Scientific Review Engineering and Environmental Sciences (2024), 33 (2), 131–143

Sci. Rev. Eng. Env. Sci. (2024), 33 (2) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.9761

Received: 08.04.2024
Accepted: 08.05.2024

Barbara KLIK[1]
Piotr JACHIMOWICZ[2]
Ernesta LINIAUSKIENE[3]
Mariusz GUSIATIN[4]
Algirdas RADZEVIČIUS[5]
Martin BRTNICKÝ[6]
Raimondas ŠADZEVIČIUS[5]
Agnieszka BĘŚ[7]
Zbigniew MAZUR[7]
Midona DAPKIENĖ[5]
Maja RADZIEMSKA[1]

[1] Warsaw University of Life Sciences – SGGW, Institute of Environmental Engineering, Warsaw, Poland
[2] VSB – Technical University of Ostrava, Institute of Environmental Technology, CEET, Ostrava, Czech Republic
[3] Kaunas Forestry and Environmental Engineering University of Applied Sciences, Faculty Environmental Engineering, Kaunas, Lithuania
[4] University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, Olsztyn, Poland
[5] Vytautas Magnus University Agriculture Academy, Faculty of Engineering, Akademija, Kaunas District, Lithuania
[6] Mendel University in Brno, Faculty of AgriSciences, Brno, Czech Republic
[7] University of Warmia and Mazury in Olsztyn, Faculty of Agriculture and Forestry, Olsztyn, Poland

Ash from gasification of poultry feathers for heavy metal immobilization under assisted phytostabilization in soils

Keywords: *Dactylis glomerata* L., soil contamination, soil amendment, land restoration

✉barbara_klik@sggw.edu.pl

Introduction

Progressing degradation of the soil environment on a global scale has led to the recultivation of contaminated areas gaining a greater role, as well as setting new trends when it comes to scientific research (Santini & Miquelajauregui, 2022). The search for complex solutions in terms of strategies for protecting soil resources, the purpose of which is returning the degraded terrain, including that contaminated with heavy metals, to its renewed use, is the greatest challenge of modern times. In this context, the method of assisted phytostabilization, which is included among gentle remediation options and interferes the least in the environment, finds application (Zhang et al., 2024). The method of assisted phytostabilization, in addition to its main role, i.e., immobilizing contaminants in the root zone, can also be used to reconstruct the grass-legume sward in zones where it was found to have disappeared in connection with the occurrence of high values of heavy metal concentrations (Lacalle et al., 2023). This multifaceted strategy not only addresses soil contamination but also contributes to ecosystem rehabilitation, offering a holistic approach to mitigating the pervasive impacts of soil degradation on a global scale.

Until now, aided phytostabilization has been the subject of many studies on the application in vast spreading post-mining areas, excavation sites, and closed waste disposal sites (Bidar et al., 2016; Teodoro et al., 2020). However, the topic undertaken in the article pertains to the terrain which is located close to urban areas, such as industrial plants involved in the recycling of metal and steel waste on various scales, where waste is very frequently stored directly on the ground without any safety measures, and it is these areas that currently present a challenge due to the need to return them to operational use. In such urban-adjacent environments, the presence of metal and steel waste without proper containment measures poses not only environmental hazards but also potential health risks to nearby communities (Abdulsalam et al., 2020; Dodd et al., 2023).

