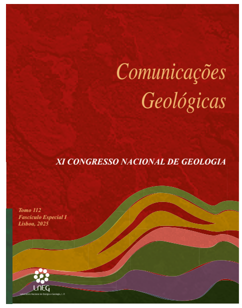
Comunicações
Geológicas

Comunicações Geológicas (2025) 112, Especial I, 293-297
ISSN: 0873-948X; **e-ISSN**: 1647-581X

Natural radioactivity of soils surrounding the deactivated Sines thermal power plant: impacts of coal combustion

Radioatividade natural de solos na envolvente da antiga central termoelétrica de Sines: impactes da combustão de carvão



J. Erbolato Filho[1*], J. Ribeiro[2, 3], A. Pereira [2, 3]

DOI: https://doi.org/10.34637/nd4b-hw06
Recebido em 02/11/2023 / Aceite em 08/02/2024
Publicado online em abril de 2025

Artigo original
Original article

Abstract: For 36 years, the coal combustion in Sines thermal power plant generated a complex mixture of gases and particles that were partially emitted into the atmosphere and the environment. The determination of radiological parameters in soils surrounding the power plant reveals that soils in the southern area have higher activity concentration of natural radionuclides (^{40}K, ^{232}Th, and ^{238}U), as well as higher exhalation rates and emanation coefficients of ^{222}Rn and ^{220}Rn than those located at north. The higher values of radiological parameters in the southern area are explained by dispersion of gases and particles driven by the preferential direction of winds and the proximity to storage facilitates of coal and products derived from combustion. The higher exhalation rates and low emanation coefficients of thoron indicates that K and Th may be accumulated and encapsulated in the mineral fraction of ash particles while U, preferentially bounded to organic matter, was mobilized during coal combustion. The results do not indicate a significant radiological risk, although it is higher in the southern area.

Keywords: coal combustion, soils, ash, environmental legacy, radiological risk.

Resumo: Durante 36 anos, a combustão do carvão na central termoelétrica de Sines gerou uma mistura complexa de gases e partículas que foram parcialmente emitidas para a atmosfera e para o ambiente. A determinação de parâmetros radiológicos nos solos no entorno da central termoelétrica revela que os solos da área sul apresentam maior concentração de atividade de radionuclídeos naturais (^{40}K, ^{232}Th e ^{238}U), assim como maiores taxas de exalação e coeficientes de emanação de ^{222}Rn e ^{220}Rn do que os localizados a norte. Os valores mais elevados dos parâmetros radiológicos na zona sul são explicados pela dispersão de gases e particular conduidas pela direção preferencial dos ventos e pela proximidade das instalações de armazenamento de carvão e produtos derivados da combustão. As maiores taxas de exalação e os baixos coeficientes de emanação do torão indicam que K e Th podem ser acumulados e encapsulados na fração mineral das cinzas enquanto o U, preferencialmente ligado à matéria orgânica, foi mobilizado durante a combustão do carvão. Os resultados não indicam um risco radiológico significativo, embora este seja maior na zona sul.

Palavras-chave: combustão de carvão, solos, cinzas, legado ambiental, risco radiológico.

[1] Universidade de Coimbra, Departamento de Ciências da Terra, Laboratório de Radioatividade Natural da Universidade de Coimbra, Rua Sílvio Lima, 3030-790 Coimbra, Portugal.
[2] Universidade de Coimbra, Instituto Dom Luiz, Rua Sílvio Lima, 3030-790 Coimbra, Portugal.

[*] Autor correspondente / Corresponding author: joseaugustobef@gmail.com

1. Introduction

Coal combustion in industrial facilities generates a complex mixture of gases and particles, which are partially emitted and dispersed into the atmosphere and surrounding environments (*e.g.* Orem and Finkelman, 2003; Yao *et al*., 2010). Considering that currently national and european policies aim the reduction of the use of coal for power generation, the investigation of the impacts caused by coal combustion is important to assess the environmental legacy left by the burning of fossil fuels. This topic is particularly pertinent in the context of the climate crisis and the energy transition.

Radionuclides occur naturally in varying concentrations in coals, and are partially mobilized during combustion. In this scenario, U is particularly relevant because it tends to occur in association with organic matter (OM) in coals (Swaine, 1990; Orem and Finkelman, 2003; Finkelman *et al*., 2018). During combustion of OM, U can be mobilized by volatilization . The occurrence of Th in coals is generally related to detrital minerals, such as zircon and monazite (Swaine, 1990). Therefore, this element is less mobile than U, but often associated with it due to chemical and physical properties. The largest portion of K present in coals is generally associated with the inorganic fraction (Swaine, 1990; Finkelman *et al*., 2018). These more resistant mineral components of coal remain after the combustion in the form of ash residues, so the radionuclides associated with mineral matter tend to be concentrated in the coal ash.

