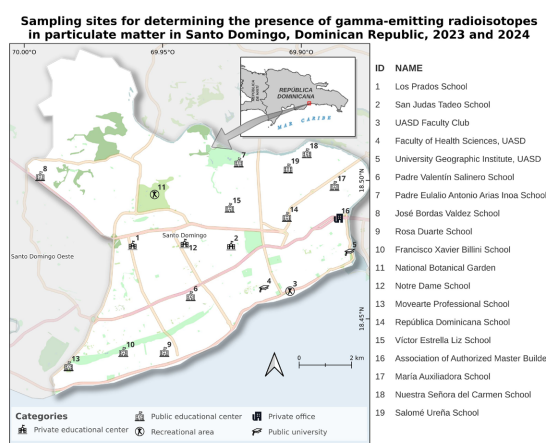


Figure 1. Map showing the locations of the sampling sites in the National District, Santo Domingo, Dominican Republic.

3. Methodology

For the selection of sampling sites, educational centers were chosen with the interest of determining the levels of exposure to which school-age children and young people are exposed to aerosols and their composition, PM_{2.5}, PM₁₀, heavy metals and radionuclides in Santo Domingo.

Sampling: Open plastic containers (ASTM D1739-98, 2026) with a diameter of 90 cm and a height of 60 cm were placed on the roofs of buildings at the sampling sites (Figure 1) for 24 hours. All particulate matter deposited in the containers was collected. Many particles were deposited along with the rain that fell during the sampling period, so the water had to be evaporated to collect the particulate matter. In places where precipitation occurred, a greater number of samples were collected; the suspended particulate matter precipitated with the rain. Items larger than half a centimeter, such as insects, leaves, or pieces of tree branches, were removed. The samples were dried and placed in plastic vials. Energy calibration of the HPGe detector, with an efficiency of 30% was performed using a certificated gamma source, and the resulting calibration was verified across the relevant energy range using naturally occurring background peaks and references radionuclides identified in the samples. The background was measured for 26 hours (see Table 1). The Minimum Detectable Activity (MDA) was calculated by using the formula: $MDA = \frac{2.71 + 4.658 \cdot \sqrt{B}}{\epsilon t I_{\gamma}}$ and the minimum limit of quantification

MLQ = 3MDA. Where B is the account number, t is the collection time, I_{γ} is the intensity, and ϵ is the efficiency (Kanisch, 2017). Three grams of the samples in the vials were placed on top of an Ortec HPGe planar detector (80 mm × 30 mm), with its respective shielding, to collect a gamma spectrum using the Maestro software provided by the spectrometer manufacturer (Ortec/Ametek). A calibration was performed beforehand using a ¹³⁷Cs source (Soliman et al., 2025), and the background was measured. The analysis was performed using the number of counts in the channel corresponding to the energy of each radioisotope. For this reason, the values obtained in some cases may reflect lower values than the actual values, since the counts close to the main (Gaussian) line were not taken into consideration (Figure 2). The study was designed as a preliminary exploratory assessment in late 2023 and early 2024, and the number of samples collected was limited by the availability of sampling equipment, detector counting time, and logistical limitations during the 2024 campaign. To explore the spatial distribution of radionuclides across the study area, geostatistical interpolation was performed using ordinary kriging (Cressie, 1989; Goovaerts et al., 1997; Isaaks & Srivastava, 1989; Matheron, 1963). Sampling locations were converted into a spatial object and reprojected from geographic coordinates (WGS84) to UTM Zone 19N (EPSG:32619) to allow distance-based calculations and spatial modeling in metric units (Pebesma, 2018; Pebesma & Bivand, 2023). All radionuclides with available measurements were included in the interpolation procedure because complete observations were available for all sampling sites. A regular interpolation grid was generated over the

study area using a fixed cell size, and a spatial buffer surrounding the sampling domain was incorporated to reduce potential edge effects during surface estimation.

Table 1. Concentrations (Bq·kg⁻¹) of the most notable radioisotopes in particulate matter from National District, Santo Domingo, Dominican Republic (2023 and 2024).

