Uddin et al. J Environ Expo Assess 2024;3:3
DOI: 10.20517/jeea.2023.36

Journal of Environmental Exposure Assessment

Perspective

Open Access

Climate change - mediated atmospheric ^{210}Po and ^{210}Pb distribution: How significant can it be for the inhalation dose to humans?

Saif Uddin[1], Aysun U. Gorgun[2], Scott W. Fowler[3], Montaha Behbehani[1], Nazima Habibi[1], Isik Filizok[4], Mohammad Al-Murad[1]

[1]Environment and Life Sciences Research Centre, Kuwait Institute for Scientific Research, Safat 13109, Kuwait.
[2]Institute of Nuclear Sciences, EGE University, Bornova, Izmir 35040, Türkiye.
[3]Institute Bobby, 8 Allee des Orangers, Cap d'Ail 06320, France.
[4]Bornova, Izmir 35050, Türkiye.

Correspondence to: Dr. Saif Uddin, Environment and Life Sciences Research Centre, Kuwait Institute for Scientific Research, PO Box 24885, Safat 13109, Kuwait. E-mail: sdin@kisr.edu.kw

How to cite this article: Uddin S, Gorgun AU, Fowler SW, Behbehani M, Habibi N, Filizok I, Al-Murad M. Climate change - mediated atmospheric ^{210}Po and ^{210}Pb distribution: How significant can it be for the inhalation dose to humans? *J Environ Expo Assess* 2024;3:3. https://dx.doi.org/10.20517/jeea.2023.36

Received: 26 Sep 2023 **First Decision:** 17 Nov 2023 **Revised:** 29 Nov 2023 **Accepted:** 15 Dec 2023 **Published:** 26 Dec 2023

Academic Editors: Stuart Harrad, Choong-Min Kang **Copy Editor:** Yanbing Bai **Production Editor:** Yanbing Bai

Abstract

The concentration of ^{210}Po and ^{210}Pb in vegetation, and their transfer from soil to vegetation and via aerosol deposited on foliage are well established. The available data show significantly higher levels of these radionuclides in ash from forest fires and aerosols downwind from industrial sites. The climate change-induced hot and dry conditions promote the spread of forest fires, which burn huge areas. On average, over 10 million hectares are reportedly lost annually. Large-scale forest fires and fossil-fuel and coal-operated Power and Desalination Plants are very likely to result in the dispersion of ^{210}Pb and ^{210}Po into the regional aerosol; such an effect has already been observed due to fires in Ukraine, Belarus, and Russia, which have led to the dispersion of ^{137}Cs over large parts of Europe. We have measured elevated levels in Kuwait, and similar observations have been reported from Portugal. The higher levels of ^{210}Po in $PM_{2.5}$ raise a serious concern about an increased inhalation dose humans could receive. Our estimate shows that humans in areas affected by forest fires might receive a dose equivalent to 2 µSv d^{-1}, which is significantly higher than 0.099 µSv d^{-1}, the dose a person gets from smoking a packet of cigarettes daily. We propose that size-fractionated aerosol sampling should be taken up in regions affected by forest fires and industrial activities that add ^{210}Po to the atmosphere in order to obtain a robust inhalation dose assessment and issue informed advisories to the public.

Keywords: Forest fires, ^{210}Po, ^{210}Pb, size-fractionated aerosol, inhalation, dose, $PM_{2.5}$

INTRODUCTION

The ubiquitous presence of ^{238}U and ^{232}Th in the environment and vegetation has been reported. Polonium-210 and lead-210 are naturally occurring radioactive isotopes and are part of the uranium radioactive decay series. Polonium-210 has a 138-day half-life, while radioactive lead-210 has a much longer half-life of 22.2 years. Both ^{210}Po and ^{210}Pb are produced as part of the decay chain of radon gas (^{222}Rn), which itself has a half-life of 3.8 days[1]. Radon, a noble gas, has a neutral electric charge, but its radioactive daughters, ^{210}Po and ^{210}Pb, are positively charged ions. These ions are highly reactive and quickly attach to airborne particles. Polonium-210 ions in the atmosphere rapidly become attached to aerosol particles within a relatively short time frame, ranging from 40 to 180 seconds after their formation from the radioactive decay of precursor radon[2]. This attachment to particles is a key factor in their atmospheric dispersion. Dry and wet atmospheric depositions continuously remove radon daughters from the atmosphere. This removal process prevents the establishment of a secular radioactive equilibrium between radon and its progeny, including ^{210}Po and ^{210}Pb. As a result, there is a significant radioactive disequilibrium between ^{210}Po and ^{210}Pb in the environment.

The $^{210}Po/^{210}Pb$ ratio in the aerosols is generally much lower than 0.1 due to the ongoing removal of radon daughters from the atmosphere[3,4]. Consequently, the concentration of ^{210}Po is typically much lower than that of ^{210}Pb in aerosol samples. This aspect highlights the dynamic behavior of these radionuclides in the atmosphere and their connection to the decay of radon gas, leading to a significant radioactive disequilibrium between ^{210}Po and ^{210}Pb in natural settings[5]. This disequilibrium is vital to consider when studying environmental radioactivity, including the mean residence time of aerosols ($^{210}Bi/^{210}Pb$ ratios for recent air mass up to a few days[5,6], and $^{210}Po/^{210}Pb$ for older air mass of a month or more[7,8]) and their potential health effects[9,10].

