JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(4), 95–105
https://doi.org/10.12911/22998993/214729
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.11.17
Accepted: 2026.02.15
Published: 2026.03.15

Transfer of polonium-210 from soil to tobacco products and their associated radiological dose to smokers in Tanzania

Nurjed Sadick Issa[1*], Elingarami Sauli Nkya[1], Shovi Furaeli Sawe[2], Ruth Lorivi Moirana[1]

[1] The Nelson Mandela African Institution of Science and Technology, School of Materials, Energy, Water, and Environmental Sciences (MEWES), Box 447, Arusha, Tanzania
[2] Tanzania Atomic Energy Commission, GPH8+5CR, Tanzania
* Corresponding author's e-mail: issan@nm-aist.ac.tz

ABSTRACT

This study investigated the transfer of polonium-210 from soil to tobacco products and the associated radiological risks to smokers. Soil, tobacco leaf, and cigarette samples were collected from three major tobacco-growing regions, Iringa (Magubike), Tabora (Sikonge), and Ruvuma (Matimila), and analyzed using an alpha spectrometry system. The polonium-210 activity in soils ranged from 178.49 ± 9.92 to 1190.20 ± 187.20 mBq/g in Iringa, 247.11 ± 9.90 to 1324.36 ± 25.76 mBq/g in Tabora, and 321.56 ± 31.52 to 1557.30 ± 41.62 mBq/g in Ruvuma, with mean values of 704.4 ± 187.2 mBq/g, 656.96 ± 25.76 mBq/g, and 819.49 ± 41.62 mBq/g, respectively. These values exceeded the global average of 25–150 mBq/g for ^{210}Po. Tobacco leaves showed polonium-210 levels ranging from 6.00 ± 0.00 to 33.99 ± 4.00 mBq/g, with a mean of 17.77 mBq/g in Iringa; in Tabora, levels ranged from 7.94 ± 0.00 to 43.91 ± 13.97 mBq/g, with a mean of 28.34 mBq/g; and in Ruvuma, the highest values ranged from 5.99 ± 0.00 to 95.29 ± 11.91 mBq/g, with a mean of 33.06 mBq/g. The soil-to-leaf transfer factors averaged 0.0768 for Iringa, 0.0662 for Tabora, and 0.0452 for Ruvuma, indicating transfer of ^{210}Po through roots and atmospheric deposition. The leaf-to-cigarette transfer factors were approximately 0.00116 for Winston, 0.00182 for Master, and 0.00248 for Portsman. Corresponding annual effective doses were 28.67 μSv for Winston, 43.00 μSv for Master, and 57.33 μSv for Portsman, which is below the limit of 1 mSv/year recommended by the International Commission on Radiological Protection. Despite a low Exposure Hazard Index, long-term inhalation risks warrant ongoing monitoring of polonium-210 in soils, tobacco, and cigarettes to protect public health.

Keywords: agricultural soils, polonium-210, tobacco, transfer factor, radiological dose.

INTRODUCTION

Tobacco use remains one of the most enduring public health issues worldwide, causing over 8 million deaths each year and impacting around 1.3 billion people globally (WHO, 2024). Cigarette smoking is linked to a range of chronic diseases, including lung cancer, heart disease, and long-term respiratory illnesses (Desorgher et al., 2023). In Tanzania, about 8.7% of adults use tobacco, resulting in roughly 17,000 deaths annually (GATS, 2018). While the harmful effects of chemicals like tar, nicotine, and carbon monoxide in tobacco smoke are well known, the radioactive element ^{210}Po has received less focus, despite its role in increasing smokers' internal radiation exposure. Polonium-210 (^{210}Po) is a naturally occurring radionuclide from the uranium-238 decay series and is a highly radiotoxic alpha emitter (UNSCEAR, 2000). With a half-life of 138.4 days, it releases high-energy alpha particles that can damage bronchial tissue upon inhalation, potentially leading to cancer (Carvalho & Oliveira, 2006; Desorgher, 2023; Godwin et al., 2010). ^{210}Po mainly originates from the decay of Radon-222 (^{222}Rn) and Lead-210 (^{210}Pb), which are emitted into the atmosphere from both natural and human sources. These radionuclides settle onto soil and plants through dry deposition and rain. Tobacco plants effectively trap these particles due to their glandular trichomes and large leaves (Liss & Slater, 1974; Skwarzec, Ulatowski, Struminska, & Boryło, 2001). Additionally, ^{210}Po can be absorbed by plant roots, especially in phosphate-rich soils (Kovács et al., 2007).

A primary human-made source of environmental ^{210}Po is phosphate fertilisers derived from uranium-rich rocks, which contain radionuclides like ^{226}Ra, ^{210}Pb, and ^{210}Po (Khater & AL-Sewaidan, 2008; Moore et al., 1976; Aoun et al., 2010). Their use leads to the accumulation of radionuclides in the soil, which then transfer to crops such as tobacco. Research confirms that the ^{210}Po levels depend on the type of fertiliser, soil, and environment (Carvalho, 2011; Dutra Garcêz et al., 2020). After harvest, ^{210}Po mainly remains in the leaves and is transferred to cigarette smoke when the leaves are burned. Approximately 50% of ^{210}Po in a cigarette is transferred to the inhaled smoke, with less in the filter (35%) and ash (15%) (Khater, 2004). Inhalation deposits the alpha radionuclide in bronchial bifurcations, causing repeated irradiation (Carvalho & Oliveira, 2006; Kovács et al., 2007). Worldwide, the ^{210}Po activity in cigarette tobacco ranges from 3.3 mBq per cigarette in India to 23.2 mBq in France, with values mainly between 4 and 30 mBq (Khater & Al-Sewaidan, 2006). Heavy smokers (20 cigarettes daily) receive annual doses of 200-1000 µSv, comparable to natural background radiation (Skwarzec et al., 2001b; Hussein et al., 2005). Although below occupational limits, these levels are concerning due to radiotoxicity and lung dose (UNSCEAR, 2000). The data from Sub-Saharan Africa, particularly Tanzania, are limited despite its prominence as a major tobacco producer.

