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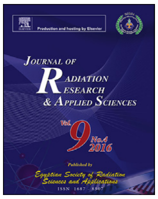

The determination of the inhalable fraction of ^{40}K activity in marijuana (*Cannabis sativa* L.) buds by instrumental neutron activation analysis and the effective dose to the body

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ABSTRACT

Total potassium in marijuana (*Cannabis sativa* L.) buds was determined using instrumental neutron activation analysis. The mass fraction of ^{40}K and its activity were derived using the natural isotopic ratios of potassium. The total potassium in the marijuana buds ranged from 0.84% to 3.15% with a mean mass fraction of 1.93%. The activity concentrations of ^{40}K in the samples of marijuana ranged from 253 to 946 Bq kg^{-1} with a mean activity concentration of 581 Bq kg^{-1}. The effective dose to the body from smoking marijuana is lower than that for comparable tobacco smoking. Simulated smoking experiments show that over 90% of ^{40}K is retained in the cigarette ash. Accepted methods of determining effective dose to the body from ^{40}K inhalation are likely overestimations for both marijuana and tobacco cigarette smoke.

1. Introduction

Potassium is the dominant intracellular cation with 97% of the total body potassium found in the cells (Ellis, 2000). The primordial radionuclide ^{40}K makes up 0.0117% of total potassium and is taken up typically through ingestion and to a lesser extent inhalation in the same manner as the two non-radioactive isotopes of potassium ^{39}K (93.26%) and ^{41}K (6.73%). The decay scheme of ^{40}K has a branching ratio of 89.3% per disintegration to ^{40}Ca by β-particle emission or to ^{40}Ar via electron capture with the emission of a γ-ray in the remaining 10.7% of decay events. The dose received from ^{40}K as a result of the ionizing radiation associated with its radioactive decay makes this radionuclide an internal hazard (Peterson, MacDonell, Haroun, & Monette, 2007).

^{40}K is typically determined directly by passive gamma spectroscopy of the 1460.8 keV photon. There are several notable disadvantages to using gamma spectroscopy, especially when considering the sample type under investigation. This methodology usually involves spectrum acquisition periods of several hours, in many cases in excess of a day to get accurate results. This necessarily reduces the sample throughput in a given time period. Secondly, a relatively large sample mass is required to accurately determine the activity of ^{40}K as it makes up such a small percentage of total potassium. While this may not necessarily be an impediment for geological samples which in general, are denser and have relatively low moisture contents, for biological samples, especially plants this may result in the need to acquire large masses of fresh sample. In the case of the cannabis samples which are the result of samples seized by law enforcement agencies and where the amount of sample is important for forensic and evidential purposes, mass becomes something of a commodity. For these reasons the indirect determination of the activity of ^{40}K from total potassium by instrumental neutron activation analysis (INAA) was an appropriate alternative.

Total potassium by neutron activation analysis (NAA) is determined via the ^{41}K (n,γ) ^{42}K capture reaction. Because the percentage of ^{40}K is always 0.0117% of total potassium the mass fraction of ^{40}K in the sample can be determined using the natural isotopic ratios (Peterson et al., 2007) and employing the activity equation $A = \lambda N$ to determine the activity of ^{40}K (Landsberger, Lara, &

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Landsberger, 2015; Sanchez, Landsberger, & Braisted, 2006; Shafaei, Saion, Wood, Naghavi, & Rezaee, 2011).

Several studies have evaluated the radioactivity of tobacco leaves and the effective dose induced to smokers from naturally occurring radionuclides from the uranium series (^{226}Ra and ^{210}Pb) and thorium series (^{228}Ra) and ^{40}K as well as the potential contamination by ^{137}Cs from the Chernobyl accident (Martinez et al., 2007; Papastefanou, 2009; Peres & Hiromoto, 2002). Cannabis (both plant and resin) is the most widely produced, consumed, and trafficked illicit drug in the world and had an estimated 183 million users in 2014 (Hurley, West, & Ehleringer, 2010; UNODC, 2013; UNODC, 2016). With the significant number of users, the aim of this study was to indirectly determine the activity of ^{40}K in marijuana from Jamaica using INAA as a method of rapid analysis and to determine the effective dose to the smoker.

2. Materials and methods

2.1. Sampling

Samples of marijuana (*Cannabis sativa* L.) were collected following seizure by local law enforcement from several local parishes and districts therein. Following chain of custody procedures, the samples were transported to, and stored in the biological sample preparation laboratory prior to sample preparation and irradiation.

2.2. Sample preparation

The buds of each plant were cut from the stems. Buds were then weighed in an aluminium foil weighing boat, washed in tap water and again in de-ionized water. The samples were oven-dried at 60 °C for two days, cooled in a desiccator for 20 min and then weighed before being ground to a fine powder using a Fritsch Pulverisette 2 automated agate mortar and pestle (Fritsch, Germany). The ground bud samples were subsequently stored in dry plastic containers, previously soaked in a 10% nitric acid solution, washed with de-ionized water and then oven-dried. Each plastic container was labelled with the unique analytical identification number generated by the database and assigned to the individual sample.