Sample	Latitude	Longitude	²¹⁰ Pb	¹³¹ I	¹³³ Ba	²²⁶ Ra	⁹⁹ Tc	²³⁵ U	²¹⁴ Bi	⁶⁷ Ga	⁷ Be	²² Na	²²⁸ Ac	⁴⁰ K	²³² Th
1	18.47667	-69.9608	3.1292	1.7881	2.0862	6.4075	2.9802	3.5763	2.9802	1.4901	0.7451	1.4901	0.0000	3.1292	0.2980
2	18.47671	-69.9253	2.9225	2.9225	2.5978	6.1697	3.4096	4.0590	2.5978	1.9483	0.6494	1.9483	0.8118	2.5978	0.4871
3	18.46011	-69.904	3.5327	2.5779	3.3417	7.2563	2.4824	4.0101	2.3869	2.5779	0.5729	1.5276	1.4322	3.3417	0.6683
4	18.46103	-69.9134	2.3200	2.3200	4.6400	3.0933	2.6514	3.3143	1.9886	1.6571	0.7733	1.4362	0.3314	3.2038	0.3314
5	18.47418	-69.8825	3.0162	3.3178	1.8097	4.8259	2.4129	3.0162	0.9049	4.2226	0.3016	0.6032	0.3016	5.7307	0.0000
6	18.45865	-69.9396	1.4530	1.2454	1.1157	1.4011	1.7903	1.5698	1.1027	0.7395	0.2984	1.1806	0.1687	0.2595	0.0778
7	18.50577	-69.9224	2.5625	3.1020	3.5066	1.7533	2.9671	3.3718	3.1020	1.4836	0.8092	2.4277	0.6744	0.9441	0.4046
8	18.50132	-69.9946	3.0238	4.6436	2.8078	7.1274	3.3477	3.9957	2.0518	1.6199	0.8639	1.4039	0.4320	2.8078	0.3240
9	18.4383	-69.9493	2.5229	2.5229	5.4664	9.5311	1.6820	3.3639	3.2238	2.3828	0.8410	3.3639	0.5607	4.3451	0.5607
10	18.43828	-69.964	2.5322	3.3762	3.6576	6.3774	3.1887	3.7514	3.2825	3.0949	0.4689	2.0633	0.9378	3.9390	0.7503
11	18.49079	-69.9587	2.2522	3.4696	4.3218	4.7479	3.1653	2.9827	3.2262	3.8349	0.6087	2.0696	0.6087	3.8957	0.6696
12	18.4768	-69.942	1.2786	2.1920	1.6440	1.8266	1.2786	2.1920	2.1920	1.2786	0.1827	2.1920	0.1827	1.0960	0.5480
13	18.43202	-69.9837	1.3234	1.7516	1.5829	1.6218	1.9981	1.6218	1.4532	1.1807	0.2206	1.3753	0.2465	0.6098	0.1038
14	18.48679	-69.9053	1.3563	1.3111	1.6728	3.2099	1.8536	1.7180	1.0398	1.1755	2.5770	0.4521	0.9946	0.3165	0.1808
15	18.49024	-69.9258	5.5031	5.5031	11.9233	20.7893	3.6687	7.3374	7.0317	5.1973	1.8344	7.3374	1.2229	9.4775	1.2229
16	18.48638	-69.8865	1.3110	2.3055	2.3055	2.3055	2.1247	1.7630	1.7178	1.4918	0.4521	1.0397	0.1808	0.4521	0.0452
17	18.49802	-69.8879	1.8344	22.0122	1.5286	1.8344	2.7515	2.4458	2.1401	1.5286	0.6115	1.5286	0.3057	1.2229	0.6115
18	18.46552	-69.9078	1.2206	4.2495	1.4467	2.8481	1.9892	2.2152	1.9439	1.7631	0.4521	1.8083	0.3165	0.6329	0.1808
19	18.50432	-69.9048	1.2205	4.2492	1.4465	2.8479	1.9890	2.2150	1.9438	1.7630	0.4520	1.8082	0.3164	0.6329	0.1808
Background			0.0040	0.0036	0.0041	0.0055	0.0056	0.0047	0.0045	0.0032	0.0009	0.0035	0.0005	0.0023	0.0007
MDA			0.0019	0.0018	0.0019	0.0022	0.0022	0.0021	0.0020	0.0017	0.0009	0.0018	0.0008	0.0015	0.0008
MLQ			0.0058	0.0055	0.0058	0.0067	0.0067	0.0062	0.0061	0.0052	0.0028	0.0054	0.0023	0.0045	0.0025

Ordinary kriging was implemented in R using the automap package. For each radionuclide, empirical semivariograms were constructed and candidate theoretical models (spherical, exponential, Gaussian, and Matérn) were evaluated automatically. Model selection was based on minimizing the residual sum of squares between empirical and theoretical semivariograms. Predicted values and kriging variances were calculated for all interpolation nodes, allowing the construction of exploratory concentration surfaces and uncertainty maps. Contour lines derived from interpolated surfaces were also generated to facilitate the visualization of spatial gradients. Because the dataset consisted of a limited number of sampling locations, the resulting kriging products were interpreted as exploratory representations of spatial structure rather than definitive estimates of environmental exposure or spatial risk.