Tanzania's key tobacco-producing regions, Iringa, Tabora, and Ruvuma, feature distinct geological formations and high fertiliser use, potentially leading to increased radionuclide accumulation in soils. Since local cigarette brands, such as Winston, Portsman, and Master primarily source their tobacco from these regions, it is crucial to assess the ^{210}Po levels throughout the soil–>tobacco–>cigarette pathway. Understanding this pathway will help evaluate how natural radioactivity and fertiliser practices influence internal radiation exposure among smokers. This study aimed to measure the activity concentration of ^{210}Po in soils, tobacco leaves, and cigarettes made in Tanzania. It also evaluates transfer factors (TFs) from soil to leaf and from leaf to cigarette, and estimates the annual committed effective dose for smokers from inhaled ^{210}Po. The findings provide essential baseline radiological data for risk assessment, support the development of safe agricultural practices, and inform national-level policies on radiation protection and tobacco control.

MATERIALS AND METHODS

Description of the study area

The soil and tobacco leaf samples used for this study were collected from three major tobacco-growing regions of Tanzania, namely: Tabora at Sikonge (grid references 5°37'60" S, 32°46' E), Ruvuma at Matimila village (10°42′37″ S, 35°48′10″ E), and Iringa at Magubike village (7°45′22″ S, 35°29′6″ E) as illustrated in Figure 1. Although ten regions cultivate tobacco in Tanzania, these locations were chosen because they are the major suppliers to the local cigarette industries (Sauer & Abdallah, 2007). Therefore, they offer a representative cross-section of the country's tobacco-growing environments.

Sample collection and preparation

The samples used for this study are soils, tobacco leaves, and locally produced cigarettes. Sampling and sample preparation were performed according to the methods by (Karagueuzian et al., 2012). Briefly, approximately 1 kg of soil was collected from each tobacco farm, covering an area of roughly 1 acre. A composite sample was created to ensure representation by randomly collecting approximately 50 g of soil from various points throughout the field. The samples were placed in clean plastic bags, labelled, and transported to the laboratory for further preparation and analysis. To ensure consistency in quality, the fresh tobacco leaves were carefully harvested from selected farms at the optimal maturity stage, which is 6 months. After collection, they were placed in breathable sacks or cartons to prevent moisture buildup and mould growth. The tobacco samples were air-dried, ground, and then analysed in the laboratory. The cigarette samples from three popular brands in Tanzania, Portsman, Winston, and Master, were purchased from the local market in Arusha, Tanzania. Four cigarettes from each pack were taken and combined to create tobacco samples in separate boxes, ensuring homogeneity

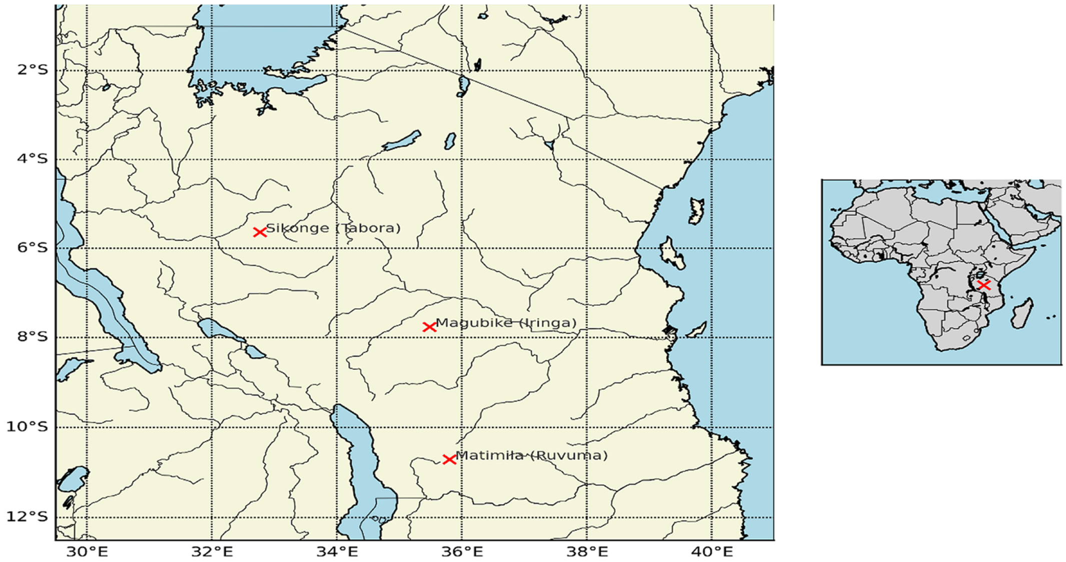

Fig. 1. Map of Tanzania showing the study areas

within each brand. The samples were then oven-dried overnight at 90°C, followed by grinding to achieve a uniform consistency. These brands were selected because they source a significant portion of their tobacco from the study areas.

Radiochemical separation and quantification of ^{210}Po in tobacco, cigarettes, and soil samples

Radiochemical separation was performed using the method described by (Zagà et al., 2024). About 5 grams of dried tobacco leaves and cigarette brands were placed in 250 mL beakers. A small amount (200 µL) of ^{209}Po tracer (Eα = 4.9 MeV), with an activity of 185 kBq (5 µCi/mL), was added to each sample to help calculate the chemical recovery of polonium following chemical treatment. The samples were dissolved in a 250 mL beaker using three portions of 50 mL nitric acid (HNO_3, 65%), followed by 10 mL of hydrogen peroxide (H_2O_2) to break down the organic matter. The samples were then evaporated to near dryness on a hot plate set at approximately 90 °C. The resulting residue was diluted with about 20 mL of distilled water and filtered through a Whatman filter paper (11.0 cm diameter, Cat. No. 1443–110/100 circles) to remove solid particles. The filtrate was evaporated to dryness again for further processing. The residue was dissolved in 6.0 M hydrochloric acid (HCl) and filtered to remove remaining impurities. To reduce Fe^{+3} interference, about 2.50 mg of ascorbic acid was added to the filtrate, and then the samples were treated with approximately 100 mL of dilute nitric acid. Lastly, polonium-210 in the solution was deposited onto a silver disc overnight. The soil samples were treated in the same way, but with the addition of hydrofluoric acid (HF) to digest silica in the samples. This process enabled the effective extraction and deposition of polonium-210 from the soil samples onto silver discs, allowing for the measurement of the ^{210}Po concentrations using an alpha spectrometer (OCTETE from ORTEC) equipped with PIPS detectors. Detector efficiencies were 26%, 21% and 24% for detectors 1, 2, and 3, respectively. The alpha spectrometer was connected to a computerised multi-channel analyser with Maestro software (ORTEC) for data acquisition and analysis. Each sample was counted for about 85,000 seconds to obtain good counting statistics.