This work aims to identify the impact of coal combustion in soils of the surrounding area of the deactivated Sines thermal power plant (STPP, in Portugal) concerning natural radionuclides. For that, (i) the activity concentration of the radionuclides U, Th and K was estimated, (ii) the exhalation rates and emanation coefficients of the gaseous radon (^{222}Rn) and thoron (^{220}Rn) were measured, and (iii) risk parameters were calculated in soil samples and other two ash samples from STPP.

2. Study area

The construction of the STPP started 1979 and was completed in 1989. The operation started in 1985 (EDP, 2019) until January of 2021. The STPP is located a few kilometers from the center of city of Sines, in Alentejo region specifically in the southwest coast of Portugal. The area ocupied by the STPP contacts directly with the limit of a natural park (*Parque Natural do Sudoeste Alentejano e Costa Vicentina* - PNSACV), being a protected area with a great natural value. Figure 1 shows the location of STPP as well as the limits of the PNSACV.

Figure 1. Parks, reserves and other protected areas in Portugal. Highlighted in red the PNSACV area and STPP approximate location (adapted from SNIAmb, 2023).

Figura 1. Parques, reservas e outras áreas protegidas em Portugal. Destacado a vermelho a área do PNSACV e localização aproximada da STPP (adaptado de SNIAamb, 2023).

The region of Sines is in an elevated surface that corresponds to a marine abrasion platform (Inverno *et al*., 1993). Practically all the Alentejo coastline is straight, but in the Sines area there is an eruptive massif that form a small litoral peninsula with a very indented coastline. Towards the interior, the rocky massif is worn down by erosion, and is almost completely covered by Quaternary deposits and dune sands, which form a platform with around 40 to 50 m (ICNB, 2008; ADSA, 2019). The STPP is located above a sandy layer generally dated to the Plio-Pleistocene; this lithology is characterized by fine-grained to coarse-grained sands occasionally with clay, scattered pebbles, clayey sandstones with medium to coarse grains and sometimes subangular pebbles (Inverno *et al*., 1993).

The soils surrounding the STPP are classified as eutric cambisols originating from post-paleozoic sedimentary rocks, have a horizon A with light colors and low organic matter, low agricultural potential, low permeability, low microorganism retention capacity, low potential cation exchange, low retention and transformation capacity for organic and inorganic pollutants, medium to high erodibility (ICNB, 2008; ADSA, 2019). Regarding the land use around the area of the STPP, it is mostly industrial, agricultural, uncultivated and forestry (ADSA, 2019).

In the STPP region the climate is classified as Mediterranean under the influence of the Atlantic Ocean regarding temperature, relative humidity, solar incidence and winds. The dominant directions of the wind are shown in figure 2, they are from north and northwest (ICNB, 2008). The wind direction can be particularly useful, providing indication of possible directions of dispersion of particles and gases from STPP, both arising from the combustion of coal, as well as the storage and management of coal and coal combustion residues.

3. Material and methods

3.1. Sampling and sample preparation

The sampling near the outer limit of STPP facilities was considered due to the lack of previous studies about soils quality in this area. A total of 28 soil samples were collected in the area surrounding the STPP, as can be observed in figure 2. Samples were collected from the surface up to 10 cm depth, after removal of vegetation, coarse pebbles and other materials. Approximately 1.5 kg was collected for each sample. Sample SS10 includes the collection of two samples (SS10A and SS10B), since an ash layer was found below the superficial soil; SS10B is a sample of soil mixed with ash.

In the laboratory, the samples were dried and sieved to obtain the soil fraction < 2 mm. Samples were compacted and sealed in *Marinelli* beakers, which were stored until secular equilibrium was obtained.

In addition to soil samples, two samples of ashes (one bottom ash and one fly ash) from STPP were also analyzed. These samples were stored in the Laboratory of Natural Radioactivity of the University of Coimbra (LRN-UC). The ash samples were also placed in *Marinelli* beakers until secular equilibrium was obtained.