4. Results

The dataset consisted of 19 sampling locations and 13 radionuclides, with complete spatial information available for all observations (see **Figure 1** and **Table 1**). No samples lacked geographic coordinates, allowing the complete integration of the dataset into subsequent spatial and geostatistical analyses. The number of radionuclides evaluated relative to the number of sampling sites provided sufficient dimensionality to explore concentration variability and spatial patterns among isotopes.

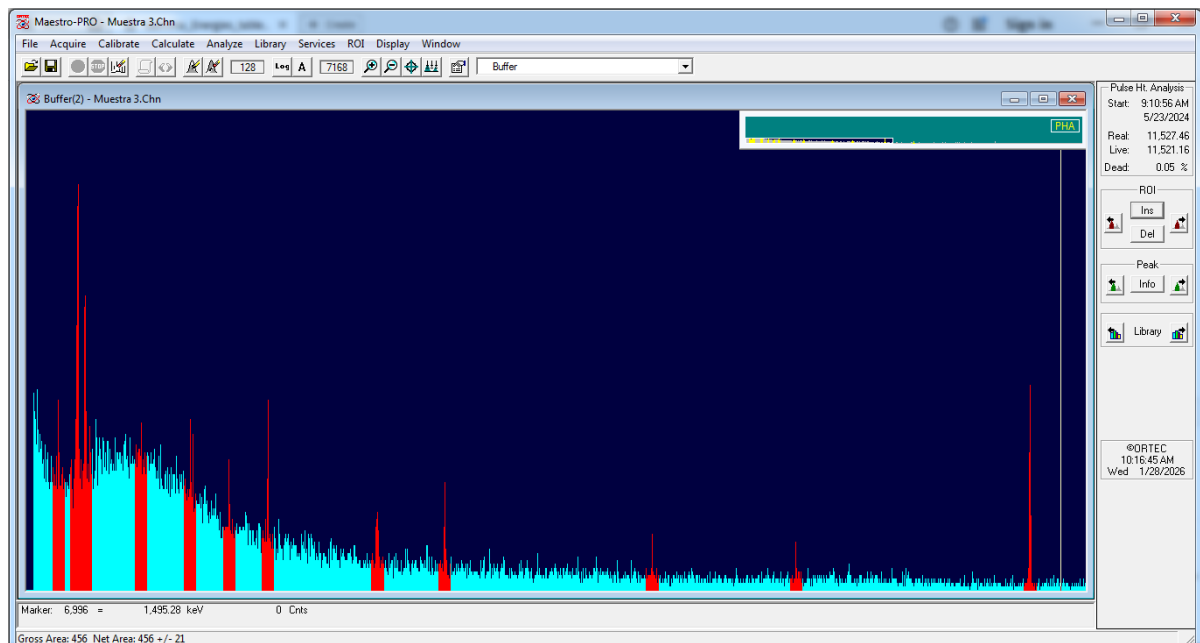


Figure 2. Characteristic spectrum of sampling locations in the National District, Santo Domingo, Dominican Republic (2023 and 2024).

The sampling sites covered multiple sectors of the National District and represented a variety of land-use contexts, including public and private educational centers, university facilities, recreational areas, and office environments (see **Figure 1**). The spatial arrangement of the sampling network provided geographic representation across northern, southern, eastern, and western sectors of the study area, reducing the concentration of observations within a single urban zone. The locations also encompassed areas characterized by different urban settings, population densities, and surrounding infrastructure. This distribution allowed the dataset to include sampling points situated under distinct environmental conditions and urban contexts, providing a broader representation of atmospheric particulate matter conditions within Santo Domingo.

Spatial visualization of radionuclide concentrations was performed to examine their geographic distribution across the National District. The interpolation maps shown in **Figure 3** provide a descriptive representation of concentration patterns

for individual radionuclides and facilitate comparison of the spatial arrangement of relative concentration values among isotopes. The spatial distribution maps showed differences in the geographic arrangement of concentration values among radionuclides (**Figure 3**). Since each radionuclide was represented using an independent scale, comparisons among maps should be interpreted in terms of relative spatial patterns rather than direct differences in concentration magnitude. The maps therefore provide a descriptive visualization of concentration gradients and spatial variation for each isotope individually.