Quantification of ^{210}Po was performed using Equation 1 (Sam, 1998):

$$A\,(Bq/Kg) = \frac{N \cdot Å}{TC \cdot SW} \tag{1}$$

where: A (Bq/Kg) is the activity concentration of ^{210}Po, N is the sample counts obtained from the sample, $Å$ is the activity of the tracer in Bq, TC is the number of counts obtained from the tracer (^{209}Po), and SW is the sample weight in kg.

Estimation of transfer factor

The transfer factor (TF) is a valuable parameter that measures the movement of radionuclides through the tobacco production process. In this study, transfer factors were calculated by using Equations 2 and 3 (Mankala et al., 2025) to assess the effectiveness of the ^{210}Po movement from soil to tobacco leaves and then from unprocessed tobacco leaves to the final cigarette product. This helps to understand how much ^{210}Po is absorbed from the soil and accumulates in the plant, as well as how much remains in the final product that smokers will consume.

Transfer factor for soil to tobacco leaves

$$TF_{soil \to Leaf} = \frac{C_{leaf}}{C_{soil}} \quad (2)$$

Transfer factor for unprocessed tobacco leaves to cigarettes

$$TF_{leaf \to Cigarette} = \frac{C_{cigarette}}{C_{Leaf}} \quad (3)$$

where: C_{soil} – activity concentration of ^{210}Po in soil (mBq/g), C_{leaf} – activity concentration of ^{210}Po in tobacco leaves (mBq/g), $C_{cigarette}$ – activity concentration of ^{210}Po in cigarette (mBq/g), *TF* – transfer factor (unitless).

Transfer factors above unity indicate high accumulation efficiency, while values below unity show low transfer efficiency. These measurements help assess the potential human exposure to ^{210}Po through the tobacco supply chain.

Quantification of radiological dose from cigarette smoking

Radiological doses were calculated based on the ^{210}Po concentrations in cigarette samples and the average cigarette consumption rate among Tanzanian daily smokers, which is approximately 8.5 cigarettes per day (GATS 2018; WHO, 2024). Urban daily smokers consumed an average of 11.3 cigarettes per day, while those in rural areas smoked 6.9 cigarettes per day. Dose coefficients from international radiation protection guidelines were applied to estimate annual committed effective doses using Equation 04 (Azman et al., 2013; Kovács et al., 2007).

$$E = F1 \times F2 \times K \times G \times C \times t \quad (4)$$

where: *E* is the committed effective dose in micro Sieverts (µSv), F1 denotes the average transfer factor from tobacco to smoke (0.7), *F*2 represents the ratio of inhaled smoke to total smoke (0.5) (Skwarzec, Ulatowski, Struminska, & Bory, 2001), *K* stands for the inhalation dose conversion factor for ^{210}Po which is 3.3 µSv Bq^{-1} (UNSCEAR, 2000), *G* indicates the number of cigarettes smoked per day (8.5 cigarettes), C represents the concentration of ^{210}Po per cigarette in Becquerel (Bq per cigarette), and *t* represents the duration of smoking in days (365 days) (Khater, 2004).

Exposure hazard index

The exposure hazard associated with polonium-210 in tobacco was assessed by calculating the annual effective dose received by individuals through cigarette consumption and comparing it to the internationally recommended safety thresholds. The exposure hazard index (EHI) was determined from the calculated annual committed effective dose (E) and the recommended yearly dose limit for the general public (1 mSv/year) using Equation 05 (ICRP, 2020a).

$$EHI = Annual\ effective\ dose\ (E) / Dose\ limit\ for\ the\ general\ public\ (D) \quad (5)$$

Analytical quality control

The average recovery rate for polonium was approximately 75%, with individual recoveries ranging from 65% to 85%. Analytical quality control included routine analysis of certified reference materials (IAEA-326 and IAEA-327) and blank samples. The obtained results were in good agreement with the certified values, indicating the validity of the reported results.

Statistical analysis

The 16 samples (M1–M5, R1–R6, S1–S5) show significant spatial variability in activity concentrations, ranging from very low levels (<8 Bq/kg in M2, M4, M7, and R15) to a prominent hotspot at Sample 11 (95.29 ± 10.58 Bq/kg), which is well above the pooled average of 26.90 ± 21.70 Bq/kg. Most samples – including M1, M3, M5, R3, R4, R6, S2, S4, and S5 – fall within moderate ranges (approximately 22–44 Bq/kg), likely influenced by factors such as soil mineralogy, fertiliser use, and land use. The high mean, along with the maximum value of 107.51 Bq/kg and the broad confidence interval at Sample 11, suggest localised enrichment that requires further investigation. Overall, activity levels vary from 3.78 to 107.51 Bq/kg, indicating uneven distribution across Magubike, Matimila, and Sikonge. Post-hoc tests (LSD and Dunnett T3) confirm significant differences among samples, especially highlighting Sample 11 as the main hotspot, with moderate variability at Samples 5, 9, 12, and 13, and low levels at Samples 2, 4, 7, and 15. These findings demonstrate clear heterogeneity driven by environmental and human factors, emphasising the importance of targeted monitoring and further environmental analysis.

RESULTS AND DISCUSSION

Activity concentrations in the analysed samples

Activity concentration of ^{210}Po in agricultural soils

The activity concentration of ^{210}Po is presented in Table 1. The activity concentration of ^{210}Po in soils at Magubike ranged from 178.49 ± 9.92 mBq/g to 1557.30 ± 187.20 mBq/g, with an average of 704.4 mBq/g. The ^{210}Po activity concentration in the soils from Sikonge ranged from 198.99 ± 3.98 mBq/g to 1330.18 ± 25.76 mBq/g, with an average of 656.96 mBq/g. In the soils from Matimila, the activity ranged from 453.11 ± 31.52 mBq/g to 1335.83 ± 25.92 mBq/g, with an average of 819.49 mBq/g. Among all the studied samples, the soils from Magubike showed the highest ^{210}Po activity concentration as seen in Figure 2, which exceeds the global recommended average range for soils of 25–150 mBq/g (UNSCEAR, 2000).

