APPLICATION OF NEUTRON ACTIVATION ANALYSIS FOR NON-DESTRUCTIVE ELEMENTAL CHARACTERIZATION OF VARIOUS SAMPLES (MOSS, LICHENS, PLANT LEAVES, SOIL, ROAD DUST, FILTERS, LEAF LITTER, CENTIPEDES) INDICATING ENVIRONMENTAL POLLUTION – 20 YEARS OF COLLABORATION BETWEEN EPL INSTITUTE OF PHYSICS BELGRADE AND FLNP JINR DUBNA

M. Aničić Urošević[1], M. Tomašević[1], A. Popović[2], G. Jovanović[1], T. Milićević[1], J. Roganović[2], M. Ilić[3], B. Mitić[4], M. Popović[1], K. Vergel[5], O. Chaligava[5], A. Uzhinskiy[5], N. Yushin[5], L.P. Strelkova[5], T. Ostrovnaya[5], Z. Goryainova[5], S.S. Pavlov[5], I. Zinicovscaia[5], M.V. Frontasyeva[5]

[1] *Institute of Physics Belgrade, University of Belgrade, Belgrade, Serbia*
[2] *Faculty of Chemistry, University of Belgrade, Belgrade, Serbia*
[3] *University of Novi Sad, Faculty of Sciences, Department of Biology and Ecology, Serbia*
[4] *Institute of Zoology, University of Belgrade – Faculty of Biology, Belgrade, Serbia*
[5] *Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Russia*

E-mail: mira.anicic@ipb.ac.rs

Since 2005, in the frame of the cooperation between the Environmental Physics Laboratory of the Institute of Physics Belgrade (Serbia) and FLNP (JINR), instrumental neutron activation analysis (INAA) has been used for elemental characterization of different types of environmental samples. Many major, minor, trace, and rare-earth elements, present in excess, proved to be potentially toxic and recommended for monitoring. A non-destructive INAA has often been used in environmental studies, capable of detecting up to 45 elements with minimal sample preparation. The collaborative studies were mainly carried out in Serbia, while the analytical part was performed using the REGATA system at the reactor IBR-2. However, there was a study carried out in parallel over Belgrade and Moscow [1]. Mosses and lichens have been among the most explored samples for the purpose of biomonitoring airborne potentially toxic elements (PTEs), both passive and active approaches. Passive approach considered using naturally growing mosses for biomonitoring purposes mainly in remote and rural areas [2] but sometimes in urban areas, too [3], while active approach implies the use of moss/lichen transplants for exposition in any place of interest – street canyons, tunnels, crossroads, parking garages, etc., mostly within `moss/lichen deserts` such as urban [4-10] or agricultural areas [11, 12]. The moss biomonitoring database has been successfully used in combination with satellite imagery and machine learning for the prediction of air pollution by PTEs [13]. Plant samples (coniferous leaves) were selected for biomonitoring of PTEs in urban areas, and these samples were used for comparative analysis of the non-destructive INAA technique and the conventionally used spectrometric ICP-OES and ICP-MS techniques [14]. Rare-earth elements have been measured in the road dust from the vicinity of coal-fired thermal power plants [15]. Quartz filters used for regulatory collection of particulate matter (PM2.5 and PM10) were analyzed by INAA. Our latest ongoing research focuses on investigating centipedes as bioindicators of anthropogenic pollution impacts on soil ecosystems by measuring PTEs in their different life forms, and in the collocated topsoil and leaf litter samples as well.

[1] Z. Goryainova, G. Vuković, M. Aničić Urošević, K. Vergel, T. Ostrovnaya, M. Frontasyeva, H. Zechmeister (2016). Assessment of vertical element distribution in street canyons using the moss *Sphagnum girgensohnii*: A case study in Belgrade and Moscow cities. Atmospheric Pollution Research 7, 690-697.
[2] M. Aničić Urošević, M. Ilić, D. Radnović, K. Vergel, N. Yushin, O. Chaligava, I. Zinicovscaia (2024). Comparative biomonitoring of airborne potentially toxic elements

using mosses (*Hypnum cupressiforme*, *Brachythecium* spp.) and lichen (*Evernia prunastri*) over remote areas. Environmental Science and Pollution Research 31, 48296-48296.
[3] M. Aničić, M.V. Frontasyeva, M. Tomašević and A. Popović (2007). Assessment of atmospheric deposition of heavy metals and other elements in Belgrade using moss biomonitoring technique and neutron activation analysis. Environmental Monitoring and Assessment 129, 207-219.
[4] M. Aničić Urošević, M. Kuzmanoski, T. Milićević, I. Kodranov, K. Vergel, A. Popović (2022). Moss bag sensitivity for the assessment of airborne elements at suburban background site during spring/summer season characterized by Saharan dust intrusions. Air Quality, Atmosphere & Health 15, 1357.
[5] G. Vuković, M. Aničić Urošević, M. Pergal, M. Janković, Z. Goryainova, M. Tomašević and A. Popović (2015). Residential heating contribution to persistent air pollutants (PAHs, trace and rare earth elements): A moss bag case study. Environmental Science and Pollution Research 22/23, 18956-18966.
[6] G. Vuković, M. Aničić Urošević, Z. Goryainova, M. Pergal, S. Škrivanj, R. Samson and A. Popović (2015) Active moss biomonitoring for extensive screening of urban air pollution: Magnetic and chemical analyses. Science of the Total Environment 521-522, 200-210.
[7] G. Vuković, M. Aničić Urošević, I. Razumenić, Z. Goryainova, M. Frontasyeva, M. Tomašević and A. Popović (2013). Active moss biomonitoring of small-scale spatial distribution of airborne major and trace elements in the Belgrade urban area. Environmental Science and Pollution Research 20, 5461-5470.
[8] M. Aničić, M. Tomašević, M. Tasić, S. Rajšić, A. Popović, M.V. Frontasyeva, S. Lierhagen and E. Steinnes (2009). Monitoring of trace element atmospheric deposition using dry and wet moss bags: Accumulation capacity versus exposure time. Journal of Hazardous Materials 171, 182-188.
[9] M. Aničić, M. Tasić, M.V. Frontasyeva, M. Tomašević, S. Rajšić, Z. Mijić and A. Popović (2009). Active moss biomonitoring of trace elements with *Sphagnum girgensohnii* moss bags in relation to atmospheric bulk deposition in Belgrade, Serbia. Environmental Pollution 157, 673-679.
[10] M. Aničić, M. Tasić, M.V. Frontasyeva, M. Tomašević, S. Rajšić, L.P. Strelkova, A. Popović and E. Steinnes (2009). Active biomonitoring with wet and dry moss: A case study in an urban area. Environmental Chemical Letters 7, 55-60.
[11] T. Milićević, M. Aničić Urošević, G. Vuković, S. Škrivanj, D. Relić, M.V. Frontasyeva, A. Popović (2017) Assessment of species-specific and temporal variations of major, trace and rare earth elements in vineyard ambient using moss bags. Ecotoxicology and Environmental Safety 144, 208-215.
[12] T. Milićević, M. Aničić Urošević, D. Relić, G. Jovanović, D. Nikolić, K. Vergel, A. Popović (2020). Environmental pollution influence to soil–plant–air system in organic vineyard: bioavailability, environmental, and health risk assessment. Environmental Science and Pollution Research 28, 3361-3374.
[13] A. Uzhinskiy, M. Aničić Urošević, M. Frontasyeva (2020). Prediction of Air Pollution by Potentially Toxic Elements over Urban Area by Combining Satellite Imagery, Moss Biomonitoring Data and Machine Learning. Ciencia e Tecnica Vitivinicola 35(12), pp. xx.
[14] J. Orlić, M. Aničić Urošević, K. Vergel, I. Zinicovscaia, S. Stojadinović, I. Gržetić, K. Ilijević (2022). Comparison of non-destructive techniques and conventionally used spectrometric techniques for determination of elements in plant samples (coniferous leaves). Journal of Serbian Chemical Society 87 (1) 69-81.
[15] J. Roganović, D. Relić, M. Zarić, M. Aničić Urošević, I. Zinicovscaia, K. Ilijević, N.M. Zarić (2025). Rare earth elements and health risk assessment of road dust from the vicinity of coal fired thermal power plants. Chemosphere 377, 144329.