The global growth of poultry production has resulted in the generation of by-products, with feathers accounting for around 10% of the waste from the poultry sector (Kwiatkowski et al., 2013). In the face of the increasing interest in technologies for the thermal processing of waste, an effective method of utilizing this type of waste is turning feathers into energy with the use of thermochemical processes (Dalólio et al., 2017). Taking into account the fact that poultry feather ash (AGF) is a side product of the thermochemical transformation of feathers, it is necessary to find a method for its management. One potential method involves using additives to assist in the phytostabilization of soil polluted with metals (Radziemska et al., 2021). The AGF demonstrates a notable adsorption capacity, characterized by an alkaline pH and a nutrient-rich composition (Fahimi et al., 2020). Consequently, it is capable of effectively immobilizing heavy metals within soil that has been contaminated by pollutants. This multifaceted approach not only mitigates metal toxicity to plants, but also enhances soil fertility, promoting the establishment of vegetation in metal-contaminated areas. Incorporating poultry feather ash as an additive in phytostabilization strategies offers a sustainable and cost-effective means of addressing metal pollution while facilitating ecosystem restoration and land remediation efforts (Jagadeesan et al., 2023). In this case, we can speak of the concept of a closed circuit model of the economy, where recovery and reuse in new processes, but also reducing the negative influence of waste materials on the environment, is crucial. Such an idea of the circular management of goods as an element of the strategies of the European bioeconomy poses a challenge of finding other applications of products or waste than those known to date. In connection with the above, the objective was to establish the usefulness of AGF on the soil phytostabilization polluted with metals by evaluating the produce of *Dactylis glomerata* L. as well as Cd, Cu, Pb, and Zn contents in its shoots and roots, at the same time indicating the pH and total exchangeable forms of Cd, Cu, Pb, and Zn contents.

Material and methods

Soil and properties poultry feather ash (AGF)

The soil was taken from the area storing various types of steel waste located in the northeast of Poland, which has been exploited for nearly 80 years, according to the methodology specified in Radziemska et al. (2021). The soil collected exhibited a slightly alkaline pH of 8.4 ±0.1 and a low organic matter content of 1.1 ±0.1%. The soil's cation exchange capacity (CEC) was measured at 56.8 ±0.1 cmol·kg^{-1}. The recorded metal concentrations are as follows (in mg·kg^{-1}): Cd – 13.6 ±1.4, Cu – 396.8 ±10.3, Pb – 10115.4 ±65.1, Zn – 3620.1 ±40.2.

The AGF was generated through the gasification of turkey feathers in a fixed bed gasifier operating at temperatures ranging from 1,000 to 1,200°C, using wood pellets. The AGF underwent a milling process prior to the experiments to achieve particles with a size of 0.5 mm or smaller. Selected parameters of AGF used as a soil supplement in the method of assisted phytostabilization are compiled in Table 1.

TABLE 1. Selected properties of poultry feather ash (n = 3, ± standard deviation)

Characteristic	Unit	Value
Surface area (Brunauer, Emmett & Teller)	$m^2 \cdot g^{-1}$	1.19
Total area in pores		0.618
pH	–	12.9 ±0.4
Volatile matter	%	1.02 ±0.03
Cd concentration	$mg \cdot kg^{-1}$	< LOD
Cu concentration		2.4 ±0.09
Pb concentration		< LOD
Zn concentration		0.3 ±0.03

< LOD – less than the limit of detection.

Source: own elaboration.

Greenhouse study

Before commencing the experiment, AGF was mixed with soil at a 3.0% (w/w) concentration and subsequently placed in polyethene pots. A series without AGF (0.0%, w/w) was also prepared and designated as the control. The soil-filled pots were located in a completely darkened room for 14 days to ensure the soil mixture was fully stabilized. *Dactylis glomerata* L., with five seeds sowed per pot, was chosen as the test plant (sourced from an authorized seed production center located in Olsztyn, Poland). The plants were watered on alternate days and were harvested after a period of 51 days. The plants were watered with distilled water, ensuring they reached 60% of the maximum water-holding capacity of the soil. Soil moisture content for each pot was regularly maintained at field capacity every three days. It is worth noting that fertilizers were not utilized in this process to prevent any potential interactions with the amendments. After this, they were weighed, divided into their respective parts, namely shoots and roots, and thoroughly cleansed with distilled water.

Physicochemical properties of plants soil and AGF

Soil samples and AGF were pH-tested in distilled water (1 : 2.5 w/v) via HI 221 pH meter. Organic matter in soil and volatile matter were determined by sample ignition in a muffle furnace at 550°C for 4 h (Jeong & Kim, 2001). Volatile matter in ash was determined in a muffle furnace at 950°C for 6 min (Liu et al., 2014). The samples were mineralized in a concentrated mixture of HCl (concentration: 1.16 g·cm^{-3}, 38%), HNO_3 (concentration: 1.40 g·cm^{-3}, 65%), and H_2O_2 (concentration: 30%) using a microwave oven. Total concentrations of Cd, Cu, Pb, and Zn were estimated with a spectrometer Varian, AA28OFS. The exchangeable soil metal fractions were determined according to Pueyo et al. (2004). The shoots and the roots of the tested plant were mineralized in HNO_3 p.a. and 30% H_2O_2 using a microwave oven.