Elevated ^{210}Po levels in soil have been identified in Egypt (Shyti et al., 2019) and Poland (Skwarzec et al., 2001), likely due to phosphate fertiliser application, soil mineralogy, and sediment phosphate deposits. The research in Sudan by (Abdulrahman, 2011b; Sam, 1998) and in Brazil by (Aparecida et al., 2017) indicates that natural radiation and farming practices also influence the ^{210}Po concentrations in soils. Therefore, the ^{210}Po enrichment results from complex interactions among geological, chemical, and human factors, underscoring the importance of localised radiological assessments. The levels of ^{210}Po in soils ranged from 178.49 to 1557.30 mBq/g, exceeding the global range of 25 to 150 mBq/g (UNSCEAR, 2000), suggesting enrichment from natural or human-related sources. Extensive evidence indicates that phosphate fertilisers are a significant source of uranium-series radionuclides, particularly ^{23}U, ^{226}Ra, and ^{210}Po. These radionuclides accumulate in soils over time, leading to higher levels of ^{210}Po in tobacco and other plants (Makweba & Holm, 1993; Mankala et al.,

Table 1. Specific radioactivity (mBq/g) of ^{210}Po in tobacco leaves and agricultural soil samples from local farms in Tanzania

Sample location	Activity concentration of ^{210}Po in tobacco leaves (mBq/g)	Activity concentration of ^{210}Po in agricultural soil (mBq/g)
Magubike-Iringa	27.92 ± 15.96	178.49 ± 9.92
	6.00 ± 0.00	1557.3 ± 187.20
	11.96 ± 0.00	269.3 ± 9.90
	7.99 ± 0.00	392.16 ± 121.57
	33.99 ± 4.00	213.81 ± 5.99
Matimila-Ruvuma	17.93 ± 3.99	453.11 ± 31.52
	5.99 ± 0.00	797.53 ± 27.91
	21.97 ± 4.00	655.33 ± 39.72
	33.70 ± 3.96	977.57 ± 230.02
	25.99 ± 2.00	1335.83 ± 25.92
	95.29 ± 11.91	697.55 ± 41.62
Sikonge-Tabora	33.95 ± 2.00	828.84 ± 75.35
	43.91 ± 13.97	419.46 ± 21.97
	29.91 ± 5.98	198.99 ± 3.98
	7.94 ± 0.00	507.33 ± 61.92
	25.99 ± 4.00	1330.18 ± 25.76

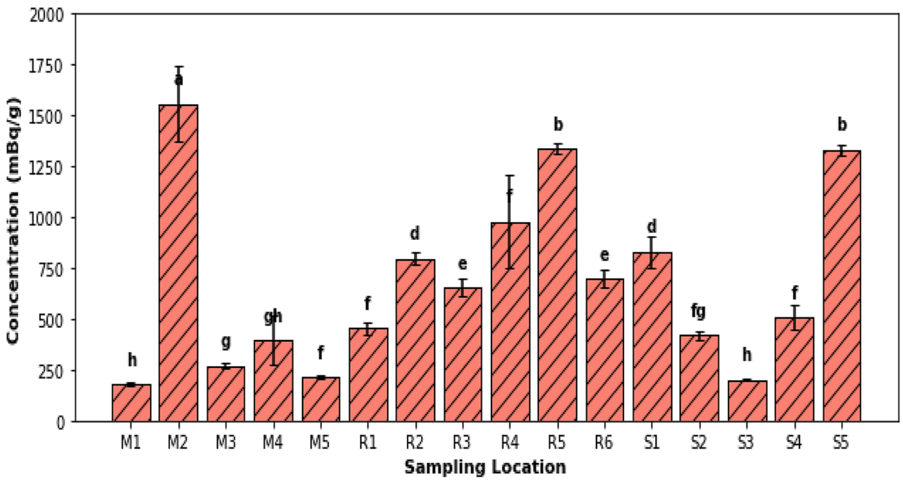

Fig. 2. Activity concentration of ^{210}Po in soil, M = Magubike (Iringa), R = Matimila (Ruvuma), and S = Sikonge (Tabora)

2025; Mun et al., 2008; Mwalongo et al., 2023). Therefore, this elevation is likely due to the use of phosphate fertiliser, which contains uranium-series radionuclides (^{238}U, ^{226}Ra, ^{210}Po), along with local geology rich in granitic and phosphate rocks, combined with atmospheric deposition of dust or rain-borne substances from nearby agricultural or mining areas.

Activity concentration of ^{210}Po in tobacco leaves

The activity concentration of ^{210}Po in tobacco leaves varied by location, as shown in Figure 3. In Magubike it ranged from 6.00 ± 0.00 mBq/g to 33.99 ± 4.00 mBq/g, with an average of 17.77 mBq/g. In Sikonge, values ranged from 7.94 ± 0.00 mBq/g to 43.91 ± 13.97 mBq/g, with an average of 28.34 mBq/g. In Matimila, the range was from 5.99 ± 0.00 mBq/g to 95.29 ± 11.91 mBq/g, with a mean of 33.06 mBq/g. Overall, the tobacco leaves from Matimila showed the highest ^{210}Po activity concentrations, while those from Magubike, Iringa, had the lowest average levels.

Matimila had the highest concentrations of ^{210}Po in tobacco, as shown in Figure 3. It could simply mean the higher concentration of ^{210}Po in the soil leads to a high concentration in the tobacco. Additionally, high concentrations of ^{210}Po found in Magubike and Sikonge are mainly influenced by regional geology, geochemical factors, and the use of phosphate fertilisers enriched with uranium-series radionuclides (Makweba & Holm, 1993; Mwalongo et al., 2023). Similar elevated soil levels, exceeding 1000 mBq/g, have been observed in Brazil and Egypt (Olszewski et al., 2010). The observed regional differences, with higher ^{210}Po concentrations in Ruvuma and lower concentrations in Iringa, may be due to variations in fertiliser use, soil pH, texture, and organic matter, which affect the ^{210}Po mobility and uptake. Mature tobacco leaves, with larger surface areas,

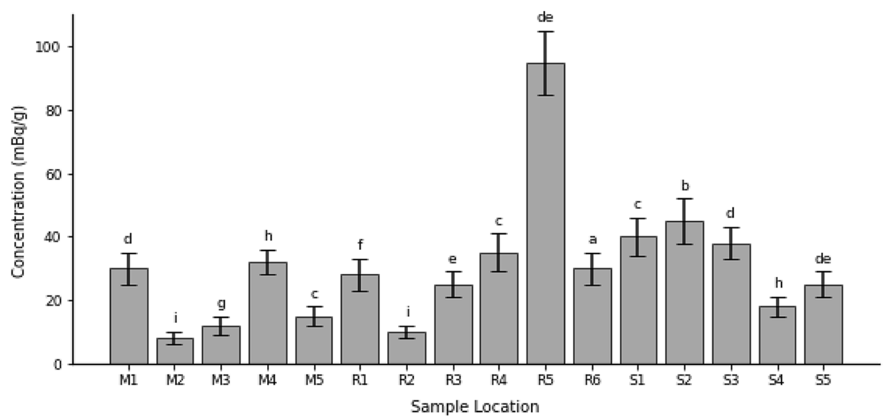

Fig. 3. Activity concentration of ^{210}Po in tobacco. Sample codes: M – Magubike (Iringa), R – Matimila (Ruvuma), S – Sikonge (Tabora)

tend to accumulate more radionuclides from atmospheric deposition ($^{210}Pb \rightarrow ^{210}Po$). Overall, these results align with the studies from Poland (7–85 mBq/g) (Skwarzec et al., 2001) and Sudan (Abdulrahman, 2011). The findings suggest that Tanzanian tobacco generally falls within the global range but is often higher, likely due to fertiliser practices and climate-facilitated deposition.

Activity concentration of ^{210}Po in cigarette brands

The activity levels of ^{210}Po in different commercial cigarette brands were measured as 8.0 ± 0.0 mBq per cigarette for Winston, 16.0 ± 5.0 mBq per cigarette for Portsman, and 12.0 ± 2.0 mBq per cigarette for Master, as observed in Table 2 and Figure 4. These values fall within the international range of 4–30 mBq per cigarette (Abdulrahman, 2011b; Cohen et al., 2014; Mwalongo et al., 2023; Skwarzec, Ulatowski, Struminska, & Boryło, 2001), as reported in the studies from Europe and North America (Cohen et al., 2014; Skwarzec, Ulatowski, Struminska, & Boryło, 2001). Variations among brands likely reflect differences in tobacco sources (local versus imported leaves), processing and filtration techniques, and brand-specific moisture content or curing methods. Among these, Portsman exhibited the highest ^{210}Po level, indicating either less dilution with low-activity tobaccos or a greater proportion of local leaves with higher ^{210}Po content.

Transfer factors of ^{210}Po

Transfer factor of ^{210}Po from soil to tobacco leaves

The transfer factor (TF) values of ^{210}Po from soil to tobacco leaves varied by location, as shown

Table 2. The specific activity concentrations of ^{210}Po in cigarette brands from Tanzania and other countries, expressed in mBq/cigarette

S/N	Brand	Country	Activity ± SD (mBq/cigarette)	Reference
1	Winston	Tanzania	8.0 ± 0.0	This study
2	Portsman	Tanzania	16.0 ± 5.0	This study
3	Master	Tanzania	12.0 ± 2.0	This study
4	Golden American	Poland	15.77 ± 0.02	(Skwarzec, Strumińska, et al., 2001)
5	Klubowe	Poland	9.33 ± 0.09	(Skwarzec, Strumińska, et al., 2001)
6	Mewa Menthol	Poland	21.52 ± 0.6	(Skwarzec, Strumińska, et al., 2001)
7	Multifilter King Size	Hungary	15.0 ± 5.7	(Kovács et al., 2007)
8	Symponia Piros	Hungary	10.0 ± 3.3	(Kovács et al., 2007)
9	Kent Gold	Hungary	32.3 ± 5.1	(Kovács et al., 2007)
10	Portugues Suave	Portugal	11.9 ± 0.0	(Carvalho & Oliveira, 2006)
11	Bringi	Sudan	32.2 ± 0.0	(Abdulrahman, 2011)
12	Benson	Sudan	14.8 ± 0.0	(Abdulrahman, 2011)

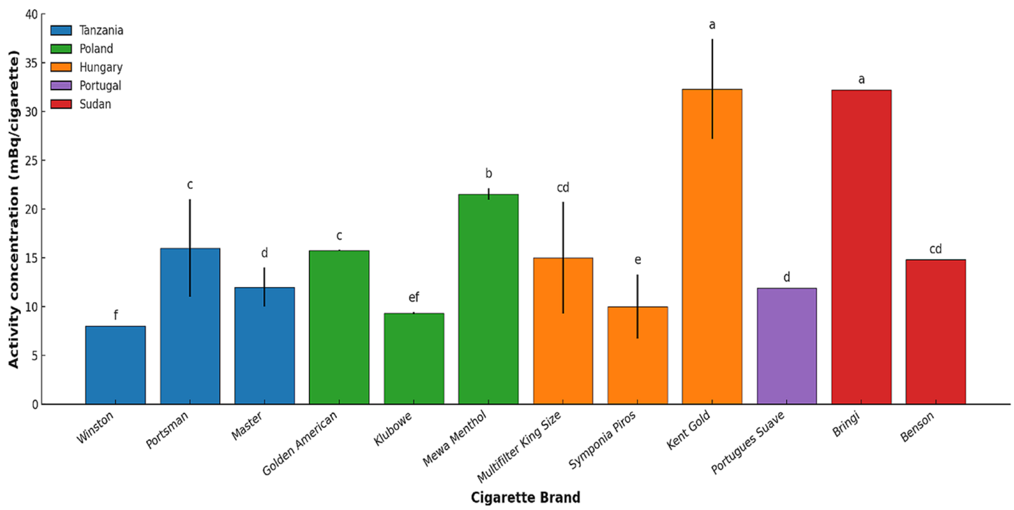

Figure 4. Specific activity of ^{210}Po in commercial cigarette brands in Tanzania and other countries

in Figure 5. At Magubike, Iringa, TF values ranged from 0.0039 to 0.1590, with an average of 0.0768. Sikonge and Tabora had TF values ranging from 0.0157 to 0.1503, with an average of 0.0662. In Matimila, Ruvuma, the values ranged from 0.0075 to 0.1366, with a mean of 0.0452. Variations in soil properties, such as pH, organic matter, and phosphate content strongly influence the bioavailability of ^{210}Po to plants. The soils rich in organic matter or phosphate tend to retain ^{210}Po through adsorption, while acidic or sandy soils enhance its solubility and uptake (Aparecida et al., 2017; Carvalho, 2011; Makweba & Holm, 1993). The higher transfer efficiency at Magubike likely reflects soil conditions that favour radionuclide mobility compared to those at Sikonge and Matimila.

Comparable studies report similar ^{210}Po transfer ranges, including 0.01–0.12 in Egypt (Shousha & Ahmad, 2012), 0.02–0.14 in Poland (Skwarzec et al., 2001), which are consistent with the present findings. The lower average TF at Matimila may result from higher organic or phosphate content, which reduces radionuclide availability. Overall, these inter-site variations highlight how soil composition, pH, and fertiliser use govern the ^{210}Po mobility and uptake. The higher TF at Magubike suggests that site-specific environmental and agronomic conditions enhance the transfer of ^{210}Po to tobacco, reinforcing the need for continued assessment of soil and fertiliser characteristics in Tanzanian tobacco-growing regions.

Transfer factor from tobacco leaves to cigarettes

The transfer factor (TF) of ^{210}Po from tobacco leaves to finished cigarettes indicates the amount of radionuclide that remains in the smoke inhaled. In this study, the TF values for Tanzanian cigarette brands were 0.00116 for Winston, 0.00248 for Portsman, and 0.00130 for Master, showing limited but measurable transfer of ^{210}Po during combustion. These values are consistent with global reports, suggesting that only a small portion of the total ^{210}Po in tobacco is released into the smoke inhaled. Numerous studies have estimated the transfer factors of ^{210}Po from tobacco leaves to finished cigarettes (ICRP, 2020b) reported the TF values of 0.22–0.65 with an average of 0.4 for Turkish cigarettes. These suggest low transfer fractions are common across tobacco types and methods.

A small proportion of ^{210}Po transferred is due to its strong binding to particles within tobacco and its retention in ash and filter during smoking (Azman et al., 2013; Godwin et al., 2010). Despite this, the energetic alpha emissions of ^{210}Po can cause significant localised lung doses (Abdulrahman, 2011; Carvalho & Oliveira, 2006; Desorgher, 2023; Godwin et al., 2010). The higher TF in Portsman may result from differences in tobacco type, burning temperature, or filter efficiency, all of which can affect radionuclide transfer. Overall, the TF results indicate that only a small fraction of ^{210}Po in tobacco is inhaled; yet, its biological impact remains significant due to the high linear energy transfer (LET) of alpha radiation. Regular monitoring of ^{210}Po in raw tobacco and smoke is crucial for accurately estimating exposure and guiding radiological risk evaluations related to smoking (Table 3–5).

Annual radiological dose to smokers

The annual radiological dose (ARD) from ^{210}Po for Tanzanian cigarette brands was assessed, and the results indicate that the annual effective

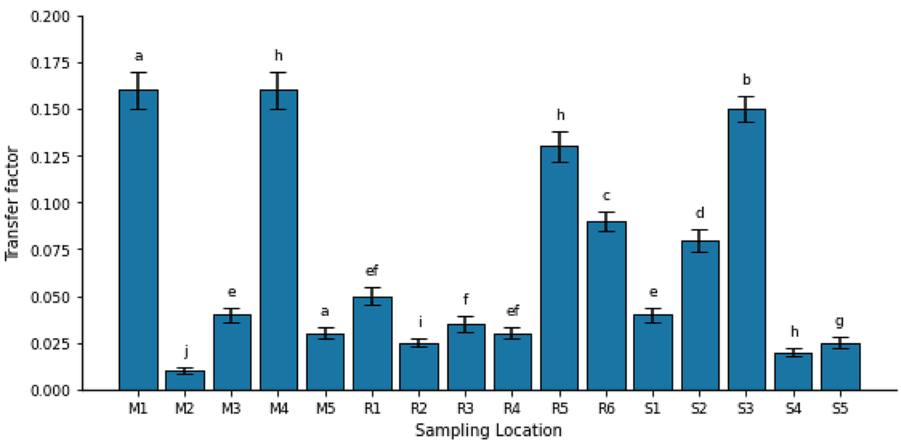

Figure 5. Transfer factor of ^{210}Po from soil to tobacco leaves

Table 3. Transfer factor of ^{210}Po from soil to tobacco leaves

Sampling area	Sample location	Transfer factor
Magubike	1	0.156423
	2	0.003853
	3	0.044411
	4	0.020374
	5	0.158973
Matimila	6	0.039571
	7	0.007511
	8	0.033525
	9	0.034473
	10	0.019456
	11	0.136607
Sikonge	12	0.040961
	13	0.104682
	14	0.150309
	15	0.015651
	16	0.019539

Table 4. Transfer factor of ^{210}Po from tobacco leaves to cigarettes

Cigarette brand	Transfer factor
Winston	0.00116
Portsman	0.00248
Master	0.0013

doses from smoking were 28.67 µSv, 57.33 µSv, and 43 µSv for Winston, Portsman, and Master, respectively, as shown in Table 5. Overall, these doses ranged from 28.67 to 57.33 µSv, indicating low but detectable radiological exposure levels in the tested cigarettes.

On the basis of an average daily intake of 8.5 cigarettes ARD from cigarette brands, the ARD is below the ICRP public exposure limit of 1 mSv/year (ICRP, 2017), but still represents detectable internal alpha radiation. Similar research in Poland and Egypt found doses of 200–1000 µSv/year (El-aziz et al., 2005; Skwarzec, Ulatowski, Struminska, & Boryło, 2001), which exceed Tanzanian figures. This difference may be due to higher ^{210}Po activity levels and cigarette consumption (15–20 cigarettes per day) for Poland and Egypt. Consequently, although Tanzanian smokers incur lower radiological doses, the combined risks from other carcinogens may increase the probability of health risks to smokers.

Exposure hazard index

The exposure hazard index (EHI) for Tanzanian cigarette brands were 0.0287 for Winston, 0.0573 for Portsman, and 0.0430 for Master. Their annual doses ranged from 28.67 to 57.33 µSv, which are well below the limit of 1 mSv (ICRP, 2012). This indicates minimal radiological risk from ^{210}Po, posing no immediate threat to smokers, though long-term exposure remains concerning. Repeated inhalation of alpha-emitting radionuclides and chemicals such as benzene and nitrosamines can increase the risk of cancer (Carvalho & Oliveira, 2006; Karagueuzian et al., 2012; Khater, 2004). Studies in Poland and Portugal (EHI 0.02–0.06) suggest that even low radiation doses, when combined with toxic substances, may pose significant health risks (Carvalho & Oliveira, 2006; Skwarzec, Ulatowski, Struminska, & Bory, 2001).

Variations in EHI among brands mainly depend on the ^{210}Po levels in tobacco and cigarettes smoked (Shafiq et al., 2018). EHI correlates with exposure, so heavier smoking or high-activity tobacco increases the radiological dose (Desorgher et al., 2023). Other factors include fertiliser type, curing techniques, and region of cultivation (Sam, 1998). Though all EHI values are below one, indicating low risk, regular monitoring is advisable. Given Tanzania's reliance on phosphate fertilisers, periodic EHI checks could detect future radionuclide increases from agricultural or industrial shifts.

CONCLUSIONS

This study investigated the transfer of ^{210}Po from soil into tobacco leaves and ultimately into cigarette products in Tanzania, highlighting its

Table 5. Specific concentration of ^{210}Po and ARD of cigarette brands

Brand	Activity (mBq/cigarette)	Activity (Bq/cigarette)	ARD (µSv/year)
Winston	8.0	0.008	28.67
Portsman	16.0	0.016	57.33
Master	12.0	0.012	43.00

potential radiological risk to smokers. The levels of ^{210}Po found in soils (178.49–1557.30 mBq/g) were significantly higher than the global average of 25–150 mBq/g (UNSCEAR, 2000), probably due to the use of phosphate fertilisers and the effects of local geological formations. In tobacco leaves, the ^{210}Po concentrations ranged from 6.00 to 95.29 mBq/g, while in cigarettes they ranged from 8.0 to 16.0 mBq per stick, indicating that some of the radionuclide is absorbed by the plant and transferred to the final product. Transfer factors for soil-to-leaf (0.0039–0.1590) and leaf-to-cigarette (0.00116–0.00248) show limited, but measurable ^{210}Po movement, consistently. For the smokers in Tanzania, the estimated yearly effective doses (28.67–57.33 µSv/year) are within the international range of 200–1000 µSv/year seen in Europe and the Middle East. Although the Exposure Hazard Index (0.0287–0.0573) is low, ongoing inhalation of alpha-emitting ^{210}Po might still contribute to the cumulative radiation dose in the lungs, slightly raising the long-term cancer risk.

Acknowledgement

The authors acknowledge that the work was carried out with the financial support of the Icipe-World Bank Financing Agreement No. D347-3A for the PASET Regional Scholarship and Innovation Fund. The views expressed herein do not necessarily reflect the official opinion of the donors.

REFERENCES

1. Abdulrahman, M.E. (2011). Determination of polonium-210 in different types of tobacco consumed in sudan determination of polonium-210 in different types of tobacco consumed in Sudan. *U.S. Department of Energy*, *January*. https://www.osti.gov/etdeweb/biblio/21557311
2. Aparecida, J., García-tenorio, R., & Marcos, D. (2017). Natural radionuclides in plants, soils and sediments affected by U-rich coal mining activities in Brazil. *Journal of Environmental Radioactivity*, *177*, 37–47.
3. Azman, M.A., Rahman, I.A., Yasir, M.S., Azman, M.A., Rahman, IA., & Yasir, M.S. (2013). 210Po concentration analysis on tobacco and cigarettes in Malaysia Po concentration analysis on Tobacco and Cigarettes in Malaysia. *AIP Conf. Proc.*, *417*(1). https://doi.org/10.1063/1.4803637
4. Carvalho, F.P. (2011). Polonium (210Po) and lead (210Pb) in marine organisms and their transfer in marine food chains. *Journal of Environmental Radioactivity*, *102*(5), 462–472. https://doi.org/10.1016/j.jenvrad.2010.10.011
5. Carvalho, F.P., & Oliveira, J.M. (2006). Polonium in cigarette smoke and radiation exposure of lungs. *Czechoslovak Journal of Physics*, *56*(SUPPL. 4), 697–703. https://doi.org/10.1007/s10582-006-0568-6
6. Cohen, B.S., Eisenbud, M., & Harley, N.H. (2014). *Smoke in Cigarette Alpha Radioactivity*, *83*(1), 190–196.
7. Desorgher, L. (2023). *Dosimetry in the lungs of α -particles (210 Po) and β -particles (210 Pb) present in the tobacco smoke of conventional cigarettes and heated tobacco products*. *263*(January), 1–7.
8. Desorgher, L., Berthet, A., Rossier, J., Bochud, F., & Froidevaux, P. (2023). Dosimetry in the lungs of α-particles (210Po) and β-particles (210Pb) present in the tobacco smoke of conventional cigarettes and heated tobacco products. *Journal of Environmental Radioactivity*, *263*(April), 1–7. https://doi.org/10.1016/j.jenvrad.2023.107178
9. Dutra Garcêz, R.W., Marques Lopes, J., da Silva Perez, S., da Costa Lauria, D., Paim Viglio, E., Gonçalves da Cunha, F., Araújo Ribeiro, F.C., & Xavier da Silva, A. (2020). Activity concentration and mapping of radionuclides in Espírito Santo State soils, Brazil. *Radiation Physics and Chemistry*, *167*(December 2018). https://doi.org/10.1016/j.radphyschem.2019.03.013
10. El-aziz, N.A., Khater, A.E.M., & Al-sewaidan, H.A. (2005). Natural radioactivity contents in tobacco. *International Congress Series, 1276*, 407–408. https://doi.org/10.1016/j.ics.2004.11.166
11. GATS (2018). *2018 Tanzania Global Adult Tobacco Survey Country Report*.
12. Godwin, W.S, Subha, V., & Feroz, K. (2010). *210-Po Radiation dose due to cigarette smoking.* Current Science, *98*(5),10.
13. ICRP (2012). *International Commission on Radiological Protection 2012 Annual Report*.
14. ICRP (2020a). *Annals of the publication 144 dose coefficients for external exposures to environmental sources*, 49(2).
15. ICRP (2020b). *Ecotoxicology and Environmental Safety Determination and distribution of 210 Po in different morphological parts of tobacco plants and radiation dose assessment from cigarettes in Turkey*, *197*(December 2019).
16. Karagueuzian, H.S., White, C., Sayre, J., & Norman, A. (2012). Cigarette smoke radioactivity and lung cancer risk. *Nicotine and Tobacco Research*, *14*(1), 79–90. https://doi.org/10.1093/ntr/ntr145
17. Khater, A.E.M. (2004). Polonium-210 budget in cigarettes. *Journal of Environmental Radioactivity,* 71.

https://doi.org/10.1016/S0265-931X(03)00118-8

18. Khater, A.E.M., & AL-Sewaidan, H.A. (2008). Radiation exposure due to agricultural uses of phosphate fertilizers. *Radiation Measurements*, *43*(8), 1402–1407. https://doi.org/10.1016/j.radmeas.2008.04.084
19. Khater, A.E.M., & Al-Sewaidan, H.A.I. (2006). Polonium-210 in cigarette tobacco. *International Journal of Low Radiation*, *3*(2–3), 224–233. https://doi.org/10.1504/IJLR.2006.012022
20. Kovács, T., Somlai, J., Nagy, K., & Szeiler, G. (2007). ^{210}Po and ^{210}Pb concentration of cigarettes traded in Hungary and their estimated dose contribution due to smoking. *Radiation Measurements*, 42(10), 1737–1741. https://doi.org/10.1016/j.radmeas.2007.07.006
21. Liss, P.S., & Slater, P.G. (1974). Flux of gases across the air-sea interface. *Nature, 247,* 181–184.
22. Makweba, M.M., & Holm, E. (1993). The natural radioactivity of the rock phosphates, phosphatic products and their environmental implications. *Science of The Total Environment*, *133*, 99–110.
23. Mankala, J.B., Moirana, R.L., & Sawe, S.F. (2025). Assessing the impact of phosphate fertilizer application on radionuclide accumulation in soil and Spinacia oleracea. *Journal of Ecological Engineering*, *26*(9), 38–48.
24. Moore, H.E., Martell, E.A., & Poet, S.E. (1976). Sources of Polonium-210 in Atmosphere. *Environmental Science and Technology*, *10*(6), 586–591. https://doi.org/10.1021/es60117a005
25. Aoun M., El Samrani A.G., Lartiges B.S., Kazpard V., Saad Z. (2010). Releases of phosphate fertilizer industry in the surrounding environment: Investigation on heavy metals and polonium-210 in soil. *Journal of Environmental Sciences*, *22*(9), 1387–1397.
26. Mwalongo, D. A., Haneklaus, N. H., Carvalho, F. P., Lisuma, J. B., & Kivevele, T. T. (2023). Influence of phosphate fertilizers on the radioactivity of agricultural soils and tobacco plants in Kenya, Tanzania, and Uganda. *Environmental Science and Pollution Research,* 30(34), 83004–83023.
27. Sam, A.K. (1998). Biochemical studies onelwironmental radioactivity in Sudan.
28. Sauer, J., & Abdallah, J. M. (2007). *Forest diversity, tobacco production and resource management in Tanzania*, *9*, 421–439. https://doi.org/10.1016/j.forpol.2005.10.007
29. Shafiq, M., Mohd, N., Abdullah, H., & Jalil, S.Z.A. (2018). A Comparison Study of Radioactivity and Radiation Hazard Index between Legal and Illegal Cigarettes. *International Journal of Integrated Engineering*, *7*, 58–65.
30. Shousha, H.A., & Ahmad, F. (2012). Natural radioactivity contents in tobacco and radiation dose induced from smoking. *Radiat Prot Dosimetry*, *150*(1), 91–95.
31. Shyti, M., Cfarku, F., Bërdufi, I., Bylyku, E., & Hoxha, R. (2019). Natural radioactivity in cigarette tobacco and radiation dose induced from smoking. *AIP Conference Proceedings*, *2075*(1), 91–95. https://doi.org/10.1063/1.5091298
32. Skwarzec, B., Ulatowski, J., Struminska, D. I., & Boryło, A. (2001). Inhalation of 210Po and 210Pb from cigarette smoking in Poland. *Journal of Environmental Radioactivity*, *57*(3), 221–230. https://doi.org/10.1016/S0265-931X(01)00018-2
33. Szarłowicz, K., & Wójcik, S. (2024). New insights in tobacco radiotoxicity: on the research of 210Po in modern heated tobacco product—radioactivity, distribution, and dose assessment. *Environmental Science and Pollution Research*, *31*(57), 65264–65272. https://doi.org/10.1007/s11356-024-35516-8
34. UNSCEAR (2000). Sources And Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, 1.
35. WHO. (2024). WHOglobalreport on trends in prevalence of tobacco use 2000–2030.
36. Wieczorek, J., & Boryło, A. (2024). Quantifying of highly radioactive and radiotoxic polonium-210 intake from cannabis (*Cannabis sativa* L.): impacts of different smoking and vaporization techniques. *Environmental Science and Pollution Research*, *31*(51), 61138–61146. https://doi.org/10.1007/s11356-024-35263-w
37. Zagà, V., Cattaruzza, M. S., Gallus, S., Zagà, V., Cattaruzza, M.S., & Gallus, S. (2024). Polonium-210 and lead-210 in heated tobacco smoke. *Tabaccologia*, *3*, 32–36.