3.2. Determination of radioisotopes activity concentration

Gamma ray spectrometry was used to determine the activity concentration of gamma emitters in the studied materials, based on the ISO 8589-3:2015 standard, together with the LRN-UC analytical and qualitative processes, which ensure the consistency and precision of the obtained results. A gamma radiation spectrometer, from *Ortec* was used, including a sodium iodine detector (NaI).

The spectrometer performs the determination of the concentrations analyzing the peak area of energy of isotopes of interest, and the software used in this case was Scintivision from Ortec. Assuming in the secular equilibrium, to determine the activity concentrations ^{238}U, ^{232}Th and ^{40}K were determined considering the peak energies of ^{214}Bi at 1764.5 keV, ^{208}Tl at 2614.5 keV and ^{40}K at 1460.8 keV, respectively (Pereira *et al*., 2013; Domingos *et al*., 2021; Sêco *et al*., 2021).

3.3. Determination of the exhalation rate and emanation coefficient of radon and toron

The determination of the exhalation rate and the emanation coefficient of radon (^{222}Rn) and thoron (^{220}Rn), which are gaseous isotopes of the natural decay chains of U and Th respectively, were performed by alpha spectrometry and using an accumulation method (Pereira *et al*., 2017).

The estimation of gaseous radioisotope activities in samples are made after obtaining the isotopic equilibrium between ^{226}Ra and ^{222}Rn, and ^{224}Ra and ^{220}Rn. Using a AlphaGuard equipment DF2000 the exhalation rate of radon and thoron are simultaneously quantified. The exhalation rates of ^{222}Rn and ^{220}Rn are determined according to the following equations:

$$\text{Radon: } E_{x\,(^{222}Rn)} = (^{222}Rn \times (V_c - V_a) \times \lambda^{222}Rn) / M_a \quad \text{(Equation 1)}$$

$$\text{Thoron: } E_{x\,(^{220}Rn)} = (^{220}Rn \times (V_c - V_a) \times \lambda^{220}Rn) / M_a \quad \text{(Equation 2)}$$

Where E_x – exhalation rate (in $Bq.kg^{-1}.h^{-1}$); ^{222}Rn and ^{220}Rn – activity concentration of radon and thoron ($Bq.m^3$) accumulated in the container; V_c - container volume (m^3); V_a - sample volume (m^3); λ - radon or toron decay constant (h^{-1}); M_a - mass of sample (kg).

The emanation coefficient (EM) is calculated through the ratio

Figure 2. Aerial image of the STPP with identification of sampling locations and dominant direction of winds.

Figura 2. Imagem aérea STPP com identificação dos locais de amostragem e direção dominante dos ventos.

between the activity concentration of ^{222}Rn and ^{220}Rn conjugated with the activity concentration of ^{226}Ra and ^{224}Ra, respectively:

$$EM = (Rn / A_{Ra}) \times 100 \text{ (Equation 3)}$$

Where Rn is the activity concentration of radon or toron and A_{Ra} is the activity concentration of ^{226}Ra or ^{224}Ra.

The EM is given as a percentage, and the higher the EM, the greater the potential for radon and thoron production of a given material.

3.4. Determination of radiological risk

Radiological risk can be assessed through the calculation of radiological parameters, such as: absorbed dose rate of gamma radiation in outdoor air (D in nGy/h, equation 4), equivalent dose effective annual outdoor exposure (DA in mSv/y, equation 5), external radiation hazard (H_{ext}, equation 6) and utilization activity index (UAI in µSv/y, equation 7) and the equivalent activity of Ra (Ra_{eq} in Bq.kg^{-1}, equation 8). These parameters of radiological risk assessment are widely used in environmental studies, including in studies related to coal combustion thermal power plants and contaminated soils (*e.g.* Durusoy *et al*., 2017; Walencik-Lata *et al*., 2020; Abedin *et al*., 2020). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recognizes and defines recommended maximum values for some of these parameters (UNSCEAR, 2000, 2008), as described below:

$$D = 0.462\ C_{Ra} + 0.604\ C_{Th} + 0.0417 C_K \text{ (Equation 4)}$$

Where C_{Ra}, C_{Th} and C_K represent the activity concentration of ^{226}Ra, ^{232}Th and ^{40}K respectively. The world average value is 60 nGy h^{-1}.

$$DA = D \times 0.7 \times 8760 \times 0.2 \times 10^{-6} \text{ (Equation 5)}$$

This value represents the equivalent dose of annual exposure of an individual who is exposed to terrestrial gamma radiation taking into account 20% of outdoor time, 0.7 Sv/Gy is the effectiveness quotient of the dose to which an individual is exposed and absorbed by the air, 8760 hours are the total number of hours in a year and 10^{-6} represents the conversion mSv. The world average value of this parameter is 0.46 mSv y^{-1}.

$$H_{ext} = C_{Ra}/370 + C_{Th}/259 + C_K/4810 \text{ (Equation 6)}$$

Since C_{Ra}, C_{Th} and C_K represent the concentrations of the isotopes ^{226}Ra, ^{232}Th and ^{40}K, respectively. This equation is based on the assumption that 370 Bq.kg^{-1} of ^{226}Ra, 259 Bq.kg^{-1} of ^{232}Th and 4810 Bq.kg^{-1} of ^{40}K produce the same gamma radiation dose rate. The maximum recommended security value is 1.

$$UAI = (C_{Ra}/50)\ f_{Ra} + (C_{Th}/50)\ f_{Th} + (C_K/500)\ f_K \text{ (Equation 7)}$$

The values of $f_{Ra} = 0.462$, $f_{Th} = 0.604$ and $f_K = 0.041$ represent the contribution of each of the elements to the total dose of gamma radiation considering ^{226}Ra, ^{232}Th and ^{40}K, respectively. The maximum reference value recommended is 2 µSv y^{-1}.

$$Ra_{Eq} = C_{Ra} + 1.43\ C_{Th} + 0.077\ C_K \text{ (Equation 8)}$$

In the equation the values of C_{Ra}, C_{Th} and C_K represent the concentrations of ^{226}Ra ^{232}Th and ^{40}K respectively. The recommended maximum safety value is equivalent to 370 Bq.kg^{-1}.

4. Results and discussion

Table 1. shows the range of activity concentrations of ^{40}K, ^{232}Th, and ^{238}U in the samples of soils and ashes.

Table 1. Range of activity concentration (Bq.kg^{-1}) of ^{40}K, ^{232}Th e ^{238}U in soils and ashes.

Tabela 1. Gama de concentração de atividade (Bq.kg-1) de ^{40}K, ^{232}Th e ^{238}U em solos e cinzas.

	Soils (n = 28)	Ashes (n = 2)
^{40}K	178 – 514	417 – 577
^{232}Th	6 – 68	45 – 51
^{238}U	7 – 42	55 – 141

The activity concentration of radionuclides in soils presents a great heterogeneity. However, samples collected in the southern area of STPP present higher values than those reported for samples collected in the north of the STPP. This is explained by the prevailing winds direction in the region and also by the proximity to storage facilities of coal and combustion by-products.

Values of activity concentration of the analyzed radionuclides in ash samples are closer or above the maximum values determined in soils, meaning that the higher values in soils can be related with contamination by ash particles. In fact, during sampling, it was possible to observed ash material mixed with soil in some specific places in the southern area of STPP.

The average values of activity concentration in soil samples are: 353.38 Bq.kg^{-1} for ^{40}K; 18.85 Bq.kg^{-1} for ^{214}Bi (^{238}U); 19.97 Bq.kg^{-1} for ^{208}Tl (^{232}Th). These average values are below values of global soils, which are 24.7 Bq.kg^{-1} of ^{226}Ra (equatable with ^{214}Bi, assuming the secular equilibrium), 36.5 Bq.kg^{-1} of ^{232}Th (equatable with ^{208}Tl by assuming secular equilibrium) and 363.8 Bq.kg^{-1} for ^{40}K (Bowen, 1979). However, some of the studied samples present higher values that exceed the reference values of activity concentration, they are:

^{226}Ra (^{214}Bi): SS4, SS5, SS8, SS10, SS11 and SS12.

^{232}Th (^{208}Tl): SS8, SS11 and SS16.

^{40}K: SS2, SS3, SS4, SS5, SS7, SS8, SS9, SS11, SS13, SS15, SS17, SS19, SS26, and SS27.

High values tend to be from the southern area of the STPP in majority of cases. But the case of the ^{40}K is possible to obseve some values that exceed the global average located in the north of STPP, which is most probably related with the geological background.

The results were compared with data from other studies about soils surrounding thermal power plants around the world (Gören *et al.*, 2017 and references therein). It was verified that the soils in the surroundings of the STPP present values of activity concentration that are closer to the minimum values recorded in these studies.

Table 2. present the range of exhalation rates and emanation coefficients of radon and thoron in soils and ashes.

Values of exhalation rate and the emanation coefficient of radon and thoron gases are related with the activity of ^{238}U and ^{232}Th, respectively, being generally higher when activity concentration is also higher. This behavior is observed in soils but is not in the ash samples. Bottom and fly ashes, despite having high activity concentration, present exhalation rates and emanation coefficients similar or lower than most of the soil samples. This can be explained by the process of ash formation during coal combustion, in which more resistant mineral phases with U and Th can be trapped in glass spheres, glass agglomerates and char particles that constitute the ashes (Fu *et al.*, 2022). Petrographic observation of the studied ash samples, reveal the presence of these constituents, as seen in figure 3.

Table 2. Range of exhalation rates (Bq.kg.h -1) and emanation coefficients of radon (222Rn) and thoron (220Rn) in soils and ashes.

Tabela 2. Gama de taxas de exalação (Bq.kg.h -1) e coeficientes de emanação de radônio (222Rn) e torão (220Rn) em solos e cinzas.

		Soils (n = 28)	Ashes (n = 2)
Exhalation rates	^{222}Rn	0.002 - 0.042	0.003 - 0.012
	^{220}Rn	2.600 - 115.0	5.600 - 21.40
Emanation coefficients	^{222}Rn	0.025 - 0.215	0.006 - 0.011
	^{220}Rn	0.006 - 0.091	0.003 - 0.091

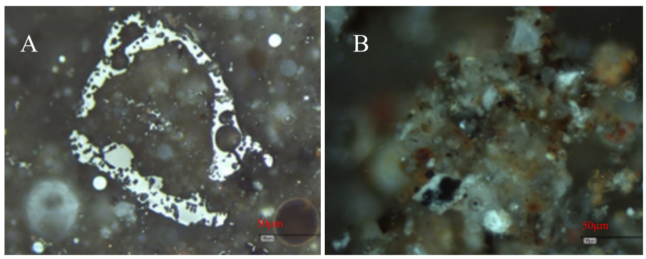


Figure 3. A) Photomicrograph of a char particle in the fly ash. B) Photomicrograph of a glass agglomerate in the bottom ash.

Figura 3. A) Microfotografia de uma partícula de carvão na cinza volante. B) Microfotografia de aglomerado de vidro na cinza de fundo.

From the considered radiological risk parameters, only the parameter D (absorbed dose rate of gamma radiation in outdoor air) has estimated values of one soil sample and ash samples above the average and recommended value of UNSCEAR (2000, 2008), which is 60 nGy h^{-1}. The parameter D estimated for soil sample SS8 (next to the coal storage and with visible mixed ash matereial in it) is 80.93 nGy h^{-1} The estimated parameter D is 119.85 nGy h^{-1} in fly ash and 69.97 nGy h^{-1} in bottom ash.

The overall results evidence that there is no radiological risk related to soils. Although the differences observed between the soils in the north and south areas of STPP are an indicator of contamination associated with industrial coal combustion.

5. Conclusions

The results of this study reveal that the activity concentration of the analysed radionuclides is heterogeneous among the studied soil samples, being the highest values determined in samples collected in southern area of STPP. These higher values of activity concentration are explained by the dispersion and deposition of contaminants with the predominant wind direction in the region, which drove the mobilization of particles. The proximity of coal and coal combustion by-products storage sites would be a possible source of mobilized material together with materials emitted from chimneys. Despite having higher activity concentration of radionuclides, the ash samples present exhalation rates and emanation coefficients similar or lower than most samples of soils, which is explained by the encapsulation of radioniclides in glass agglomerates, glass spheres, and char particles in ashes. This encapsulation decreases the risk related to emanation of radon and thoron, but this should be considered in the long-term stability of these materials and also in the possibility of recycling the ashes for rehabilitation purposes and other uses. The results of this work do not indicate a significant radiological risk, although it is higher in the southern area.

Acknowledgments

The authors acknowledge the support provided by LRN-UC. This work was funded by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) - UIDB/50019/2020-IDL.

References

Abedin, M. J., Karim, M. R., Khandaker, M. U., Kamal, M., Hossain, S., Miah, M. H. A., Bradley,D.A., Faruque, M.R.I., Sayyed, M. I., 2020. Dispersion of radionuclides from coalfired brick kilns and concomitant impact on human health and the environment. Radiation Physics and Chemistry, **177**: 109165.

ADSA, Águas de Santo André S.A., 2019. Nova conduta adutora entre a ETA de Morgavel e o reservatório de Monte Chãos. Capitulo IV. Situação atual do ambiente. https://siaia.apambiente.pt/aiadoc/aia3281/vol2_rs_rev01_capiv201978151659.pdf.

Bowen, H. J. M., 1979. Environmental chemistry of the elements. Academic Press.

Domingos, F. P., Sêco, S. L., Pereira, A. J., 2021. Thoron and radon exhalation and emanation from granitic rocks outcropping in the Central Iberian Zone (Portugal). Environmental Earth Sciences, **80**: 1-18.

Durusoy, A., Yildirim, M., 2017. Determination of radioactivity concentrations in soil samples and dose assessment for Rize Province, Turkey. Journal of Radiation Research and Applied Sciences, **10**: 348-352.

EDP, Energias de Portugal, 2019. Central termoelétrica de Sines, declaração ambiental 2019. Atualização da declaração ambiental de 2018.https://emas.apambiente.pt/sites/default/files/files/emas/declaracoes/da_12.pdf.

Finkelman, R. B., Palmer, C. A., Wang, P., 2018. Quantification of the modes of occurrence of 42 elements in coal. International Journal of Coal Geology, **185**: 138-160.

Fu, B., Hower, J. C., Zhang, W., Luo, G., Hu, H., Yao, H., 2022. A review of rare earth elements and yttrium in coal ash: Content, modes of occurrences, combustion behaviour, and extraction methods. Progress in Energy and Combustion Science, **88**: 100954.

Gören, E., Turhan, Ş., Kurnaz, A., Garad, A. M. K., Duran, C., Uğur, F. A., Yeğingil, Z. E. H. R. A., 2017. Environmental evaluation of natural radioactivity in soil near a lignite-burning power plant in Turkey. Applied Radiation and Isotopes, **129**: 13-18.

Inverno, C., Manuppella, G., Zbyszewski, G., Pais, J., Ribeiro, M. L., 1993. Carta Geológica de Portugal na escala de 1/50 000. Notícia Explicativa da Folha 42-C Santiago do Cacém. Serviços Geológicos de Portugal.

ICNB, Instituto da Conservação da Natureza e da Biodiversidade, I.P., 2008. Plano de Ordenamento do Parque Natural do Sudoeste Alentejano e Costa Vicentina. Estudos de Base, Etapa 1 - Descrição, Volume 1.

Orem, W. H., Finkelman, R. B., 2003. Coal formation and geochemistry. In: Holland, H.D., Turekian, K.K., Mackenzie, F.T., (Eds.), Treatise on Geochemistry, Sediments Diagenesis and Sedimentary Rocks vol. 7, Elsevier, Amsterdam, 191-222.

Pereira, A. J. S. C., Pereira, D., Neves, L., Peinado, M., Armenteros, I., 2013. Radiological data on building stones from a Spanish region: Castilla y León. Natural Hazards and Earth System Sciences, **13**: 3493-3501.

Pereira, A., Lamas, R., Miranda, M., Domingos, F., Neves, L., Ferreira, N., Costa, L., 2017. Estimation of the radon production rate in granite rocks and evaluation of the implications for geogenic radon potential maps: A case study in Central Portugal. Journal of environmental radioactivity, **166**: 270-277.

Sêco, S. L., Pereira, A. J., Duarte, L. V., Domingos, F. P., 2021. Sources of uncertainty in field gamma-ray spectrometry: Implications for exploration in the Lower-Middle Jurassic sedimentary succession of the Lusitanian Basin (Portugal). Journal of Geochemical Exploration, **227**: 106799.

SNIAmb, Sistema Nacional de Informação de Ambiente, 2023. Visualisador SNIAmb, Atlas do Ambiente. Acedido em outubro de 2023. https://sniamb.apambiente.pt/content/geo-visualizador

Swaine, D.J., 1990. Trace elements in coal, Butterworths.

UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation, 2000. Sources, effects and risks of ionizing radiation. Report to the general assembly, with scientific annexes.

UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation, 2008. Sources, effects and risks of ionizing radiation. Report to the general assembly, with scientific annexes.

Walencik-Łata, A., Smołka-Danielowska, D., 2020. ^{234}U, ^{238}U, ^{226}Ra, ^{228}Ra and ^{40}K concentrations in feed coal and its combustion products during technological processes in the Upper Silesian Industrial Region, Poland. Environmental Pollution, **267**: 115462.

Yao, Q., Li, S. Q., Xu, H. W., Zhuo, J. K., Song, Q., 2010. Reprint of: Studies on formation and control of combustion particulate matter in China: A review. Energy, **35**: 4480-4493.