Statistical evaluation

Statistica 13.3 (StatSoft) was used to conduct the statistical analysis. ANOVA was used to calculate significant differences between the groups (control and AGF) for the Cu, Cd, Pb, and Zn concentrations and in the average values of plant biomass for these same groups. Upon carrying out ANOVA, Tukey's test was conducted to identify significant differences. All analyses were carried out at a significance level equal to 5%.

Results and discussion

Chemical parameters of soil after phytostabilization

The main aim of treatments used to immobilize heavy elements in the soil is to increase the pH value, thereby decreasing their bioavailability (Alvarenga et al., 2009; Radziemska et al., 2022). Upon carrying out the AGF-assisted phytostabilization experiment, soil pH was found to be slightly alkaline (pH 8.5–8.1) in both amended and control soils (Fig. 1). This alkaline pH can be attributed to the presence of alkaline compounds, such as calcium carbonate and calcium oxide, in AGF (Fahimi et al., 2020; Gusiatin et al., 2020). When AGF is applied to the soil, these alkaline compounds dissolve and react with soil moisture, releasing hydroxide ions (OH-) into the soil solution, consequently raising the soil pH towards the alkaline range. Additionally, AGF may also act as a buffer, neutralizing soil acidity resulting from metal contamination (Hedayati, 2022). This proves the usefulness of applying byproducts of the thermochemical conversion of feathers in the context of increasing the value of soil pH subjected to aided phytostabilization treatments. Positive results were also obtained in studies where this type of soil amendment was applied to soils that had undergone long-term contamination with Cu, Ni, Cd, Pb, Zn, and Cr, where *Lupinus luteus* L. was the test plant, in which pH increased by 1.42 units upon completion of the experiment (Radziemska et al., 2021).

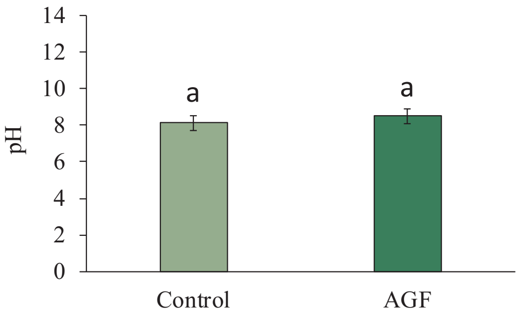

FIGURE 1. Levels of pH in amended and control soils following poultry feather ash (AGF) assisted phytostabilization. Lowercase letters show statistically significant differences among control and AGF treatments for a given metal ($p < 0.05$)

Source: own elaboration.

Both mobilities, as well as the availability of heavy metals in soils, depend on their total concentration as well as exchangeable forms. The content of the analyzed heavy metals in the soil at the end of the experiment was significantly dependent on AGF as a soil amendment (Fig. 2). Linked with the control, the treatment with AGF reduced the exchangeable form of Zn, Cu, Cd, and Pb by 25%, 23%, 20%, and 12%, respectively. This reduction can be attributed to the sorptive properties of AGF, which effectively bind heavy metals in the soil, thereby decreasing their solubility and availability for leaching (Moon, 2019). The sorption process involves multiple mechanisms, including adsorption, precipitation, and complexation, facilitated by AGF's high adsorption capacity owing to its porous structure and extensive surface area (Table 1).