While the radioactive decay of atmospheric radon is one source of ^{210}Po and ^{210}Pb, later research has identified additional sources, including volcanic emissions, industrial facilities, forest fires, coal burning, and nuclear weapons tests[11-17]. These sources can release significant quantities of ^{210}Po and sometimes ^{210}Pb into the atmosphere. Fossil fuel and coal-based Power and Desalination plants and Oil refineries are known to contribute to significantly higher concentrations of ^{210}Po and ^{210}Pb[18,19]. Importantly, these additional sources can significantly increase the $^{210}Po/^{210}Pb$ ratios in the atmosphere[14,17]. Both ^{210}Po and ^{210}Pb can be inhaled when they are adhered to ultra-fine particles in the air. This type of exposure to these radionuclides can result in internal radiation doses to human beings [Figure 1], particularly from ^{210}Po, which is generally higher than other naturally occurring radionuclides, except for radon[20]. The activity-to-dose conversion factor is 2.2 μSv/Bq for inhaled ^{210}Po[21], which is higher than other naturally occurring radionuclides, including ^{210}Pb.

The redistribution of ^{137}Cs was first noticed in Europe after the extensive forest fires in Ukraine, Belarus, and Russia during 2010[22]. However, not much attention has been given to natural radionuclides associated with vegetation that are released into the atmosphere during forest fires[14,23]. Given the potential health risks associated with exposure to ^{210}Po and ^{210}Pb, monitoring their presence and redistribution in the environment consequent to forest fires is crucial. With an increase in the frequency of forest fires globally, mainly due to climate change, about 9.3×10^6 hectares of tree cover were lost in 2021, and Russia alone lost 5.4×10^6 hectares of tree cover to fire in 2021[24]. The more recent statistics are even more striking; the Forest Fire Centre, Canada estimated an area of 9.5×10^6 hectares was burned in the seven months of 2023, between January and July, keeping in view the recurrence and increasing spatial scale of the forest fires, it is quite likely that the activity concentration of ^{210}Po, ^{210}Pb and other radionuclides could be considerably enhanced

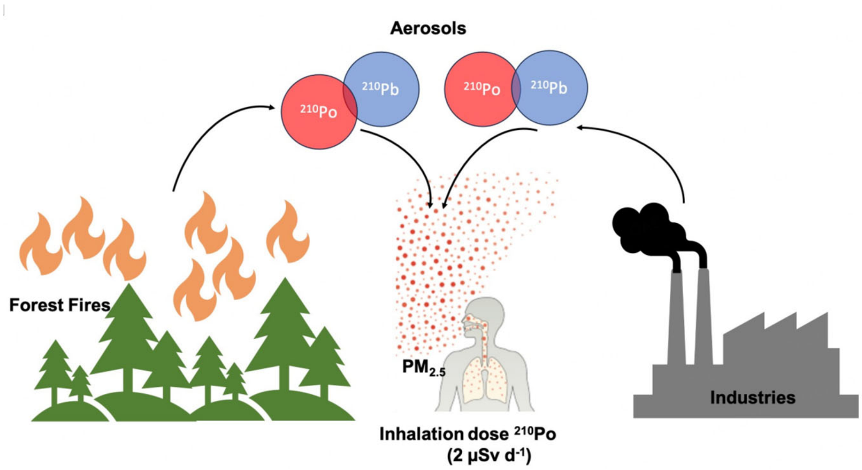

Figure 1. Graphical representation of ^{210}Po and ^{210}Pb sources and a likely inhalation dose.

in the surface air over areas beyond the charred forests.

RESULTS AND DISCUSSION

Certain investigations have documented ^{210}Po/^{210}Pb ratios surpassing one. These escalated ratios are frequently linked to the release of ^{210}Po from human-made sources involving high temperatures, such as metal smelters, ceramic kilns, incinerators, and forest fires[2,3,10,17,25-27]. Studies analyzing radionuclides in aerosols have revealed that a significant amount of polonium activity is associated with fine and ultrafine aerosol particles. In Japan, over 70% of ^{210}Po activity in aerosols was detected in particles smaller than 0.7 μm[28]. In Poland, 82% of ^{210}Po found in aerosols was measured within the particle size range of 0.1 - 0.3 μm, primarily attributed to emissions from industrial sources[27]. Similarly, in Portugal, research on smoke from vegetation and forest fires indicated that most of the ^{210}Po in aerosols were linked to particles smaller than 1 μm. Kuwait has also reported relatively high levels of ^{210}Po in aerosols countrywide. The major fraction of this activity was identified in the fine fraction of aerosol particulates, specifically in the size range of 0.39 - 2.5 μm[18,19,29], consistent with observations in other studies[2,3,10,14-16,19,27,30-36].

Several studies have highlighted the concentration of ^{210}Po and ^{210}Pb in vegetation [Table 1] and aerosols [Table 2]. The concentration in vegetation samples exhibited ^{210}Pb concentrations ranging from 0.98 to 20.27 Bq kg^{-1} and ^{210}Po concentrations ranging from 0.97 to 49.4 Bq kg^{-1}, where the aerosol-containing combusted particles showed a significant increase in ^{210}Po and ^{210}Pb concentrations. A significant variation in ^{210}Po levels was observed in non-fire impacted aerosol in which the ^{210}Po on the filter sample was 111 Bq kg^{-1}[17], while in fly ash collected on filters of an aerosol sampler, concentrations varied between 3,604 - 7,255 Bq kg^{-1} and was 1,115 Bq kg^{-1} in ground ash from forest fires. The enhanced concentration of ^{210}Po in fly ash was a result of forest fire-contributed aerosol.

Since ^{210}Po and ^{210}Pb are non-essential for any growth and metabolic functions in plants, a detailed study has provided data to underpin the hypothesis that both ^{210}Po and ^{210}Pb are taken up by plants from soil[37]. In spite of the restrictive uptake of potentially toxic elements by plants in metalliferous soils, ^{210}Po and ^{210}Pb accumulation has been observed in both metal-tolerant and non-tolerant plants[38]. ^{210}Pb and ^{210}Po enter the vegetation through root uptake and aerial deposition on foliage[39].

Table 1. ^{210}**Pb and** ^{210}**Po concentration (in Bq kg**$^{-1}$ **dry weight) in various plants, and soil**

Country	Sample	^{210}Pb	^{210}Po	Reference
Viseu region, North Portugal, (late summer 2012)	Citrus bushes	9.90 ± 0.35	12.0 ± 2.4	[16]
	Oak tree trunk wood	3.27 ± 0.16	5.51 ± 0.02	
	Oak tree, leaves	17.2 ± 0.4	30.8 ± 1.2	
	Eucalyptus, trunk wood	0.98 ± 0.03	1.68 ± 0.05	
	Eucalyptus bark	1.88 ± 0.09	2.60 ± 0.06	
	Eucalyptus leaves	10.3 ± 0.4	49.4 ± 2.3	
	Acacia tree, trunk wood	2.04 ± 0.05	4.05 ± 0.15	
	Acacia tree, leaves	20.27 ± 0.47	8.61 ± 0.33	
	Pine tree trunk wood	1.43 ± 0.13 to 1.98 ± 0.09	0.97 ± 0.003 to 1.53 ± 0.006	
	Pine tree, bark	2.80 ± 0.08	2.87 ± 0.06	
	Pine tree, needle (leaves)	10.36 ± 0.31	3.10 ± 0.08	
	Ashes from the ground after forest fire	402 ± 6	1115 ± 66	
	Size fractionated aerosol (Fly ash)	923 ± 53 to 2070 ± 88	3604 ± 148 to 7255 ± 285	
	Aerosol (without fire smoke)	5895 ± 218	114 ± 7	
Wyoming, USA	Soil	0.1073 ± 0.02 to 3.108 ± 0.24	0.078 ± 0.009 to 2.997 ± 0.333	[38]
	Sagebrush	0.016 ± 0.006 to 0.051 ± 0.034	0.022 ± 0.003 to 0.198 ± 0.107	
	Mixed grasses	0.020 ± 0.008 to 0.481 ± 0.159	0.020 ± 0.004 to 0.355 ± 0.112	
	Mixed Forbs	0.031 ± 0.003 to 0.322 ± 0.199	0.008 ± 0.001 to 0.777 ± 0.249	
	All plants	0.021 ± 0.003 to 0.444 ± 0.126	0.017 ± 0.003 to 0.577 ± 0.145	
Portugal	Cabbage leaves	0.435	0.044	[16]
	Maize aerial parts	0.304	0.217	
	Olive tree leaves	22.381	2.50	
	Olive tree trunk wood	10.24	0.333	
	Olive tree roots	3.333	2.619	
	Palm tree leaves	12.857	2.548	
	Palm Tree bark	0.786	0.214	
	Tobacco leaves (cured)	11.90	11.19	
	Soil (0 - 30 cm)	100	100	

The evidence of the accumulation of these radionuclides in vegetation is explicit. The edibles (fruits and vegetables) are likely to contribute to the internal radiation dose to consumers. The data are compelling that ^{210}Po and ^{210}Pb are significantly incorporated in these fruits and vegetables, which follow a non-linear uptake pattern mathematically. Plant concentration for ^{210}Pb is expressed as

$$Vegetation\ Concentration = 0.74\left(1 - e^{-1.4 concentration\ in\ substrate}\right) + 0.16_{concentration\ in\ substrate},$$

while for ^{210}Po, the concentration is expressed as:

$$Vegetation\ Concentration = 70.0 \times 1.08^{-350.0\, x\, 1.08^{-0.4 concentration\ in\ substrate}} + 1.2$$

Table 2. ^{210}**Pb and** ^{210}**Po concentration (in Bq kg**$^{-1}$ **dry weight) in aerosols**

Country	Sample	^{210}Pb	^{210}Po	Reference
Viseu region, North Portugal, (late summer 2012)	Size fractionated aerosol (Fly ash)	923 ± 53 to 2070 ± 88	3604 ± 148 to 7255 ± 285	[16]
	Aerosol (without fire smoke)	5895 ± 218	114 ± 7	
Kuwait, January 2018 - November 2019	Aerosol PM $_{\geq 10}$ (R,Su)		228 - 279	[19, 29, 41]
	Aerosol PM $_{\geq 10}$ (U, Su)		252 - 288	
	Aerosol PM $_{\geq 10}$ (I, Su)		370 - 406	
	Aerosol PM $_{\geq 10}$ (R, Au)		199 - 210	
	Aerosol PM $_{\geq 10}$ (U, Au)		207 - 245	
	Aerosol PM $_{\geq 10}$ (I, Au)		311 - 344	
	Aerosol PM $_{\geq 10}$ (R, Wi)		121 - 176	
	Aerosol PM $_{\geq 10}$ (U, Wi)		133 - 190	
	Aerosol PM $_{\geq 10}$ (I, Wi)		288 - 301	
	Aerosol PM $_{\geq 10}$ (R, Sp)		155 - 193	
	Aerosol PM $_{\geq 10}$ (U, Sp)		170 - 198	
	Aerosol PM $_{\geq 10}$ (I, Sp)		305 - 336	
	Aerosol PM$_{2.5-10}$ (R,Su)		303 - 342	
	Aerosol PM$_{2.5-10}$ (U, Su)		288 - 326	
	Aerosol PM$_{2.5-10}$ (I, Su)		406 - 411	
	Aerosol PM$_{2.5-10}$ (R, Au)		265 - 278	
	Aerosol PM$_{2.5-10}$ (U, Au)		294 - 451	
	Aerosol PM$_{2.5-10}$ (I, Au)		349 - 387	
	Aerosol PM$_{2.5-10}$ (R, Wi)		190 - 223	
	Aerosol PM$_{2.5-10}$ (U, Wi)		252 - 284	
	Aerosol PM$_{2.5-10}$ (I, Wi)		330 - 335	
	Aerosol PM$_{2.5-10}$ (R, Sp)		220 - 251	
	Aerosol PM$_{2.5-10}$ (U, Sp)		252 - 284	
	Aerosol PM$_{2.5-10}$ (I, Sp)		352 - 403	
	Aerosol PM$_{0.39-2.5}$ (R,Su)		515 - 596	
	Aerosol PM$_{0.39-2.5}$ (U, Su)		705 - 746	
	Aerosol PM$_{0.39-2.5}$ (I, Su)		944 - 960	
	Aerosol PM$_{0.39-2.5}$ (R, Au)		481 - 502	
	Aerosol PM$_{0.39-2.5}$(U, Au)		631 - 698	
	Aerosol PM$_{0.39-2.5}$ (I, Au)		903 - 913	
	Aerosol PM$_{0.39-2.5}$(R, Wi)		435 - 436	
	Aerosol PM$_{0.39-2.5}$(U, Wi)		572 - 661	
	Aerosol PM$_{0.39-2.5}$ (I, Wi)		863 - 904	
	Aerosol PM$_{0.39-2.5}$ (R, Sp)		466 - 479	
	Aerosol PM$_{0.39-2.5}$ (U, Sp)		606 - 700	
	Aerosol PM$_{0.39-2.5}$ (I, Sp)		896 - 897	
Vienna, Austria*	Aerosol PM$_{0.15-0.3}$ (23.04.1996)	7.5 ± 0.4	1.5 ± 0.17	[42]
	Aerosol PM$_{0.3-0.6}$ (23.04.1996)	17.4 ± 0.7	1.8 ± 0.17	
	Aerosol PM$_{0.6-1.2}$ (23.04.1996)	14.6 ± 1.0	2.2 ± 0.2	
	Aerosol PM$_{1.2-2.4}$ (23.04.1996)	3.85 ± 0.3	0.2 ± 0.03	
	Aerosol PM$_{2.4-5.0}$ (23.04.1996)	1.9 ± 0.2		
	Aerosol PM$_{5.0-10}$ (23.04.1996)	0.88 ± 0.1		
	Aerosol PM$_{0.15-0.3}$ (12.06.1996)	9.3 ± 0.5	0.55 ± 0.08	
	Aerosol PM$_{0.3-0.6}$ (12.06.1996)	15 ± 0.7	0.5 ± 0.08	
	Aerosol PM$_{0.6-1.2}$ (12.06.1996)	15.8 ± 0.7	0.52 ± 0.08	

	Aerosol $PM_{1.2-2.4}$ (12.06.1996)	3.15 ± 0.2	
	Aerosol $PM_{2.4-5.0}$ (12.06.1996)	0.95 ± 0.1	0.2 ± 0.04
	Aerosol $PM_{0.15-0.3}$ (12.08.1996)	12.4 ± 0.5	1.33 ± 0.15
	Aerosol $PM_{0.3-0.6}$ (12.08.1996)	13.7 ± 0.7	0.7 ± 0.1
	Aerosol $PM_{0.6-1.2}$ (12.08.1996)	6.5 ± 0.4	
	Aerosol $PM_{1.2-2.4}$ (12.08.1996)	1.7 ± 0.2	
	Aerosol $PM_{0.15-0.3}$ (2.10.1996)	3.3 ± 0.40	0.19 ± 0.12
	Aerosol $PM_{0.3-0.6}$ (2.10.1996)	5.5 ± 0.50	0.62 ± 0.15
	Aerosol $PM_{0.6-1.2}$ (2.10.1996)	4.8 ± 0.50	0.19 ± 0.12
	Aerosol $PM_{1.2-2.4}$ (2.10.1996)	0.7 ± 0.30	0.17 ± 0.13
	Aerosol $PM_{2.4-5.0}$ (2.10.1996)	0.25 ± 0.23	0.24 ± 0.14
	Aerosol $PM_{0.15-0.3}$ (13.11.1996)	7.5 ± 0.4	12.3 ± 0.5
	Aerosol $PM_{0.3-0.6}$ (13.11.1996)	10.5 ± 0.6	2 ± 0.2
	Aerosol $PM_{0.6-1.2}$ (13.11.1996)	10.2 ± 0.6	0.7 ± 0.1
	Aerosol $PM_{1.2-2.4}$ (13.11.1996)	1.2 ± 0.1	0.2 ± 0.04
	Aerosol $PM_{2.4-5.0}$ (13.11.1996)	1.9 ± 0.2	0.2 ± 0.04
	Aerosol $PM_{5.0-10}$ (13.11.1996)	0.7 ± 0.1	0.07 ± 0.02
	Aerosol $PM_{0.15-0.3}$ (17.12.1996)	10.8 ± 0.6	0.5 ± 0.2
	Aerosol $PM_{0.3-0.6}$ (17.12.1996)	25 ± 0.9	0.9 ± 0.2
	Aerosol $PM_{0.6-1.2}$ (17.12.1996)	38.8 ± 1.3	0.8 ± 0.2
	Aerosol $PM_{1.2-2.4}$ (17.12.1996)	20 ± 0.9	0.5 ± 0.1
	Aerosol $PM_{2.4-5.0}$ (17.12.1996)	1.2 ± 0.3	0.1 ± 0.1
	Aerosol $PM_{5.0-10}$ (17.12.1996)	5.8 ± 0.4	0.1 ± 0.1
	Aerosol $PM_{0.15-0.3}$ (12.02.1997)	4.8 ± 0.3	0.69 ± 0.1
	Aerosol $PM_{0.3-0.6}$ (12.02.1997)	7.7 ± 0.4	1.45 ± 0.15
	Aerosol $PM_{0.6-1.2}$ (12.02.1997)	5.8 ± 0.4	0.33 ± 0.05
	Aerosol $PM_{1.2-2.4}$ (12.02.1997)	1.3 ± 0.1	0.26 ± 0.05
	Aerosol $PM_{2.4-5.0}$ (12.02.1997)	1.1 ± 0.1	
	Aerosol $PM_{0.15-0.3}$ (11.03.1997)	6.4 ± 0.4	1.4 ± 0.2
	Aerosol $PM_{0.3-0.6}$ (11.03.1997)	11.8 ± 0.6	1.4 ± 0.2
	Aerosol $PM_{0.6-1.2}$ (11.03.1997)	7.2 ± 0.4	0.98 ± 0.18
	Aerosol $PM_{1.2-2.4}$ (11.03.1997)	1.7 ± 0.2	0.3 ± 0.05
	Aerosol $PM_{2.4-5.0}$ (11.03.1997)	0.4 ± 0.04	
	Aerosol $PM_{0.15-0.3}$ (29.04.1997)	3.6 ± 0.3	
	Aerosol $PM_{0.3-0.6}$ (29.04.1997)	5.9 ± 0.4	0.12 ± 0.03
	Aerosol $PM_{0.6-1.2}$ (29.04.1997)	3.3 ± 0.3	
	Aerosol $PM_{1.2-2.4}$ (29.04.1997)	1.2 ± 0.1	
	Aerosol $PM_{2.4-5.0}$ (29.04.1997)	1.8 ± 0.2	
	Aerosol $PM_{0.15-0.3}$ (21.05.1997)	3.3 ± 0.25	
	Aerosol $PM_{0.3-0.6}$ (21.05.1997)	5.9 ± 0.4	0.14 ± 0.03
	Aerosol $PM_{0.6-1.2}$ (21.05.1997)	4 ± 0.28	0.07 ± 0.02
	Aerosol $PM_{1.2-2.4}$ (21.05.1997)	0.8 ± 0.08	
	Aerosol $PM_{2.4-5.0}$ (21.05.1997)	0.2 ± 0.02	
Badgastein, Austria*	Aerosol $PM_{0.15-0.3}$ (09.01.1999)	9.5 ± 0.5	1.7 ± 0.2
	Aerosol $PM_{0.3-0.6}$ (09.01.1999)	7.9 ± 0.4	
	Aerosol $PM_{0.6-1.2}$ (09.01.1999)	4.7 ± 0.3	
	Aerosol $PM_{1.2-2.4}$ (09.01.1999)	0	
	Aerosol $PM_{0.15-0.3}$ (28.05.1999)	14.3 ± 0.6	0.85 ± 0.10
	Aerosol $PM_{0.3-0.6}$ (28.05.1999)	24.9 ± 0.9	1.04 ± 0.20
	Aerosol $PM_{0.6-1.2}$ (28.05.1999)	11.5 ± 0.6	0.76 ± 0.10
	Aerosol $PM_{1.2-2.4}$ (28.05.1999)	1.7 ± 0.1	

Stubnerkogel, Austria*	Aerosol $PM_{0.15-0.3}$ (25.05.1999)	22.8 ± 0.9	4.1 ± 0.3
	Aerosol $PM_{0.3-0.6}$ (25.05.1999)	11.3 ± 0.6	1.5 ± 0.2
	Aerosol $PM_{0.6-1.2}$ (25.05.1999)	7.8 ± 0.5	1.2 ± 0.1
	Aerosol $PM_{1.2-2.4}$ (25.05.1999)	1.1 ± 0.1	0.5 ± 0.1
	Aerosol $PM_{0.15-0.3}$ (27.05.1999)	8.9 ± 0.5	1 ± 0.12
	Aerosol $PM_{0.3-0.6}$ (27.05.1999)	10.5 ± 0.5	0.6 ± 0.08
	Aerosol $PM_{0.6-1.2}$ (27.05.1999)	9 ± 0.5	0.6 ± 0.08
	Aerosol $PM_{1.2-2.4}$ (27.05.1999)	0.9 ± 0.1	

R: Remote Site; U: Urban Site; I: downwind of Industrial Site; Su: Summer; Au: Autumn; Wi: winter; Sp: Spring; *: in mBq/100 m^3 air.

The data depict that bioaccumulation takes place at even lower substrate concentrations and ^{210}Po accumulation exceeds ^{210}Pb by about a factor of 2[37]. The much higher ^{210}Po and ^{210}Pb concentrations in aerosols emanating from forest fires, power and desalination plants, and oil installations highlight the considerable dose humans can get from inhalation. The issue is exacerbated given that frequent forest fires are linked to climate change. An extensive area is lost to forest fires year after year globally, most recently in Australia, Canada, Spain, Belarus, Russia, Portugal, and Turkiye. A very detailed spatial distribution of forest fires[24] provides an overview of approximately 10 million hectares of forest lost yearly.

It will be quite imperative to conduct aerosol sampling and define the concentration of these radionuclides in size-fractionated aerosols. We have found a six-stage cascade impactor mounted on a high-volume air sampler to be very effective in determining radioactivity in respirable and inhalable fractions[19,29,40,41]. The likelihood of volatilization of ^{210}Po in forest fires is relatively high as temperatures above 1,000 °C have been reported from forest fires[17]. The considerable reduction of volume due to fire and the positive charge of gaseous ^{210}Po can result in the recapture of ^{210}Po and ^{210}Pb on ash particles, resulting in higher concentrations of these radionuclides in ash and aerosols.

The highest concentration of ^{210}Po in the vicinity of forest fires and downwind industrial sites is associated with $PM_{0.39-2.5}$ and $PM_{2.5-10}$ sizes. Considering an average breathing rate of 6 L min^{-1}, an adult breathes about 8.64 m^3 daily. The ^{210}Po concentration in forest fires in Portugal was reported as 70 mBq m^{-3}, resulting in an inhalation rate of 0.605 Bq d^{-1}. Using the dose conversion factor of 3.3×10^{-6} Sv Bq^{-1}, a 2 μSv d^{-1} dose is imparted due to inhalation; although it is not a permanent event, it can extend for weeks and months. It is interesting to put it in perspective: an individual who smokes a packet of cigarettes daily gets about 0.099 μ Sv d^{-1}, which is significantly lower than the population exposure during forest fires.

CONCLUSION

Forest fires play a significant role in the redistribution of ^{210}Po and ^{210}Pb. These fires not only release these isotopes into the atmosphere but also facilitate their transport over considerable distances. The combustion of organic matter during forest fires liberates substantial quantities of ^{210}Po and ^{210}Pb into the air, where they can attach to aerosol particles. Studies have shown that these isotopes often exhibit elevated concentration ratios in the aftermath of forest fires, surpassing unity in some instances.

The resultant aerosols, laden with ^{210}Po and ^{210}Pb, disperse throughout the atmosphere. Fine and ultrafine aerosol particles become carriers for a significant portion of these isotopes. Research has indicated that a substantial percentage, sometimes over 70%, of ^{210}Po activity in aerosols is associated with particles smaller than 2.5 μm. The ultrafine particles are reported to have the highest levels of these isotopes post-forest fires. This pattern aligns with observations not only in forests but also in areas affected by other combustion sources, such as industrial emissions across different geographical locations. The highest concentrations are observed in inhalable and respirable fractions of the aerosols that are more likely to enhance the radiation dose humans receive due to inhalation, i.e., the ~2 μSv d^{-1} dose from forest fires and ~ 0.002 - 0.042 μSv d^{-1} dose from industrial emissions. From the dose perspective, the climate change-mediated fires and increase in fossil fuel and coal-based power generation are likely to result in the redistribution of ^{210}Po and ^{210}Pb and impart a dose that is several orders of magnitude higher than the normal background doses and likely to significantly contribute to the 1 mSv permissible annual dose.

Understanding the dynamics of ^{210}Po and ^{210}Pb redistribution in the aftermath of forest fires is crucial for comprehending their environmental impact and potential implications for human health. Tracking the dispersion of these radionuclides and their attachment to aerosols can shed light on the broader implications of these natural events on atmospheric radioactivity and the subsequent exposure risks to ecosystems and populations downwind from these fire-affected regions.

DECLARATIONS

Acknowledgments

The authors appreciate the Kuwait Institute for Scientific Research's support for project EM090C and the Kuwait Foundation for Advancements of Sciences for partially supporting the study PR18-14SE-01. The authors would also like to thank the Institute of Nuclear Sciences, EGE University, Turkiye for supporting the aerosol study.

Authors' contributions

Conceptualized and designed the study: Uddin S
Performed data analysis: Gorgun AU, Behbehani M, Habibi N
Helped with the interpretation: Fowler SW , Filizok I
Done the data acquisition: Uddin S, Behbehani M.
Provided the technical and material support: Fowler SW, Al-Murad M, Uddin S

Availability of data and materials

Not applicable.

Financial support and sponsorship

Kuwait Institute for Scientific Research funding for project EM090C and Kuwait Foundation for Advancement of Sciences grant PR18-14SE-01. The funding bodies had no role in the experiment design, collection, analysis and interpretation of data, and writing of the manuscript.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

REFERENCES

1. Baskaran M. Radon: a tracer for geological, geophysical and geochemical studies. Springer Cham; 2016. p. 260.
2. Długosz-Lisiecka M. Excess of ^{210}polonium activity in the surface urban atmosphere. Part (1) fluctuation of the ^{210}Po excess in the air. *Environ Sci Process Impacts* 2015;17:458-64. DOI PubMed
3. Długosz-Lisiecka M. The sources and fate of ^{210}Po in the urban air: A review. *Environ Int* 2016;94:325-30. DOI PubMed
4. UNSCEAR report. Sources, effects and risks of ionising radiation. Available from: https://www.unscear.org/unscear/en/publications/1988.html [Last accessed on 27 Dec 2023].
5. Poet SE, Moore HE, Martell EA. Lead 210, bismuth 210, and polonium 210 in the atmosphere: Accurate ratio measurement and application to aerosol residence time determination. *J Geophys Res* 1972;77:6515-27. DOI
6. Papastefanou C, Bondietti E. Mean residence times of atmospheric aerosols in the boundary layer as determined from 210Bi/210Pb activity ratios. *J Aerosol Sci* 1991;22:927-31. DOI
7. Peirson DH, Cambray RS, Spicer GS. Lead-210 and polonium-210 in the atmosphere. *Tellus* 1966;18:427-33. DOI
8. Nevissi A, Beck JN, Kuroda PK. Long-lived radon daughters as atmospheric radioactive tracers. *Health Phys* 1974;27:181-8. DOI PubMed
9. Semertzidou P, Piliposian GT, Appleby PG. Atmospheric residence time of ^{210}Pb determined from the activity ratios with its daughter radionuclides ^{210}Bi and ^{210}Po. *J Environ Radioactiv* 2016;160:42-53. DOI
10. Baskaran M. Po-210 and Pb-210 as atmospheric tracers and global atmospheric Pb-210 fallout: a review. *J Environ Radioact* 2011;102:500-13. DOI PubMed
11. Carvalho FP. Origins and concentrations of ^{222}Rn, ^{210}Pb, ^{210}Bi and ^{210}Po in the surface air at Lisbon, Portugal, at the Atlantic edge of the European continental landmass. *Atmospheric Environment* 1995;29:1809-19. DOI
12. Ram K, Sarin M. Atmospheric ^{210}Pb, ^{210}Po and ^{210}Po/^{210}Pb activity ratio in urban aerosols: temporal variability and impact of biomass burning emission. *Tellus B: Chemical and Physical Meteorology* 2012;64:17513. DOI
13. Yi Y, Zhou P, Liu G. Atmospheric deposition fluxes of ^{7}Be, ^{210}Pb and ^{210}Po at Xiamen, China. *J Radioanal Nucl Chem* 2007;273:157-62. DOI
14. Carvalho FP, Oliveira JM, Malta M. Vegetation fires and release of radioactivity into the air. W*IT Trans Biomed Health* 2011;15:3-9. DOI
15. Carvalho FP, Oliveira JM, Malta M. Exposure to forest fires, radioactivity and health risks. 8th International Symposium on Occupational Safety and Hygiene (SHO); 2012 126-130. Available from: https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/2648989 [Last accessed on 22 Dec 2023].
16. Uddin S, Fowler SW, Behbehani M. ^{210}Po in the environment: reassessment of dose to humans. *Sustainability* 2023;15:1674. DOI
17. Carvalho FP, Oliveira JM, Malta M. Exposure to radionuclides in smoke from vegetation fires. *Sci Total Environ* 2014;472:421-4. DOI PubMed
18. Behbehani M, Carvalho FP, Uddin S, Habibi N. Enhanced polonium concentrations in aerosols from the gulf oil producing region and the role of microorganisms. *Int J Environ Res Public Health* 2021;18:13309. DOI PubMed PMC
19. Behbehani M, Uddin S, Baskaran M. ^{210}Po concentration in different size fractions of aerosol likely contribution from industrial sources. *J Environ Radioact* 2020;222:106323. DOI PubMed
20. UNSCEAR. Sources and effects of ionizing radiation. Available from: https://www.unscear.org/unscear/en/publications/2008_1.html [Last accessed on 22 Dec 2023].
21. Eckerman K, Harrison J, Menzel H, Clement C. ICRP publication 119: compendium of dose coefficients based on ICRP publication 60. *Ann ICRP* 2013;42:1-130. DOI
22. Evangeliou N, Balkanski Y, Cozic A, Hao WM, Møller AP. Wildfires in chernobyl-contaminated forests and risks to the population and the environment: a new nuclear disaster about to happen? *Environ Int* 2014;73:346-58. DOI
23. Bae MS, Shin JS, Lee KY, Lee KH, Kim YJ. Long-range transport of biomass burning emissions based on organic molecular markers and carbonaceous thermal distribution. *Sci Total Environ* 2014;466-467:56-66. DOI PubMed
24. MacCarthy J, Richter J, Tyukavina S, Weisse M, Harris N. The latest data confirms: forest fires are getting worse. Available from: https://www.wri.org/insights/global-trends-forest-fires [Last accessed on 22 Dec 2023].
25. Kim G, Hong YL, Jang J, Lee I, Hwang DW, Yang HS. Evidence for anthropogenic 210Po in the urban atmosphere of Seoul, Korea. *Environ Sci Technol* 2005;39:1519-22. DOI PubMed
26. Tadmor J. Radioactivity from coal-fired power plants: a review. *J Environ Radioactiv* 1986;4:177-204. DOI
27. Długosz-Lisiecka M. Excess of polonium-210 activity in the surface urban atmosphere. Part 2: origin of ^{210}Po excess. *Environ Sci Process Impacts* 2015;17:465-70. DOI PubMed
28. Suzuki T, Maruyama Y, Nakayama N, Yamada K, Ohta K. Measurement of the ^{210}Po/^{210}Pb activity ratio in size fractionated aerosols from the coast of the Japan sea. *Atmospheric Environment* 1999;33:2285-8. DOI
29. Behbehani M, Uddin S. Atmospheric concentrations of ^{210}Pb, ^{210}Bi and ^{210}Po in Kuwait. Available from: http://kdrviewer.kisr.edu.kw/BookViewer/?book_id=7205&keyword=Atmospheric%20Concentrations%20of%20210Pb,%20210Bi%20and%20210Po%20in%20Kuwait [Last accessed on 22 Dec 2023].
30. Carvalho FP. Tobacco Smoking, Indoor Exposure and the Lung Radioactivity. Proceedings of the SHO2009: International Symposium on Occupational Safety and Hygiene; Guimaraes, Portugal. 5–6 February 2009; pp. 131–135.

31. Uddin S, Behbehani M, Fowler SW, Al-Ghadban A, Dupont S. Assessment of loss of ^{210}Po from fish and shrimp by cooking and its effect on dose estimates to humans ingesting seafood. *J Environ Radioact* 2019;205-6:1-6. DOI PubMed
32. Carvalho FP, Oliveira JM. Polonium in cigarette smoke and radiation exposure of lungs. *Czech J Phys* 2006;56:D697-703. DOI
33. Uddin S, Habibi N, Fowler SW, et al. Aerosols as vectors for contaminants: a perspective based on outdoor aerosol data from Kuwait. *Atmosphere* 2023;14:470. DOI
34. Carvalho FP, Oliveira JM, Malta M, Lemos ME. Radioanalytical assessment of environmental contamination around non-remediated uranium mining legacy site and radium mobility. *J Radioanal Nucl Chem* 2014;299:119-25. DOI
35. Church T, Rigaud S, Baskaran M, et al. Intercalibration studies of ^{210}Po and ^{210}Pb in dissolved and particulate seawater samples. *Limnology & Ocean Methods* 2012;10:776-89. DOI
36. Du J, Du J, Baskaran M, Bi Q, Huang D, Jiang Y. Temporal variations of atmospheric depositional fluxes of ^{7}Be and ^{210}Pb over 8 years (2006-2013) at Shanghai, China, and synthesis of global fallout data. *JGR Atmospheres* 2015;120:4323-39. DOI
37. Simon SL, Ibrahim SA. The plant/soil concentration ratio for calcium, radium, lead, and polonium: Evidence for non-linearity with reference to substrate concentration. *J Environ Radioactiv* 1987;5:123-42. DOI
38. Ibrahim S, Whicker F. Plant accumulation and plant/soil concentration ratios of 210Pb and 210Po at various sites within a uranium mining and milling operation. *Environ Exp Bot* 1987;27:203-13. DOI
39. Whicker FW, Schultz V. Radioecology: nuclear energy and environment. Available from: https://inis.iaea.org/Search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=15009266 [Last accessed on 22 Dec 2023].
40. Behbehani M, Uddin S, Al-Rashed Z, et al. Atmospheric concentration of 210-Pb, 210-Bi, and 210-Po in Kuwait. Available from: https://www.researchgate.net/publication/343480947_Atmospheric_Concentration_of_210Pb_210Bi_and_210Po_in_Kuwait [Last accessed on 22 Dec 2023].
41. Behbehani M, Uddin S, Habibi N, et al. ^{210}Po in ultrafine aerosol particles and its likelihood to mutate the microbial community. http://kdrviewer.kisr.edu.kw/BookViewer/?book_id=8484&keyword= [Last accessed on 22 Dec 2023].
42. Wallneri G. Distribution of ^{212}Pb, ^{214}Pb and ^{210}Pb with its daughter products on aerosol fractions from Vienna and Badgastein (Austria). *Radiochimica Acta* 2001;89:791-8. DOI