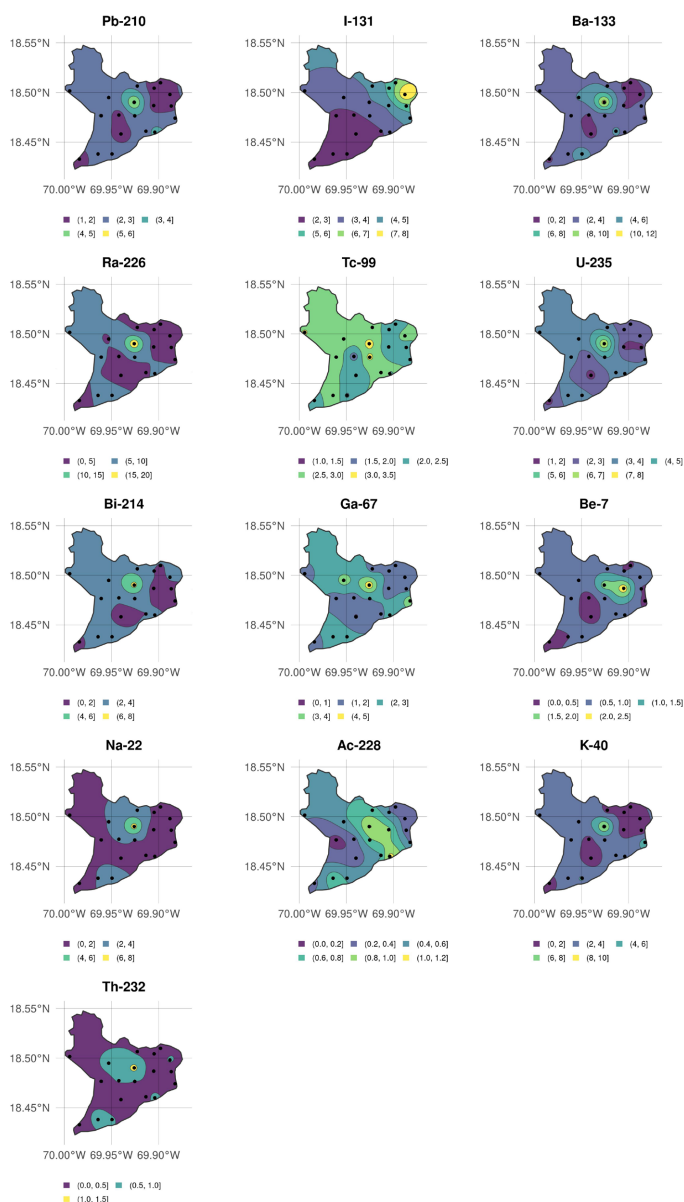


Figure 3. Exploratory kriging-based spatial distribution of selected radioisotopes in atmospheric particulate matter from the National District, Santo Domingo, Dominican Republic (2023 and 2024). Colors represent relative concentration gradients within each radioisotope, from lower values (dark purple) to higher values (yellow), and are intended to emphasize spatial patterns rather than direct comparisons among isotopes.

Some radionuclides exhibited relatively narrow concentration ranges and limited variability among sites, whereas others displayed larger differences between minimum and maximum values (Table 2). Concentrations varied substantially among radionuclides, indicating considerable heterogeneity in both abundance and dispersion patterns across the sampled locations (see Table 1 and Figure 4). Likewise, the spread of values differed among isotopes, with some showing more homogeneous distributions and others presenting more pronounced fluctuations among observations. The graphical representation of the data also showed that concentration values were not uniformly distributed among radionuclides, with certain isotopes exhibiting comparatively higher values at specific locations. Overall, the observed patterns indicate substantial variability in radionuclide concentrations throughout the study area.

Table 2. Particulate radioactivity in the national district, Santo Domingo, Dominican Republic (2023 and 2024).

Radioisotope	Minimum Bq·Kg ⁻¹	Maximum Bq·Kg ⁻¹	Mean Bq·Kg ⁻¹	Desv.Stand
²¹⁰ Pb	1.2205	5.5031	2.3324	1.0847
¹³¹ I	1.2454	22.0122	3.9400	4.5228
¹³³ Ba	1.1157	11.9233	3.1001	2.4703
²²⁶ Ra	1.4011	20.7893	5.0513	4.4913
⁹⁹ Tc	1.2786	3.6687	2.5122	0.6818
²³⁵ U	1.5698	7.3374	3.0800	1.3417
²¹⁴ Bi	0.9049	7.0317	2.4373	1.3413
⁶⁷ Ga	0.7395	5.1973	2.1279	1.1724
⁷ Be	0.1827	2.5770	0.7218	0.5753
²² Na	0.4521	7.3374	1.9503	1.4590
²²⁸ Ac	0.0000	1.4322	0.5276	0.3916
⁴⁰ K	0.2595	9.4775	2.5597	2.3420
²³² Th	0.0000	1.2229	0.4024	0.3061

The resulting interpolated surfaces revealed differences in the spatial distribution patterns of selected radionuclides across the National District (Figure 3). While some radionuclides exhibited broader and more diffuse concentration gradients extending over larger portions of the study area, others displayed more localized concentration peaks and sharper spatial transitions. Differences were also observed in the extent, continuity, and spatial arrangement of predicted values, indicating that radionuclides differed in the way concentration values were distributed throughout the sampling domain. The resulting surfaces provide a continuous representation of concentration variation between sampling locations and facilitate visualization of spatial heterogeneity among radionuclides.

Activity concentrations measured at the sampling sites showed substantial variation among radionuclides and among locations throughout the study area. The

observations presented in **Table 1** indicate differences in concentration magnitude and range among isotopes, with some radionuclides displaying relatively narrow intervals and others showing broader ranges between minimum and maximum recorded values. The distribution of observations across the nineteen sampling locations provides an overview of how radionuclide concentrations varied among sites within the National District.

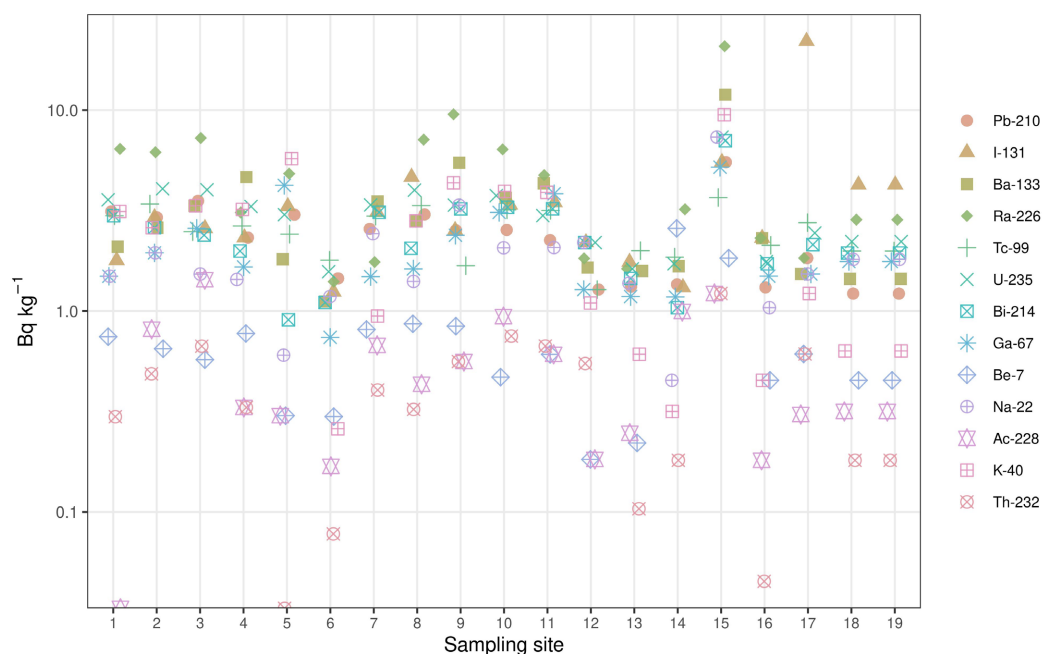


Figure 4. Activity concentrations of gamma-emitting radioisotopes across sampling sites in the National District, Santo Domingo, Dominican Republic, 2023 and 2024. Values are shown on a logarithmic scale in $\text{Bq}\cdot\text{kg}^{-1}$; points represent individual radioisotopes at each sampling site.

Standardized scores were calculated to identify observations with comparatively high or low values relative to the overall distribution of each radionuclide. Values with absolute standardized scores equal to or greater than two were considered potential global outliers. The standardized analysis identified observations exceeding the selected threshold for multiple radionuclides. Elevated standardized values were observed at several sampling locations, including Víctor Estrella Liz School, María Auxiliadora School, República Dominicana School, and UASD Faculty Club. The identified observations represent the most extreme values relative to the distribution of each radionuclide within the dataset.

The graphical representation of activity concentrations by sampling site shows that concentration values differed among radionuclides and among locations (**Figure 4**). Several sites presented comparatively higher values for one or more radionuclides, whereas other locations showed lower values across most isotopes. The logarithmic scale allowed simultaneous visualization of radionuclides with different concentration magnitudes while preserving the relative distribution of observations among sites.

5. Discussion of Results

The average value of ^{40}K in soil is $370 \text{ Bq}\cdot\text{kg}^{-1}$, so its presence in aerosols depends heavily on the amount of dust stirred up. In our case, the values did not exceed $10 \text{ Bq}\cdot\text{kg}^{-1}$, so the presence of ^{40}K in the 19 analyzed samples of particulate matter from Santo Domingo does not represent any health risk. This radioisotope is of natural origin and can be found everywhere, including in fruits and vegetables, as it is incorporated by the plant due to the lack of differentiation between ^{39}K and ^{40}K (see **Table 3**).

Table 3. Range of concentrations of Radionuclides found in various countries, with which we can compare those determined in the particulate matter of the National District of Santo Domingo, Dominican Republic.

Natural radionuclide content in soil											
Data not referenced are from UNSCEAR survey of Natural Radiation Exposures											
Region/country	Population in 1996 (10 ⁶)	Concentration in soil (Bq·kg ⁻¹)									
		⁴⁰ K		²³⁸ U		²²⁶ Ra		²³² Th			
		Mean	Range	Mean	Range	Mean	Range	Mean	Range		
Africa											
Algeria	28.78	370	66 - 1150	30	2 - 110	50	5 - 180	25	2 - 140		
Egypt	63.27	320	29 - 650	37	6 - 120	17	5 - 64	18	2 - 96		
North America											
Costa Rica	3.50	140	6 - 380	46	11 - 130	46	11 - 130	11	1 - 42		
United States [M7]	269.4	370	100 - 700	35	4 - 140	40	8 - 160	35	4 - 130		
South America											
Argentina	35.22	650	540 - 750								
East Asia											
Bangladesh	120.1	350	130 - 610			34	21 - 43				
China [P16, Z5]	1232	440	9 - 1800	33	2 - 690	32	2 - 440	41	1 - 30		
Hon Kong SAR [W12]	6019	530	80 - 1100	84	25 - 130	59	20 - 110	95	16 - 200		
India	944.6	400	38 - 760	29	7 - 81	29	7 - 81	64	14 - 160		
Japan [M5]	125.4	310	15 - 990	29	2 - 59	33	6.98	28	2 - 88		
Kazakhstan	16.82	300	100 - 200	37	12 - 120	35	12 - 120	60	10 - 220		
Korea, Rep. of	45.31	670	17 - 1500								
Malaysia	20.58	310	170 - 430	66	49 - 86	67	38 - 94	82	63 - 110		
Thailand	58.70	230	7 - 712	114	3 - 370	48	11 - 78	51	7 - 120		
West Asia											
Armenia	3.64	360	310 - 420	46	20 - 78	51	32 - 77	30	29 - 60		
Iran (Islamic Rep. of)	69.98	640	250 - 980			28	8 - 55	22	5 - 42		
Syrian Arab Republic	14.57	270	87 - 780	23	10 - 64	20	13 - 32	20	10 - 32		

^{210}Pb , which is a descendant in the decay chain of ^{226}Ra , a descendant of ^{222}Rn ,

risks into the atmosphere due to its gaseous nature, decaying into ^{210}Po , ^{214}Pb , ^{214}Bi , ^{210}Pb , and ^{210}Pb , which then precipitate and bind to the particulate matter because they are solid. The values were less than $6.0 \text{ Bq}\cdot\text{kg}^{-1}$ values that do not represent a risk human health (Flynn, 1968). Higher values have been found in tobacco from Greece ($6.3 - 18.2 \text{ Bq}\cdot\text{kg}^{-1}$), China, Italy, Brazil, and India (Schayer et al., 2007; Desideri et al., 2007; Savidou et al., 2006; Peres et al., 2002; Papastefanou, 2007).

The highest ^{131}I value exceeded $22 \text{ Bq}\cdot\text{kg}^{-1}$ representing a hotspot compared to the other sampled locations, the next highest value was $5.5 \text{ Bq}\cdot\text{kg}^{-1}$. This radioisotope is of artificial origin, so its source must be improperly disposed of as medical waste from medical centers that use it in medical treatment, primarily in nuclear medicine, to treat hyperthyroidism or goiter, kidney diseases, and differentiated thyroid cancer (papillary or follicular) (Gallegos-Villalobos et al., 2014), among other diseases. Improper waste management by medical centers, as well as by individuals undergoing treatment, often results in a failure to take radiological safety measures, exposing others. Furthermore, the waste is released into the environment (Conrad & Hilchey, 2011), where it is then carried by the wind and becomes part of atmospheric particulate matter that later settles, posing a health risk to healthy individuals. The other values did not exceed $6.0 \text{ Bq}\cdot\text{kg}^{-1}$; however, they still represent a health problem since this radioisotope should not be present in the environment under normal conditions, given its nature.

^{133}Ba is of artificial origin and is often used to calibrate gamma radiation measuring equipment. At one of the sampling points, its value was $11.9 \text{ Bq}\cdot\text{kg}^{-1}$, which represents a health risk since this element should not be present in the particulate matter. In the other samples, the values were less than $5.0 \text{ Bq}\cdot\text{kg}^{-1}$, but its presence in the particulate matter still warrants attention, as this indicates that sources of ^{133}Ba or material containing this radioisotope may be being disposed of as waste into the environment by institutions that use it to calibrate gamma emitter measuring equipment, such as medical centers, laboratories, and industries.

^{226}Ra , a naturally occurring radioisotope resulting from the decay of ^{238}U , is used in nuclear medicine, for calibrating research laboratory equipment, and in medical and industrial applications. According to the International Atomic Energy Agency (IAEA), the average value in soil is approximately $25 \text{ Bq}\cdot\text{kg}^{-1}$, although these values are typically between 50 and $60 \text{ Bq}\cdot\text{kg}^{-1}$ in uncontaminated areas. In our case, the maximum value of ^{226}Ra was $20.8 \text{ Bq}\cdot\text{kg}^{-1}$; that is, all values were below the IAEA average (UNSCEAR, 2000b). The presence of ^{226}Ra in particulate matter is the result of dust being stirred up by wind, industrial activities, and vehicles. Exposure to ^{226}Ra can cause anemia, cataracts, cancer, and even death, ^{226}Ra bioaccumulate in bones because its chemical properties are similar to those of calcium, which can cause bone cancer (Holtzman, 1962). Similar values found in this study have been reported (Sroor et al., 2001).

During the analysis of particulate samples in Santo Domingo, ^{235}U was found in all samples, with values ranging from 1.6 to $73.1 \text{ Bq}\cdot\text{kg}^{-1}$. This radioisotope is naturally occurring, and its normal value is between 0.7 and $4.0 \text{ Bq}\cdot\text{kg}^{-1}$

(UNSCEAR, 2008). Comparing the values obtained, we observed that they were normal values, not representing a health risk outside of natural environmental conditions.

Another element used in nuclear medicine is ^{99m}Tc , the most widely used, which is obtained from ^{99}Mo in nuclear reactors. It was found in the particulate matter collected in Santo Domingo. ^{99m}Tc is used in diagnostic imaging (scintigraphy, SPECT) to visualize blood flow, study organs such as the heart, brain, lungs, liver, kidneys, and thyroid, and detect tumors. Its presence in the particulate matter, between 1.0 and 4.0 $\text{Bq}\cdot\text{kg}^{-1}$, is possibly due to the improper handling of medical waste or the feces of individuals receiving the “drug” who are not following radiation protection protocols for patients. This radioisotope should not be found in the particulate matter; its presence indicates that the established protocols have not been properly followed.

^{214}Bi , a naturally occurring radioisotope resulting from the decay of ^{226}Ra and ^{222}Rn , was found in particulate matter from Santo Domingo at concentrations between 0.9 and 3.5 $\text{Bq}\cdot\text{kg}^{-1}$. This isotope is an indicator of the presence of ^{222}Rn in the environment. The average value, like the radius, is about 25 $\text{Bq}\cdot\text{kg}^{-1}$, in general, since it is in secular equilibrium with ^{226}Ra , its normal values range between 50 - 60 $\text{Bq}\cdot\text{kg}^{-1}$. The concentrations found in the Santo Domingo particulate matter are significantly lower than these averages and do not pose any unusual health risks, as there has been no enrichment due to human activity.

^{67}Ga , used to identify infectious foci and chronic inflammatory processes, was also found in the Santo Domingo particulate matter at concentrations between 0.7 and 5.2 $\text{Bq}\cdot\text{kg}^{-1}$. Due to its affinity for plasma proteins and inflammatory cells, it is susceptible to accumulating in tissues, making it an excellent tracer. This is why it is used in nuclear medicine for scintigraphy of neoplasms, cancers, and osteomyelitis. ^{67}Ga is produced in cyclotrons by bombarding zinc nuclei with protons. Its presence in particulate matter originates from the deposition of medical waste and from patients who are exposed to it. When on the ground, it is lifted by the wind, mixing with soil dust particles that then settle elsewhere. Although its half-life is relatively short, it poses a health risk to people who are unknowingly exposed by coming into contact with particulate matter contaminated with the ^{67}Ga radioisotope.

As expected, we found ^7Be in the particulate matter. ^7Be is a radioisotope produced by the bombardment of nitrogen or oxygen by particles from space, and it is found in the soil through deposition by rain. It also binds to particulate matter in the atmosphere before it falls and is lifted again by the wind, mixing with the particulate matter. Its concentrations ranged from 0.2 to 2.6 $\text{Bq}\cdot\text{kg}^{-1}$. Like other radioisotopes, whether natural or artificial, ^7Be can pose a health risk when its concentration exceeds tolerable levels, causing damage to susceptible organs.

Another element of space origin, and whose concentration in soil and particulate matter is generally at trace levels, was ^{22}Na . Its concentrations ranged from 0.5 to 7.5 $\text{Bq}\cdot\text{kg}^{-1}$ in particulate matter from Santo Domingo. This radioisotope is

commonly used in positron emission tomography (PET). The abundance of particulate matter could be related to improperly dispose medical waste from the medical centers that use it and/or from patients. When dispersed by the wind, it became part of the particulate matter that later settled and was collected at the sampling sites.

Another radioactive element found was ^{228}Ac , with concentrations ranging from 0 to $1.5 \text{ Bq}\cdot\text{kg}^{-1}$. ^{228}Ac is naturally occurring. Its presence in the particulate matter is due to natural causes and is a result of the decay chain of ^{232}Th , which is also present in the particulate matter. Like all radionuclides, high concentrations represent a health risk.

The concentrations of ^{232}Th in the particulate matter samples from Santo Domingo ranged from 0 to $1.3 \text{ Bq}\cdot\text{kg}^{-1}$. This radioisotope is naturally occurring, so it is normal to find it in particulate matter. Its concentrations do not represent a risk beyond what is normal for naturally occurring radioisotopes. Higher values have been found in other locations; for example, Th-232 values found in soils from Bahr El-Baqar, Egypt, ranged from 3.71 to $10.26 \text{ Bq}\cdot\text{kg}^{-1}$ (El-Farrash et al., 2012). Because this study was intended as a preliminary exploratory assessment of radionuclide occurrence in atmospheric particulate matter, a detailed comparison with international regulatory exposure limits and dose-based standards was beyond the scope of the present work.

6. Conclusions

Although the present study is exploratory in nature, the detection of both natural and anthropogenic radionuclides in atmospheric particulate matter highlights the need for more comprehensive long-term investigations with larger sample sets and detailed radiological assessments. The presence of radioisotopes in particulate matter in the city of Santo Domingo originates from both natural and artificial radionuclides. The most significant natural isotopes found were ^{210}Pb , ^{226}Ra , ^{235}U , ^7Be , ^{22}Na , ^{40}K , ^{228}Ac , and ^{232}Th . The ^{22}Na concentrations do not correspond solely to ambient sodium, but also to the improper disposal of medical waste from positron emission tomography (PET) calibration and diagnostic procedures. The use of the radioisotopes ^{131}I , ^{99}Tc , ^{67}Ga , and ^{133}Ba as drugs in medical diagnosis and treatment is very common in nuclear medicine. Their presence in particulate matter indicates that waste is being mishandled by medical and diagnostic centers, as well as by patients in the city of Santo Domingo, who are exposing it to the public. This poses a health risk because water and wind disperse the particulate matter. The highest concentrations were found near nuclear medicine diagnostic and treatment centers.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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