Heavy metals present in the soil solution can readily bind to the surface of AGF particles, leading to a decrease in their concentration in the soil water and mitigating their potential for leaching. Additionally, the alkaline nature of AGF promotes the precipitation of heavy metals as insoluble hydroxides or carbonates, further immobilizing them within the soil matrix (Fahimi et al., 2020). As a result, soil quality was improved; the lower availability of heavy metals reduces their risk of leaching into

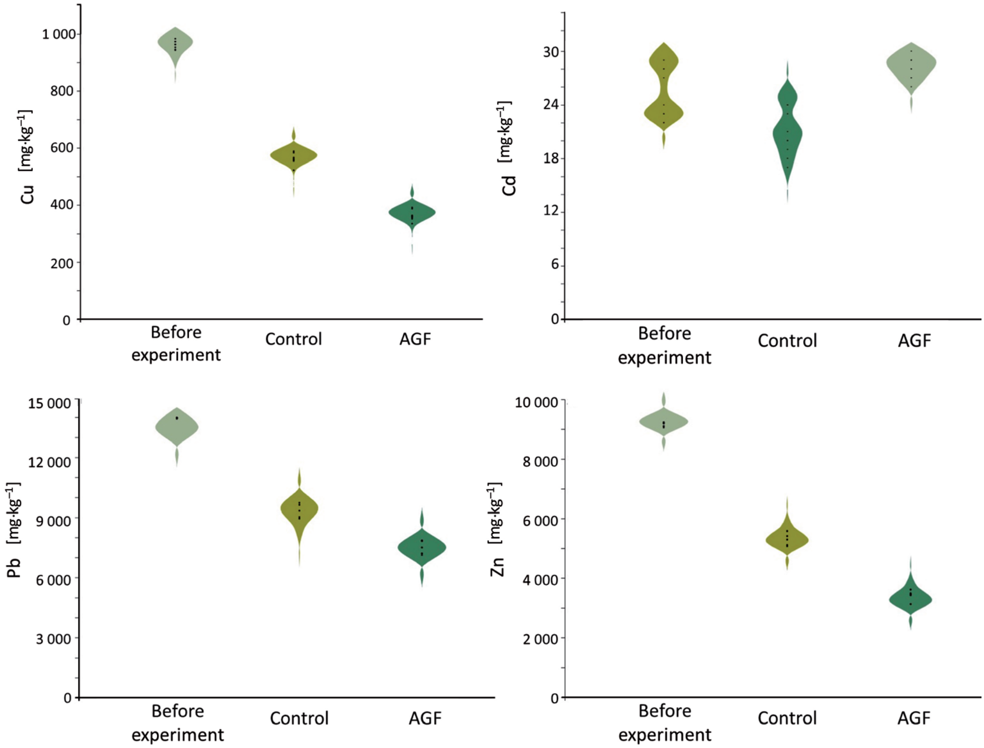

FIGURE 2. Content of heavy metals in soils
Source: own elaboration.

the groundwater and surface waters (Mohamed et al., 2023; Shahrokh et al., 2023). The reduction of complete forms of Cu and Zn, on the other hand, was decreased in both cases by 35%, with Pb and Cd by 20% and 17%, respectively, when likened to the control series. The obtained results clearly indicate that the addition of AGF can effectively decrease the mobility of Cd, Cu, Pb, and Zn in the soil. These findings are consistent with previous studies that showcased the remarkable efficacy of waste chicken feather-derived hydrolysates initiated by malic acid (Solcova et al., 2024). Authors demonstrated notable extraction efficiencies for various heavy metals from industrial soil, including 100% for As, 34.4% for Cr, 0.6% for Cu, 29.5% for Fe, 9.5% for Mn, 19.8% for Ni, and 19.8% for Zn. The parallels between our findings and those of Solcova et al. (2024) highlight the potential of utilizing agricultural waste-derived solutions for both extraction and immobilization purposes, offering a comprehensive approach to addressing heavy metal contamination in soils from industrial settings.

Klik, B., Jachimowicz, P., Liniauskiene, E., Gusiatin, M., Radzevičius, A., Brtnický, M., Šadzevičius, R., Bęś, A., Mazur, Z., Dapkienë, M., Radziemska, M. (2024). Ash from gasification of poultry feathers for heavy metal immobilization under assisted phytostabilization in soils. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 131–143. DOI 10.22630/srees.9761

Dactylis glomerata L. biomass and chemical composition

Maintaining an adequate vegetation layer in areas exposed to long-term pollution with heavy metals is one of the key reasons why treatments taking advantage of aided phytostabilization have been gaining so much popularity. According to Beddows (1959), *Dactylis glomerata* L. exhibits satisfactory growth at pH levels between 6.0 and 7.0, but also tolerates values as high as 8.5. This dependency held in results connected to the plant yield upon completion of the experiment. It was shown that the plant field of *Dactylis glomerata* L. is significantly dependent on the Cu, Cd, Pb, and Zn contents in the soil, as well as the addition of AGF (Fig. 3).

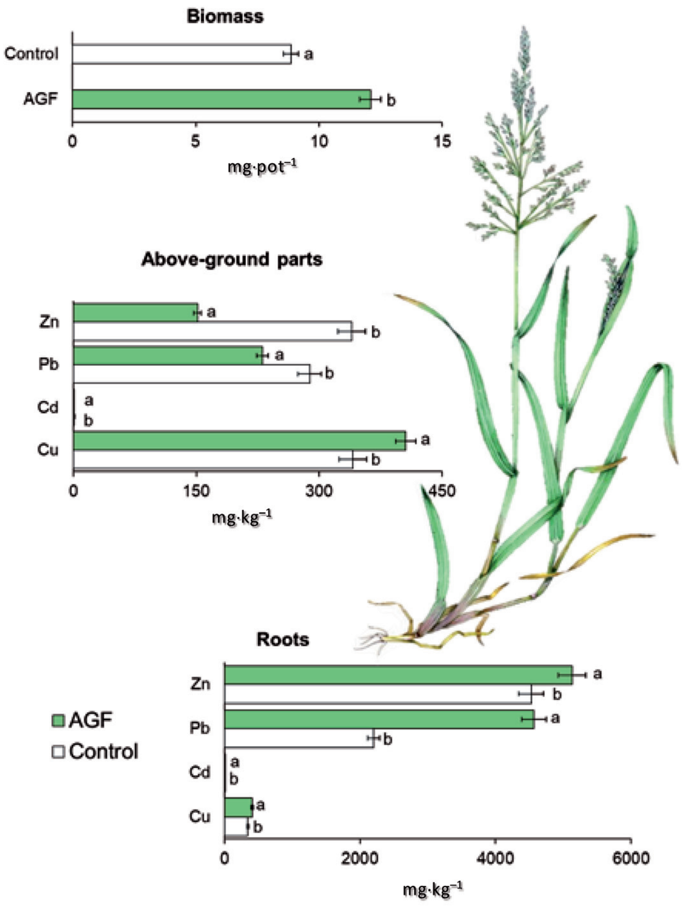

FIGURE 3. Plant biomass after phytostabilization with poultry feather ash (AGF) and metals concentration in shoots and roots of *Dactylis glomerata* L. Lowercase letters show statistically significant differences between control and AGF treatments for a given metal ($p < 0.05$)

Source: own elaboration.

The use of the analyzed soil amendment had a positive influence on the yield of the tested plant, which was 31% higher in this case when compared to the control series. This observation was similar to that reported by Radziemska et al. (2021), where the positive impact of AGF on *Lupinus luteus* L. growth was also observed. In the case of the mentioned studies, the test plant yield was 28% higher than in the control series. Similarly, Adekiya et al. (2019) demonstrated the beneficial effects of poultry feathers on soil characteristics, growth, and yield of tomato plants. The observed increase in plant yield following the AGF application was attributed to improvements in soil physical and chemical properties, enhanced nutrient availability, and the promotion of beneficial microbial activity. The combination of these factors creates a favorable environment for plant growth and development, ultimately leading to higher yields. One of the main advantages of applying various types of soil amendments to contaminated soils is stabilizing or restricting the mobility of heavy metals in the rhizosphere (Shackira & Puthur, 2019). In the carried out experiment, the roots of *Dactylis glomerata* L. were characterized by significantly higher contents of Cu, Cd, Pb and Zn, both in the control series as well as upon adding AGF to the soil. This dependency has been confirmed in the studies of other authors, in case of which the tested plants revealed higher heavy metal contents in their roots than in the shoots (Ivanov et al., 2003; Franco-Hernández et al. 2010; Khanthom et al., 2021). The higher accumulation of heavy metals in the roots of *Dactylis glomerata* L. can be attributed to two main factors: rhizosphere acidification and chelation processes, as well as the high cation-exchange capacity of cell walls (Sumiahadi & Acar, 2018; Shrivastava et al., 2019). Rhizosphere acidification and chelation processes involve plants releasing protons into the soil through plasma membrane-localized proton pumps, which lowers the pH of the rhizosphere. This acidification increases the solubility of metal ions, making them more available for root uptake (Sumiahadi & Acar, 2018). Additionally, plants exude low-molecular-weight compounds, such as organic acids and phytochelators, into the rhizosphere. These compounds form stable complexes with metal ions, enhancing metal uptake by plant roots (Rasci & Navari-Izzo, 2011). Furthermore, the high cation-exchange capacity of cell walls in root tissues plays a crucial role in limiting the translocation of heavy metals to shoots (Cui et al., 2021). Cell walls contain negatively charged sites that attract and bind positively charged metal ions, effectively immobilizing them within the root tissues. This restricts the movement of heavy metals to shoots and leaves, leading to their preferential accumulation in the roots (Shrivastava et al., 2019). Upon applying AGF as an additive aiding phytostabilization, the higher concentration of heavy metals in the roots of *Dactylis glomerata* L. was most apparent for Cu, Cd, Pb, and Zn. In this case, the contents of individual metals were higher by 16%, 37%, more than twice as high, and 12% when compared to the control series.

Conclusions

The application of AGF had a positive influence on the *Dactylis glomerata* L. plant yield. The plant biomass was 31% higher in pots to which AGF had been applied, as compared to the control series. The roots in the series with AGF were characterized by higher values of the analyzed heavy metals in relation to the shoots, which was noticeable in the case of Pb (over twice higher) and Cd – 37%. AGF influenced an increase in the pH values of soil (by 0.4 units) and to the highest degree limited exchangeable forms of Zn (25%), Cu (23%), Cd (20%), and Pb (12%) as well as total forms of Cu (35%), Zn (35%), Pb (20%) and Cd (17%) in the soil as compared to the control series. To sum up, the application of this type of waste material can be an important element of studies on the technologies of managing and reusing waste products in environmentally friendly solutions. What is more, the introduction of AGF as a soil amendment is an advancement in terms of environmental engineering activities in the scope of soil protection, facilitating the usefulness of the method of assisted phytostabilization, both in terms of the effectiveness of immobilizing heavy metals as well as the development of plant biomass in the contaminated area.

Acknowledgments

Piotr Jachimowicz is a recipient of a scholarship supported by the Foundation for Polish Science (FNP). This work was financially supported by the European Union under the REFRESH –Research Excellence For REgion Sustainability and High-tech Industries project No. CZ.10.03.01/00/22_003/0000048 via the Operational Programme Just Transition.

References

Abdulsalam, S., Bajoga, A., & Dala, H. (2020). Determination of some heavy metals concentrations from top soil of metals scrap yards and their corresponding control areas within gombe metropolis, gombe state, nigeria, using atomic absorption spectrometry. *Bima Journal of Science and Technology*, *4* (02), 31–38.

Adekiya, A. O. (2019). Green manures and poultry feather effects on soil characteristics, growth, yield, and mineral contents of tomato. *Scientia Horticulturae*, *257*, 108721. https://doi.org/10.1016/j.scienta.2019.108721

Alvarenga, P., Gonçalves, A. P., Fernandes, R. M., Varennes, A. de, Vallini, G., Duarte, E., & Cunha-Queda, A. C. (2009). Organic residues as immobilizing agents in aided phytostabilization: (I) Effects on soil chemical characteristics. *Chemosphere*, *74* (10), 1292–1300. https://doi.org/10.1016/j.chemosphere.2008.11.063

Beddows, A. R. (1959). *Dactylis glomerata* L. *The Journal of Ecology*, *47* (1), 223–239. https://doi.org/10.2307/2257254

Bidar, G., Waterlot, C., Verdin, S., Proix, N., Courcot, D., Détriché, S., Fourrier, H., Richard, A., & Douay, F. (2016). Sustainability of an in situ aided phytostabilisation on highly contaminated soils using fly ashes: Effects on the vertical distribution of physicochemical parameters and trace elements. *Journal of Environmental Management*, *171*, 204–216. https://doi.org/10.1016/j.jenvman.2016.01.029

Cui, X., Mao, P., Sun, S., Huang, R., Fan, Y., Li, Y., Li, Y., Zhuang, P., & Li, Z. (2021). Phytoremediation of cadmium contaminated soils by *Amaranthus Hypochondriacus* L.: The effects of soil properties highlighting cation exchange capacity. *Chemosphere*, *283*, 131067. https://doi.org/10.1016/j.chemosphere.2021.131067

Dalólio, F. S., Silva, J. N. da, Oliveira, A. C. C. de, Tinoco, I. D. F. F., Barbosa, R. C., Oliveira Resende, M. de, Albino, L., & Coelho, S. T. (2017). Poultry litter as biomass energy: a review and future perspectives. *Renewable and Sustainable Energy Reviews*, *76*, 941–949. https://doi.org/10.1016/j.rser.2017.03.104

Dodd, M., Amponsah, L. O., Grundy, S., & Darko, G. (2023). Human health risk associated with metal exposure at Agbogbloshie e-waste site and the surrounding neighbourhood in Accra, Ghana. *Environmental Geochemistry and Health*, *45* (7), 4515–4531. https://doi.org/10.1007/s10653-023-01503-0

Fahimi, A., Bilo, F., Assi, A., Dalipi, R., Federici, S., Guedes, A., Valentim, B., Olgun, H., Ye, G., Bialecka, B., Fiameni, L., Borgese, L., Cathelineau, M., Boiron, M. C., Predeanu, G., & Bontempi, E. (2020). Poultry litter ash characterisation and recovery. *Waste Management*, *111*, 10–21. https://doi.org/10.1016/j.wasman.2020.05.010

Franco-Hernández, M. O., Vásquez-Murrieta, M. S., Patińo-Siciliano, A., & Dendooven, L. (2010). Heavy metals concentration in plants growing on mine tailings in Central Mexico. *Bioresource Technology*, *101* (11), 3864–3869. https://doi.org/10.1016/j.biortech.2010.01.013

Gusiatin, Z. M., Kumpiene, J., Janiszewska, S., Kasiński, S., Pecio, M., Piec, R., & Radziemska, M. (2020). A mineral by-product from gasification of poultry feathers for removing Cd from highly contaminated synthetic wastewater. *Minerals*, *10* (12), 1048. https://doi.org/10.3390/min10121048

Hedayati, A. (2022). *Ash transformation in thermochemical conversion of different biomass resources with special focus on phosphorus* (doctoral dissertation). LuleÍ University of Technology. https://www.diva-portal.org/smash/get/diva2:1653111/FULLTEXT01.pdf

Ivanov, V. B., Bystrova, E. I. & Seregin, I. V. (2003). Comparative impacts of heavy metals on root growth as related to their specificity and selectivity. *Russian Journal of Plant Physiology*, *50*, 398–406. https://doi.org/10.1023/A:1023838707715

Jagadeesan, Y., Meenakshisundaram, S., Raja, K., & Balaiah, A. (2023). Sustainable and efficient-recycling approach of chicken feather waste into liquid protein hydrolysate with biostimulant efficacy on plant, soil fertility and soil microbial consortium: a perspective to promote the circular economy. *Process Safety and Environmental Protection*, *170*, 573-583. https://doi.org/10.1016/j.psep.2022.12.029

Jeong, Y. K., & Kim, J. S. (2001). A new method for conservation of nitrogen in aerobic composting processes. *Bioresource Technology*, *79* (2), 129–133. https://doi.org/10.1016/S0960-8524(01)00062-1

Khanthom, S., Stewart, T. N., & Prapagdee, B. (2021). