Remediation of coal ash and slag disposal site : comparison of radiological risk assessments

Getaldić, Ana; Surić Mihić, Marija; Veinović, Želimir; Skoko, Božena; Petrinec, Branko

Source / Izvornik: **Rudarsko-geološko-naftni zbornik, 2023, 38, 95 - 104**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.17794/rgn.2023.3.8

RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 621.039.7
DOI: 10.17794/rgn.2023.3.8

Original scientific paper

Remediation of coal ash and slag disposal site: Comparison of radiological risk assessments

Ana Getaldić[1]; Marija Surić Mihić[2]; Želimir Veinović[1]; Božena Skoko[3]; Branko Petrinec[4]

[1] *Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, p.p. 390, HR-10000 Zagreb, Croatia, ORCID: 0000-0002-0529-2036*

[2] *Ministry of the Interior, Civil protection Directorate, Nehajska 5, HR-10000, Croatia, ORCID: 0000-0002-0265-3203*

[3] *Ruđer Bošković Institute, Bijenička cesta 54, HR-10000 Zagreb, Croatia, ORCID: 0000-0003-2631-7201*

[4] *Institute for Medical Research and Occupational Health, Ksaverska cesta 2, HR-10001 Zagreb, Croatia, ORCID: /0000-0001-9272-3828*

Abstract

Residuals from coal combustion are known as a potential source of radiation exposure, especially in cases where the coal used in the combustion is characterized by increased radioactivity, resulting in coal ash and slag with potentially high activity concentration of radionuclides. This paper presents the results of the radiological risk assessments based on the ERICA Tool approach, used to estimate dose rates to terrestrial biota in the proximity of a coal fired thermal power plant in Croatia. The study consists of three radiological risk assessments using environmental data on activity concentration ($Bqkg^{-1}$) from samples collected prior to the remediation of the disposal site and samples after the remediation implementation was completed. The resulting total dose rate to biota derived using data prior to the remediation ranged from 3.28 μGyh^{-1} to 147.68 μGyh^{-1}. Assessment results of total dose rate based on the data from the studied area after remediation ranged from 0.23 μGyh^{-1} to 18.06 μGyh^{-1}. The results showed that after the remediation only the total dose rate for lichens and bryophytes slightly exceeded ERICA Tool conservative screening value of 10 μGyh^{-1}, which implies that environmental risks in relation to exposure to the disposal site can be considered negligible. The study results confirm the applicability of the ERICA Tool for the assessment of potential radiological impact and the effective remediation implementation at the coal and ash slag disposal site.

Keywords:

radiological risk assessment; NORM; coal fired power plant; remediation; environmental monitoring

1. Introduction

Although the use of renewable energy sources is on the rise, worldwide statists show that coal use as a primary energy source still accounts for approximately a quarter of the global energy mix (**Ritchie et al., 2022**). In addition, European countries still significantly rely on fossil fuels (**Martins et al., 2018**). The disposal of residues related to coal use is associated with different environmental challenges, engineering solutions, and resource management strategies. The disposal of coal combustion residues (coal fly ash and slag) is often related to large waste quantities and requires that specific environmental and safety standards are met (**Hirschi and Chugh, 2019**).

Naturally occurring radioactive materials (NORM) are found in different natural resources. Various industrial processes generate NORM residues and present a potential for radiation exposure. The international community has recognized the risk associated with natural radioactivity and radiation exposure through different legal acts (e.g. The European Council 2013/59/Euratom) and international guidance documents (**IAEA, 2003; IAEA, 2013; IAEA, 2022; ICRP, 2019**). Coal combustion presents a potential source of radiation exposure, where the resulting coal ash and slag can contain considerable activity concentrations of radionuclides, which are usually related to the activity concentrations present in the parent coal used in the combustion in the first place (**IAEA, 2003**). These radionuclides, contained in coal ash, can later be transported to the environment by different pathways, like dispersion and leaching, and can be associated with detrimental environmental and health effects. In order to mitigate potential adverse effects, NORM-related industries are required to establish and implement radiological protection principles, including the principle of justification and, in different industrial stages, optimization through the use of a graded approach (**Lecomte, 2020**).

The international community provided recommendations on radiation protection, including non-human biota (**ICRP, 2007; NEA, 2007**), and the need for it to be sci-

Corresponding author: Ana Getaldić
e-mail address: agetaldic@rgn.hr

entifically and independently assured through the use of ecological risk assessment paradigm, defined dose limits and reference organisms, and considering the geographic region (**Delistraty, 2008**). Potential environmental impacts related to the exposure of non-human biota to ionizing radiation can be estimated using different models and approaches, including concentration ratios, kinetic models, compartment models, and an allometry approach (**Higley and Bytwer, 2007; Beresford et al., 2010; Pentreath and Woodhead, 2001**). The ERICA Tool was developed as a part of the European Union co-funded 6th Framework Program EURATOM project named Environmental Risk from Ionising Contaminants Assessment and Management (ERICA). The ERICA Tool uses concentration ratios to calculate activity concentrations in the whole organism, and together with the activity data from environmental media, estimates dose rates (internal, external, and total) to organisms (**Johansen et al., 2012**). In the ERICA Tool, the radiological risk assessment is defined by comparing the calculated total dose rate and the exposure levels associated with known detrimental radiation effects (**Brown et al., 2008; Brown et al., 2013**). The ERICA Tool and Approach is applicable to various exposure situations, including planned and existing exposure situations and activities, including NORM/TENORM (**Beresford et al., 2007**). Several studies have used the ERICA Tool to assess the radiological impacts of NORM-related industries. A study by **Ćujić and Dragović (2018)** assessed dose rates to terrestrial biota around a coal-fired power plant in Serbia. Research from **Mrdakovic Popic et al. (2020)** used ERICA for the estimation of dose rate at the NORM legacy mining site in Norway. ERICA Tool was used for radiological risk assessment at different mining sites in Central Asia in a study by **Oughton et al. (2013)**. **Skoko et al. (2019)** used the ERICA Tool for risk assessment of the coal ash and slag legacy disposal site in Croatia.

Previous research conducted at the location includes studies of radionuclides in the soil and their distribution (**Kovac and Bajlo, 1996; Ernečić et al., 2014; Radolić et al., 2019; Dvoršćak et al., 2019**), investigations related to coal used at the power plant and resulting waste (**Marović et al., 2008**), and environmental impacts studies of the disposal site (**Skanata et al., 1996a; Marović et al., 1997; Marović et al., 2004; Bituh et al., 2017**).

Although the management of NORM residues is increasingly focusing on approaches other than disposal, such as recycling and use as by-products, the disposal of NORM residues is still very much present. In the context of NORM residue disposal, the implementation of remediation must include principles of optimization and justification and ensure that the radiological and environmental impacts of these activities are within the acceptable limits, and provide long-term protection and safety (**IAEA, 2013**).

The aim of this paper is to estimate potential impacts to the terrestrial biota from coal ash and slag disposal using the Erica Tool and compare the estimations in relation to the implemented remediation of the disposal site. The study used several spatial and temporal data sets before and after the site remediation was performed. The results from different assessments provide insight into the degree to which the deposited material is contained and can be used as a reference in the design of future estimations and assessments of radiological impacts at similar locations. In addition, the study confirms the importance of environmental monitoring in the implementation of radiological protection in NORM-related industries.

2. Materials and Methods

This study compares the results of three radiological risk assessments performed with the ERICA Tool for terrestrial biota at a disposal site near a coal-fired power plant in Croatia. The disposal site contains large quantities of residues resulting from coal combustion.

2.1. Assessment site

The study focused on the location of the coal-burning power plant "TE Plomin" in Croatia, situated on the eastern coast of the Istrian Peninsula, in the northern part of the Adriatic Sea (see **Figure 1**). Areas with slightly elevated natural background radioactivity are present in the Istrian region (**Marović et al., 2004**), studies on radioactivity in the soil also showed that activity concentrations of soil were above the national average (**Šoštarić et al., 2021**).

The site consists of two facilities: Plant I and Plant II. Plant I has been operational since the 1970s and is known for using local coals (anthracite, lignite, and brown coal) until 1999 when Plant II was constructed. Anthracite coal, also known as Raša coal, was characterized by elevated levels of radioactivity and, owing to its high content of organic sulphur (up to 14%), was classified as a superhigh-organic-sulphur coal (**Medunić et al., 2016**). The radioactivity of the resulting coal ash and slag from coal combustion was increased. Local mines were eventually closed during the 1990s due to environmental unacceptability, insufficient reserves, and lack of profit (**Medunić et al., 2016**). Hence, Plant II used imported coal with low sulphuric content and low radioactivity (**Marović et al., 2004**).

Waste from the plant's routine operation was continuously disposed of at the site. The disposal site was remediated during the 1990s. The remediation included the use of geo-synthetic material as a ground sealing layer, a protective cover consisting of an earth layer and grass, and the implementation of rainwater channels and a settling tank (**Marović et al., 2008**).

Figure 1: Study site location

2.2. Use of the ERICA Assessment Tool

Estimation of potential dose rates to terrestrial biota from exposure to radionuclides detected in samples collected from the research site, before and after the remediation, was done using the ERICA Tool (version 2.0), freely available to users online. The ERICA Tool relies on activity concentrations in the environmental media (sediment, soil, water, and air) as input data, activity concentrations in organisms, and uses reference organisms as generalised ecosystem representations of animal and plant species (**Beresford et al., 2007; Brown et al., 2008**). Radionuclides available in the Tool and the concept of reference organisms follow the guidelines proposed by the International Commission on Radiological Protection (**ICRP, 2007; ICRP, 2008**). The ERICA Tool is suited for environmental assessments related to the potential impacts of radiation due to planned or existing exposure situations, including scenarios related to NORM/TENORM, remediation, radioactive waste disposal, decommissioning of various nuclear facilities, and nuclear accidents (**Beresford et al., 2007**).

In the ERICA Tool, the estimation of environmental transfer of radionuclides to the biota is performed by using the concentration ratio (CR) values which represent the ratio between activity concentrations of radionuclides in the biota (whole body) and activity concentrations in the selected environmental media (soil, water, and air) (**Beresford et al., 2007; Brown et al., 2008; Brown et al., 2016**). In assessing the potential effects of internal and external exposure to ionizing radiation, the ERICA Tool uses Dose Conversion Coefficients (DCC_{int} and DCC_{ext}) in μGyh^{-1} per $Bqkg^{-1}$ fresh weight and compares the data on activity concentration in the biota and the environmental media (**Beresford et al., 2007; Brown et al., 2008; Brown et al., 2013**). Other parameters and values used to perform the assessment include weighting factors, used to address different components of radiation (low β, β + γ, and α) (**Brown et al., 2008; Brown et al., 2016**). The assessor conducting the assessment can select one of the three ecosystems (freshwater, terrestrial, and marine) and either the Tool's default screening dose rate value of 10 μGyh^{-1} (**Brown et al., 2008**), 400 μGyh^{-1} (**UNSCEAR, 1996**), or a custom as-

 pp. 95-104, DOI: 10.17794/rgn.2023.3.8

sessment screening dose rate value. The Tool uses uncertainty factors (UF), 3 and 5, to ensure conservativism between Tier 1 (a simple assessment requiring minimal data input) and Tier 2 assessments, which are defined as the ratio between the 95th and 99th percentile of the risk quotient and the expected value of the probability distribution of the dose rate (**Beresford et al., 2007**). The default UF values of 3 and 5 have the role of ensuring that the assessment is run for a 5% and 1% probability of exceeding the dose rate screening value (**Brown et al., 2016**). One of the risk assessment outputs is the risk quotient (RQ), which is a unitless value that the Tool calculates by comparing the selected assessment screening dose rate and the total estimated whole-body absorbed dose rate for each organism (**Beresford et al., 2007; Brown et al., 2008**). A conservative risk quotient is calculated by multiplying the expected RQ value and the uncertainty factor (**Beresford et al., 2007**). All radiological risk assessments performed in this study used the default values of weighting factors, occupancy factors, screening dose rate value, and uncertainty factors.

2.3. Assessment input data

The overview of assessment input data for scenarios before and after the remediation is given in **Table 1**. Radiological risk assessment related to the environmental scenario before the remediation of the disposal site was based on laboratory gamma-spectrometric measurements of the samples collected at the disposal site published in previous studies by **Marović and Bauman (1986)** and **Skanata et al. (1996b)**. The average values of the activity concentrations in coal ash and slag samples and activity concentration ranges are presented in **Table 2**. For the risk assessment of the potential environmental impact of the disposal site after the remediation, available data from a previous study by **Marović et al. (2008)** was used. This study included data from in situ gamma-spectrometry measurements and gamma-spectrometry measurements in the laboratory that were carried out using an HPGe detector. Details on the measurement methods and sampling are available in **Marović et al. (2008)**. **Table 3** presents the activity concentrations in the media that were used as assessment input data.

An additional radiological risk assessment scenario for the plant site was performed using the extensive data on 50 surface soil samples taken at the plant perimeter in 2015 as a part of environmental monitoring conducted by the Institute for Medical Research and Occupational Health, Zagreb, Croatia. Sampling was carried out in accordance with the procedures proposed by International Atomic Energy Agency (**IAEA, 1989**). The sampling method included the removal of vegetation and sampling of the surface layer of soil (0 - 10 cm). The samples were oven-dried at 105°C and then sieved. The dried and sieved samples were sealed with PVC in 1000 mL volume Marinelli containers. To ensure radioactive equilibrium the samples were stored for at least 30 days before conducting measurements. Radionuclide activity concentrations were determined by high-resolution gamma-ray spectrometry using HPGe detectors. The activity concentration of ^{238}U was determined based on the activ-

Table 1: Assessment parameters for scenarios before and after* the remediation

Ecosystem type	Radionuclides	Reference organisms
Terrestrial	^{238}U ^{226}Ra ^{238}U* ^{226}Ra* ^{232}Th*	Amphibian Annelid Arthropod - detritivorous Bird Flying insects Grasses & Herbs Lichen & Bryophytes Mammal - large Mammal - small-burrowing Mollusc - gastropod Reptile Shrub Tree

Table 2: Average activity concentrations (Bqkg^{-1} dry mass) in samples collected prior to the remediation (AM ± SD, range) (adopted from **Marović and Bauman, 1986** and **Skanata et al., 1996b**)

Radionuclide	Activity concentration (Bqkg^{-1})
^{238}U	1344 ± 653 (882 – 1806)
^{226}Ra	1180 ± 543 (796 – 1565)

Table 3: Average activity concentrations (Bqkg^{-1} dry mass) in samples collected after the remediation (AM ± SD, range) (adopted from **Marović et al., 2008**)

Radionuclide	Activity concentration (Bqkg^{-1})
^{238}U	105 ± 35 (69 – 139)
^{226}Ra	79 ± 33 (49 – 115)
^{232}Th	57 ± 1 (56 – 59)

Table 4: Average activity concentrations (Bqkg^{-1} dry mass) in surface soil samples collected in 2015 (AM ± SD, range)

Radionuclide	Activity concentration (Bqkg^{-1})
^{238}U	96 ± 65 (17 – 304)
^{226}Ra	106 ± 64 (18 – 299)
^{232}Th	37 ± 24
^{210}Pb	(3 – 96) 115 ± 147 (15 – 710)

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 95-104, DOI: 10.17794/rgn.2023.3.8

ity concentration of ^{234}Th (photopeaks at 63.29 keV and 92.38 keV) under the assumption that secular equilibrium had been established. Activity concentration of ^{226}Ra was determined from that of ^{214}Pb (photopeaks at 295.22 keV and 351.93 keV) and activity concentration of ^{232}Th from the activity of ^{228}Ac based on photopeaks at 338.32 keV, 911.20 keV and 968.97 keV. ^{210}Pb activity concentration was obtained from photopeak at 46.54 keV. The average activity concentrations data for this assessment scenario are given in **Table 4**.

3. Results and Discussion

The results from the radiological risk assessment based on the data from 1990s before the remediation (adopted from **Marović and Bauman, 1986; Skanata et al., 1996b**), showed that the overall expected risk quotient (unitless) and the conservative risk quotient values were the highest in lichen and bryophytes, with a risk quotient of 14.77 and a conservative risk quotient of 44.3. Regarding the data set from 2008, the overall calculated risk quotient values were much lower, with the highest risk quotient value estimated for lichen and bryophytes equal to 1.92. A comparison of the risk quotient for all reference organisms in both assessment scenarios is given in **Figure 2**.

The estimated total dose rate in the assessment scenario before the remediation exceed the screening value of 10 μGyh^{-1} for 9 out of 13 reference organisms included in the risk assessment, with the highest estimated to-

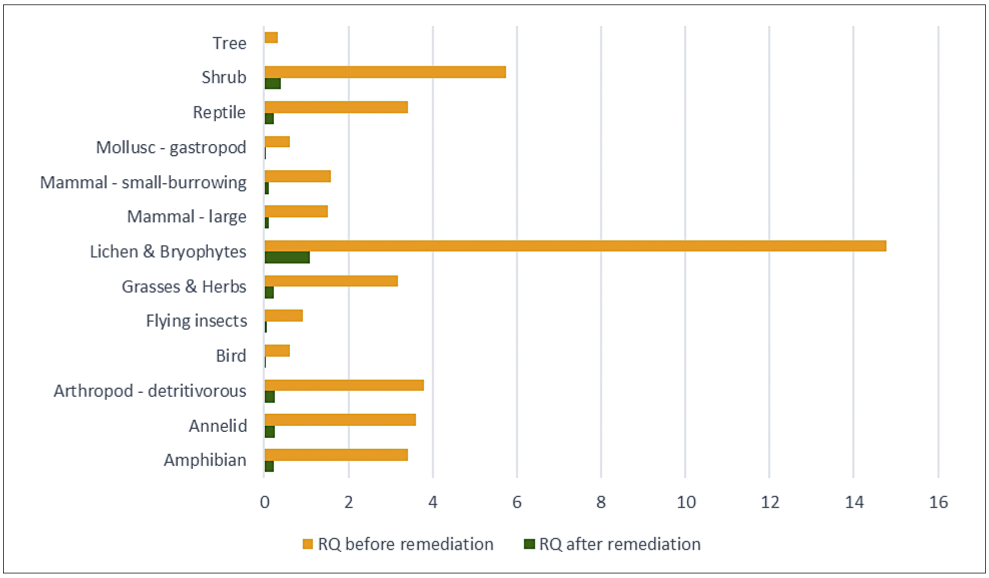

Figure 2: Comparison of the RQ results in assessment scenarios before and after the remediation

Table 5: Comparison of estimated total dose rates (μGyh^{-1}) to reference organisms in assessment scenarios before and after the remediation

Reference organism	Total Dose Rate (μGyh^{-1}) before remediation	Total Dose Rate (μGyh^{-1}) after remediation
Amphibian	34.10	2.30
Annelid	35.94	2.45
Arthropod - detritivorous	37.97	2.62
Bird	6.17	0.42
Flying insects	9.27	0.63
Grasses & Herbs	31.66	2.40
Lichen & Bryophytes	147.68	10.92
Mammal - large	15.15	1.02
Mammal - small-burrowing	15.82	1.07
Mollusc - gastropod	6.02	0.44
Reptile	34.11	2.30
Shrub	57.43	3.98
Tree	3.28	0.23

 pp. 95-104, DOI: 10.17794/rgn.2023.3.8

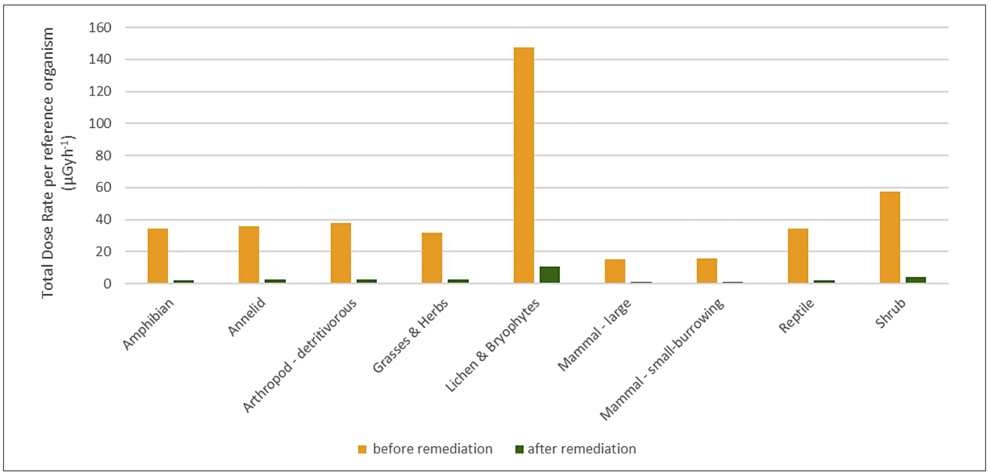

Figure 3: Comparison of total dose rate to most affected reference organisms from assessment scenarios before and after the remediation

tal dose rate for lichen and bryophytes being 147.68 µGyh^{-1}. In the assessment scenarios referring to post-remediation, estimated total dose rates were much lower, with the total dose rate for lichen and bryophytes of 10.92 µGyh^{-1}, almost equal to the selected screening value. **Table 5** presents the comparison of data on the estimated total dose rate to all reference organisms in assessment before and after remediation of the disposal site, where **Figure 3** shows the comparison of total dose rates to 9 reference organisms for which the screening dose rate in the assessment scenario before the remediation of the site was exceeded.

The results of the assessment scenario before the remediation showed that the total dose rate estimation can primarily be attributed to the internal exposure, with ^{226}Ra as the main contributor, especially for lichen and bryophytes and a shrub as reference organisms. The distribution of radionuclides that contribute to the external dose rate also includes ^{226}Ra as a key contributor and amphibian, annelid, arthropod, mammal (small-burrowing) and reptile as the most affected reference organisms.

The total dose rate results for the post-remediation assessment scenario also show that internal exposure contributes the most to the total dose rate to all reference organisms. Again, ^{226}Ra is the main contributor to the internal dose rate, with the highest dose internal rate in lichen and bryophytes and a shrub. **Sotiropoulou et al. (2016)** from Greece also found ^{226}Ra to be the main contributor to the internal dose rate to lichen and bryophytes. External dose rate can primarily be attributed to ^{226}Ra, with the highest dose rates in amphibian, annelid, arthropod, mammal (small-burrowing) and reptile. The distribution of internal and external dose rates from exposure to ^{226}Ra before and after the remediation for the most affected reference organisms is given in **Figure 4** and **Figure 5**.

The assessment results from additional assessment based on the data on soil samples from 2015 are in line with the results of the assessment scenario based on the data from 2008, although the activity concentrations from 2015 resulted in slightly higher dose rate estimations. The overall highest estimated value was found in lichen and bryophytes 18.06 µGyh^{-1}, where data from 2008 resulted in predicted total dose rate to lichen and bryophytes of 10.92 µGyh^{-1}. ^{226}Ra was found to contribute the most to both internal and external dose rates to reference organisms.

As lichen and bryophytes were found to be the most affected organisms in the scenario before the remediation, **Table 6** presents the distribution of total, internal and external dose rate to lichen and bryophytes from an assessment run with data before the disposal site remediation.

The results from the assessment that relied on data before the disposal site remediation are in line with re-

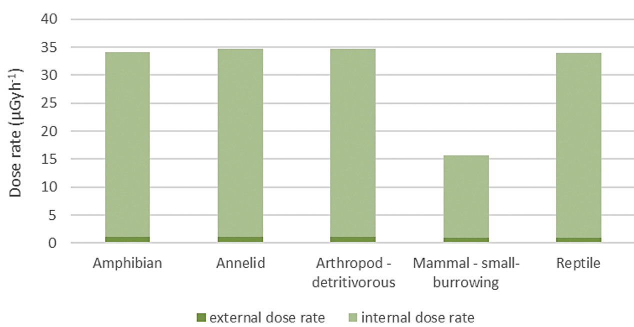

Figure 4: ^{226}Ra contribution to external and internal dose rates to the most affected reference organisms before disposal site remediation

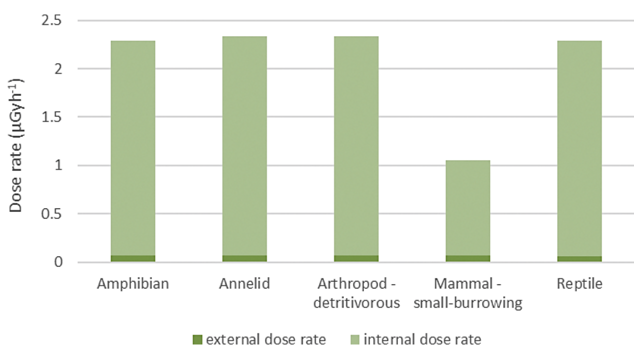

Figure 5: ^{226}Ra contribution to external and internal dose rates to the most affected reference organisms after remediation disposal site

Table 6: Distribution of internal and external dose rate to lichen and bryophytes assessed based on the sample data before the disposal site remediation

Isotope	External Dose Rate ($\mu Gy\ h^{-1}$)	Internal Dose Rate ($\mu Gy\ h^{-1}$)	Total Dose Rate* ($\mu Gy\ h^{-1}$)
^{238}U	0.01	30.35	30.36
^{226}Ra	0.31	116.9	147.68

* The total dose rate presented includes contributions from other radionuclides besides the ^{238}U and ^{226}Ra listed in this table

sults from previous studies on total dose rates to terrestrial biota that focused on NORM legacy site and mining. The study by **Mrdakovic Popic et al. (2020)**, at the legacy NORM site in Norway, reported the highest predicted total dose rate of 206 μGyh^{-1} to lichen and bryophytes when default CR values were used and 23 μGyh^{-1} when site-specific soil and plant activity concentrations were used. **Oughton et al. (2013)** conducted risk assessments at several mining sites in Central Asia. Risk assessments used site-specific data and included calculated dose rates to aquatic and terrestrial biota. Findings from the study include assessment results related to disposal site containing tailings with the highest total dose rate value of 660 μGyh^{-1} predicted to lichen and bryophytes. Additionally, this study also reported ^{226}Ra as the main contributor to the internal and external dose rates (**Oughton et al., 2013**), which was also the case in our assessments that used data before the site remediation. The assessment of dose rate to terrestrial biota in the area around coal fired power plant in Serbia also resulted in screening dose rate being exceeded only for lichen and bryophytes (**Ćujić and Dragović, 2018**).

Regarding the results of the total dose rate after the site remediation, which only slightly exceeded the ERICA Tool conservative screening value of 10 μGyh-1 for lichen and bryophytes but were still below the value of 40 and 400 μGyh^{-1} for terrestrial biota for which no effects on population levels should be expected (**UNSCEAR, 2008**), the overall risk can be regarded as negligible. This conclusion is also supported by the fact that lichen and bryophytes are considered highly radiosensitive organisms and, as a result, are often used as biomonitors of potential contamination and concerning both artificial and natural radionuclides (**Marović et al., 2008; Garty et al., 2003; Kirchner and Daillant, 2002; Loppi et al., 2003**).

Both assessment scenarios and respective results should be observed considering several uncertainties. The study used two sets of data on soil activity concentrations that included a limited number of soil samples and relatively small number of radionuclides. Although soil samples are from the same disposal site, given the remediation of the disposal site, they were taken from different sampling locations. Hence, the data sets should be regarded as different spatial and temporal sets of data. An additional source of uncertainty is the lack of other site-specific data, such as CR values and activity concentrations in plants or animals. Considering that the ERICA tool is known to use a conservative approach when the Tool's default CR values are used, an overestimation of the total dose rate results in both assessment scenarios is possible.

4. Conclusions

In cases where coal with elevated levels of natural radioactivity is used as a primary energy source, coal combustion can be a source of exposure to radiation due to the resulting coal ash and slag accumulating significant activity concentrations of radionuclides. Remediation of such coal and ash slag disposal site provided research context for our study of radiological risk assessment for terrestrial biota. In order to assess the potential impacts of the disposal site and the effects of the remediation, the environmental data on activity concentration in the soil before and after the disposal site remediation was used to conduct radiological risk assessments using the ERICA tool.

The results from the assessment related to the period before the remediation showed that for several reference organisms, the estimated total dose rate exceeded the default screening value, with the highest predicted value of 147.68 μGyh^{-1} to lichens and bryophytes, which is not surprising as they are considered as most radiosensitive organisms. The assessed radiological risk and respective dose rates to reference organisms after the site remediation were significantly lower, with the total dose rate to lichens and bryophytes being 10.92 μGyh^{-1}, which is almost equal to the assessment's conservative screening dose rate of 10 μGyh^{-1}. In both assessment scenarios, internal exposure attributed the most to the estimated total dose rate, with ^{226}Ra contributing the most to both the internal and external dose rates, around 80%. This finding is in line with results from similar studies conducted at different locations from other authors.

Assessment results indicate that remediation of the site was adequate and that the overall radiological risk to terrestrial biota from the disposal site can be considered negligible, and that the estimated total dose rates to biota are below the levels that can be associated with detrimental effects. It should be stressed that environmental monitoring of the site is required to ensure reliable long-term radiological and environmental protection and safety. The results from both radiological risk assessment scenarios can serve as an example for the future estimation of potential radiological impacts of similar disposal sites and radiological risk assessment design.

Acknowledgement

The authors would like to thank Ms Jasminka Senčar and Dr Gordana Marović from the Institute for Medical Research and Occupational Health, Zagreb, Croatia for their support in identification and collection of relevant data.

5. References

Bituh, T., Babić, D., Senčar, J., and Marović, G. (2017): Natural Radioactivity of Ground Waters in the Vicinity of the Coal Fired Power Plant Plomin. Proceedings of 11th Symposium of the Croatian Radiation Protection Association, 402, Croatia: Croatian Radiation Protection Association.

Beresford, E.N., Brown, J., Copplestone, D., Garnier, J., Howard, B., Larsson, C., Oughton, D., Pröhl, G. and Zinger, I. (2007): D-ERICA: an integrated approach to the assessment and management of environmental risks from ionising radiation. Deliverable of the ERICA Project (FI6R-CT-2004-508847). Swedish Radiation Protection Authority, Stockholm, Sweden.

Beresford, N. A., Barnett, C. L., Brown, J. E., Cheng, J. J., Copplestone, D., Gaschak, S., Hosseini, A., Howard, B. J., Kamboj, S., Nedveckaite, T., Olyslaegers, G., Smith, J. T., Vives I Batlle, J., Vives-Lynch, S. and Yu, C. (2010): Predicting the radiation exposure of terrestrial wildlife in the Chernobyl exclusion zone: an international comparison of approaches. Journal of radiological protection: official journal of the Society for Radiological Protection, 30(2), 341–373. https://doi.org/10.1088/0952-4746/30/2/S07

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplestone, D., Pröhl, G. and Ulanovsky, A. (2008): The ERICA Tool. J. Environ. Radioact. 99, 1371–1383. https://doi.org/10.1016/j.jenvrad.2008.01.008

Brown, J.E., Beresford, N.A. and Hosseini, A. (2013): Approaches to providing missing transfer parameter values in the ERICA Tool - how well do they work? J. Environ. Radioact., 126, 399–411. https://doi.org/10.1016/j.jenvrad.2012.05.005

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplestone, D. and Hosseini, A. (2016): A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals. J. Environ. Radioact., 153, 141-148. https://doi.org/10.1016/j.jenvrad.2015.12.011

Ćujić, M.; Dragović, S. (2018): Assessment of dose rate to terrestrial biota in the area around coal fired power plant applying ERICA tool and RESRAD BIOTA code. J. Environ. Radioact., 188, 108–114. https://doi.org/10.1016/j.jenvrad.2017.09.014

Delistraty D. (2008): Radioprotection of nonhuman biota. J. Environ. Radioact., 99(12), 1863–1869. https://doi.org/10.1016/j.jenvrad.2008.09.001

Dvoršćak, M., Stipičević, S., Mendaš, G., Drevenkar, V., Medunić, G., Stančić, Z. and Vujević, D. (2019): Soil burden by persistent organochlorine compounds in the vicinity of a coal-fired power plant in Croatia: a comparison study with an urban-industrialized area. Environmental Science and Pollution Research International, 26(23), 23707-23716. https://doi.org/10.1007/s11356-019-05605-0

Ernečić, G., Lovrenčić Mikelić, I. and Medunić, G. (2014): Distribution of Ra-226 in the surface soil in the vicinity of the thermal power plant Plomin (Croatia). Ed.: Pál-Molnár, E. (ur.) Acta Mineralogica-Petrographica, Abstract Series.

Garty, J., Tomer, S., Levin, T. and Lehr, H. (2003): Lichens as biomonitors around a coal-fired power station in Israel. Environmental research, 91(3), 186–198. https://doi.org/10.1016/s0013-9351(02)00057-9

Hirschi, J. C. and Chugh, Y. P. (2019): 13 - Sustainable coal waste disposal practices, Editor(s): Joseph Hirschi, Advances in Productive, Safe, and Responsible Coal Mining, Woodhead Publishing, 2019, 245-269. https://doi.org/10.1016/B978-0-08-101288-8.00012-2

Higley, K. A. and Bytwerk, D. P. (2007): Generic approaches to transfer. . J. Environ. Radioact, 98(1-2), 4–23. https://doi.org/10.1016/j.jenvrad.2007.02.013

IAEA (International Atomic Energy Agency). (1989): Measurement of Radionuclides in Food and the Environment, Technical Reports Series No. 295, IAEA, Vienna.

IAEA (International Atomic Energy Agency). (2003): Technical Reports Series No. 419. Extent of environmental contamination by naturally occurring radioactive material (NORM) and technological options for mitigation, IAEA, Vienna.

IAEA (International Atomic Energy Agency). (2013): Management of NORM Residues, IAEA-TECDOC-1712, IAEA, Vienna.

IAEA (International Atomic Energy Agency). (2022): Proceedings Series - International Atomic Energy Agency. Management of Naturally Occurring Radioactive Material (NORM) in Industry, IAEA, Vienna.

ICRP (International Commission on Radiological Protection). (2007): The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).

ICRP (International Commission on Radiological Protection). (2008): Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4-6).

ICRP, 2019. Radiological protection from naturally occurring radioactive material (NORM) in industrial processes. ICRP Publication 142. Ann. ICRP 2019, 48(4).

Johansen, M. P., Barnett, C. L., Beresford, N. A., Brown, J. E., Černe, M., Howard, B. J., Kamboj, S., Keum, D. K., Smodiš, B., Twining, J. R., Vandenhove, H., Vives i Batlle, J., Wood, M. D. and Yu, C. (2012): Assessing doses to terrestrial wildlife at a radioactive waste disposal site: inter-comparison of modelling approaches. The Science of the total environment, 427-428, 238–246. https://doi.org/10.1016/j.scitotenv.2012.04.031

Kirchner, G. and Daillant, O. (2002): The potential of lichens as long-term biomonitors of natural and artificial radionuclides. Environmental pollution, 120(1), 145–150. https://doi.org/10.1016/s0269-7491(02)00139-2

Kovac, J. and Bajlo, M. (1996): Natural radioactivity around the coal-fired power plant (INIS-XA-C--071). Glavic-Cidro, D. (Ed.). International Atomic Energy Agency (IAEA).

Lecomte, J.F. (2020): ICRP approach for radiological protection from NORM in industrial processes. Ann. ICRP 2020, 49 (1), 84-97. https://doi.org/10.1177/0146645320940825

Loppi, S., Riccobono, F., Zhang, Z. H., Savic, S., Ivanov, D. and Pirintsos, S. A. (2003): Lichens as biomonitors of uranium in the Balkan area. Environmental pollution. 125(2), 277–280. https://doi.org/10.1016/s0269-7491(03)00057-5

Marović G. and Bauman, A. (1986): Radioaktivnost termoelektrana na ugljen (*Radioactivtiy of coal-powered power plants*). Kemija u industriji, 35 (8), 427-470. (*in Croatian with abstract in English*)

Marović, G., Kovač, J., Franić, Z., and Senčar, J. (1997): Impact of technologically natural radioactivity on marine environment in Croatia. The second regional Mediterranean congress on radiation protection; 20th Regional Congress of the Israel Radiation Protection Association, p. 321, Israel: Israel Radiation Protection Association.

Marović, G., Senčar, J., Kovač, J. and Prlić, I. (2004): Improvement of the radiological environmental situation due to remedial actions at a coal-fired power plant. Journal of Radioanalytical and Nuclear Chemistry, 261, 451–455. https://doi.org/10.1023/B:JRNC.0000034884.26071.a9

Marović, G., Franić, Z., Senčar, J., Petrinec, Branko, Bituh, T. and Kovač, J. (2008): Natural radionuclides in coal and waste material originating from coal fired power plant. IRPA 12: 12 International congress of the International Radiation Protection Association (IRPA): Strengthening radiation protection worldwide, Argentina: SAR.

Marović, G., Franić, Z., Senčar, J., Bituh, T. and Vugrinec, O. (2008): Mosses and Some Mushroom Species as Bioindicators of Radiocaesium Contamination and Risk Assessment. Collegium antropologicum, 32 - Supplement 2 (2), 109-114.

Martins, F., Felgueiras, C. and Smitková, M. (2018): Fossil fuel energy consumption in European countries, Energy Procedia., 153, 107-111. https://doi.org/10.1016/j.egypro.2018.10.050

Medunić, G., Rađenović, A., Bajramović, M., Švec, M. and Tomac, M. (2016): Once grand, now forgotten: what do we know about the superhigh-organic-sulphur Raša coal?. Rudarsko-geološko-naftni zbornik, 31, 3 (Sep. 2016), 27–45. https://doi.org/10.17794/rgn.2016.3.3

Mrdakovic Popic, J., Oughton, D.H., Salbu, B. and Skipperud, L. (2020): Transfer of naturally occurring radionuclides from soil to wild forest flora in an area with enhanced legacy and natural radioactivity in Norway. Environ. Sci., 22 (2), 350-363.

NEA (2007): Scientific issues and emerging challenges for radiological protection Report of the Expert Group on the Implications of Radiological Protection Sciences Report No. 6167, Paris: Nuclear Energy Agency.

Oughton, D. H., Strømman, G. and Salbu, B. (2013): Ecological risk assessment of Central Asian mining sites: application of the ERICA assessment tool. Journal of environmental radioactivity, 123, 90–98. https://doi.org/10.1016/j.jenvrad.2012.11.010

Pentreath, R. J., and Woodhead, D. S. (2001): A system for protecting the environment from ionising radiation: Selecting reference fauna and flora, and the possible dose models and environmental geometries that could be applied to them. The Science of the Total Environment, 277, 33–43.

Ritchie, H., Roser, M. and Rosado, P. (2022): Energy. URL: https://ourworldindata.org/energy (accessed on March 23 2023)

Radolić, V., Miklavčić, I., Poje Sovilj, M., Stanić, D., Petrinec, B. and Vuković, B. (2019): The natural radioactivity of Istria, Croatia, Radiation Physics and Chemistry, 155, 332-340. https://doi.org/10.1016/j.radphyschem.2018.08.005

Skanata, D., Sinka, D., Lokner, V., and Schaller, A. (1996a): Preliminary risk assessment of Power Plant Plomin site contaminated by radioactive slag and ash. Proceedings of the International conference: Nuclear option in countries with small and medium electricity grid, p. 595, Croatia: Croatian Nuclear Society.

Skanata, D., Sinka, D., Lokner, V. and Schaller, A. (1996b): Usporedba različitih modela za proračun radijacijskih doza na primjeru analize za lokaciju TE Plomin (*Comparison of different models for calculation of radiation doses on the example of TE Plomin site analysis*). Proceedings of the Third symposium of the Croatian Radiation Protection Association, p. 414, Croatia: Croatian Radiation Protection Association. (*in Croatian with abstract in English)*

Skoko, B., Babić, D., Marović, G. and Papić, S. (2019): Environmental radiological risk assessment of a coal ash and slag disposal site with the use of the ERICA Tool. Journal of environmental radioactivity,. 208-209, 106018. https://doi.org/10.1016/j.jenvrad.2019.106018

Sotiropoulou, M., Florou, H. and Manolopoulou, M. (2016): Radioactivity measurements and dose rate calculations using ERICA tool in the terrestrial environment of Greece. Environ Sci Pollut Res., 23, 10872–10882. https://doi.org/10.1007/s11356-016-6240-1

Šoštarić, M., Petrinec, B., Avdić, M., Petroci, L., Kovačić, M., Zgorelec, Ž., Skoko, B., Bituh, T., Senčar, J., Branica, G., Franić, Z., Franulović, I., Rašeta, D., Bešlić, I. and Babić, D. (2021): Radioactivity of soil in Croatia I: naturally occurring decay chains. Archives of Industrial Hygiene and Toxicology, 72 (1), 6-14. https://doi.org/10.2478/aiht-2021-72-3439

UNSCEAR (1996): Sources and Effects of Ionizing Radiation United Nations Scientific Committee on the Effects of Atomic Radiation.

SAŽETAK

Sanacija odlagališta ugljenoga pepela i šljake: usporedba procjena radiološkoga rizika

Ostatci od spaljivanja ugljena poznati su kao potencijalni izvor izloženosti zračenju, posebno u slučajevima kada je ugljen koji se koristi u spaljivanju karakteriziran povećanom radioaktivnošću, što rezultira pepelom i šljakom s potencijalno visokom aktivnošću koncentracije radionuklida. U radu su prikazani rezultati procjene radiološkoga rizika temeljeni na pristupu ERICA alata korištenim za procjenu brzine doza za kopnenu biotu u blizini termoelektrane na ugljen u Hrvatskoj. Studija se sastoji od triju procjena radiološkoga rizika korištenjem podataka o koncentraciji aktivnosti ($Bqkg^{-1}$) u okolišu iz uzoraka prikupljenih prije sanacije odlagališta i uzoraka nakon završetka sanacije. Rezultirajuća ukupna brzina doze za biotu dobivena korištenjem podataka prije sanacije kretala se od 3,28 μGyh^{-1} do 147,68 μGyh^{-1}. Rezultati procjene ukupne brzine doze na temelju podataka s istraživanoga područja nakon sanacije kreću se od 0,23 μGyh^{-1} do 18,06 μGyh^{-1}. Rezultati su pokazali da je nakon sanacije samo ukupna brzina doze za lišajeve i briofite neznatno premašila konzervativnu vrijednost provjere ERICA alata od 10 μGyh^{-1}, što implicira da se rizici za okoliš u odnosu na izloženost odlagalištu mogu smatrati zanemarivima. Ovi rezultati studije potvrđuju prikladnost korištenja ERICA alata za procjenu potencijalnoga radiološkog utjecaja i učinkovite provedbe sanacije odlagališta ugljena i šljake.

Ključne riječi:
procjena radiološkoga rizika, NORM, elektrana na ugljen, sanacija, monitoring okoliša

Author's contribution

Ana Getaldić (MEng, PhD Candidate) proposed and defined the idea for the manuscript, conducted all assessments, and prepared the original manuscript draft. **Marija Surić Mihić** (PhD, Senior Research Associate, Radiation Protection Expert), **Želimir Veinović** (PhD, Associate Professor, Radiation Protection Expert) provided supervision, performed the formal analysis of the results and the factual review. **Božena Skoko** (PhD) performed the formal analysis of the results and the factual review. **Branko Petrinec** (PhD, Senior Research Associate, Radiation Protection Expert) provided the data and performed the formal analysis of the results.