2.3. Sample packing, irradiation and analysis

Samples were irradiated using the SLOWPOKE-2 research reactor (Atomic Energy of Canada Limited, ON, Canada). For the determination of potassium in marijuana samples approximately 500 mg of bud sample was weighed out in 1.65 cm^3 pre-cleaned polyethylene capsules which were then heat sealed in 9.50 cm^3 polyethylene vials and irradiated for 4 h at a thermal neutron flux of $\Phi_{th} = 1 \times 10^{12}$ n cm^{-2} s^{-1}, allowed a decay period of 4 days and counted for up to 3600s (Lalor et al., 2000). The samples were counted on an Ortec High-Purity germanium (HPGe) coaxial gamma photon detector system with an efficiency of 71% and a resolution of 1.9 keV at the ^{60}Co 1332 keV gamma line and a Peak to Compton ratio of 78:1 at the ^{60}Co 1332 keV gamma line.

^{42}K has a half-life of 12.4 h making it suitable for determination via a shorter irradiation regime. Approximately 500 mg of sample was weighed out into pre-cleaned double polyethylene bags and heat sealed in pre-cleaned 9.50 cm^3 polyethylene vials. Each sample was irradiated for 3 min at a thermal neutron flux of $\Phi_{th} = 5 \times 10^{11}$ n cm^{-2} s^{-1} and allowed decay periods of approximately 60 min before counting for 600 s. The samples were counted on the Ortec HPGe coaxial gamma photon detector system previously described. The total potassium results showed agreement of better than 95% between the two irradiation regimes; the limit of detection was however significantly higher for the shorter irradiation at lower neutron flux.

2.4. Quality control

The stability of the neutron flux of the SLOWPOKE-2 reactor allows for the modification of the classic relative method of INAA and therefore the calibration of the HPGe counting system. The irradiation and counting geometries for elements are standardized by irradiation of single elements standards. The sensitivity constants are recorded in tables that are used for extended periods and without the need for the co-irradiation of flux monitors or standards (Kennedy & St-Pierre, 1993).

Approximately 13% of the samples were analysed in duplicate, with the differences between duplicates being less than 5%. Certified reference materials used for this study were the IAEA (International Atomic Energy Agency, Vienna, Austria) 336 – Lichens, NIST (National Institute of Standards and Technology, MD, USA) 1547 Peach Leaves and NIST 1515 Apple Leaves. These reference materials were analysed under the irradiation and analytical conditions previously stated as part of sample batches. The observed values for the reference materials are presented in Table 1.

3. Results and discussion

The total potassium in the marijuana buds ranged from 0.84% to 3.15% with a mean mass fraction of 1.93% (see Table 2). The activity concentrations of ^{40}K in the samples of marijuana ranged from 253 to 946 Bq kg^{-1} with a mean activity of 581 Bq kg^{-1} (see Table 2). Considering the lack of papers on radioactivity of marijuana buds, comparison with tobacco leaves may be most appropriate considering that both are used as ingredients for cigarettes. In the work looking at the radioactivity of tobacco leaves from Greece, the ^{40}K activity concentration ranged from 273 to 2080 Bq kg^{-1} with a mean of 823 Bq kg^{-1} (Papastefanou, 2009). Similarly, the ^{40}K activity concentrations from Mexican brands of tobacco ranged from 1020 to 1590 Bq kg^{-1} with a mean of approximately 1290 Bq kg^{-1} (Martinez et al., 2007). In a Jamaican study the minor and trace element content of various tobacco leaf samples were analysed for by INAA (Grant, Lalor, & Vutchkov, 2004). The same methodology used in this paper could be used to derive the ^{40}K activities; the artisanal tobacco ^{40}K activities ranged from 871 to 1742 Bq kg^{-1} with a mean activity of 1231 Bq kg^{-1}. The two local brands assessed had ^{40}K activities of 721 and 781 Bq kg^{-1} and the imported brands ranged from 751 to 1502 Bq kg^{-1} with a mean activity of 1051 Bq kg^{-1} (Grant et al., 2004). Potassium is a major element for plant nutrition and is taken up from the soil and added fertilizers via the roots of plants. The potassium content and therefore the ^{40}K activities appear to be lower in marijuana buds than in tobacco leaves. This may be a result of several factors; species-specific uptake, differences in the potassium content of varying plant compartments, the use of marginal lands and fertilizer use (or lack thereof) for the illicit crop or a combination of these factors.

Given the large population of cannabis users, globally it is useful to determine the dose received from exposure to ^{40}K activity from

Table 1
Total potassium quality control data for IAEA 336 Lichens, NIST 1547 Peach Leaves and NIST 1515 Apple Leaves.

Reference Materials	Reference Value (%)	Observed value (%)
IAEA 336 Lichens	0.184 ± 0.20	0.179 ± 0.01
NIST 1547 Peach Leaves	2.43 ± 0.03	2.46 ± 0.02
NIST 1515 Apple Leaves	1.61 ± 0.02	1.60 ± 0.01

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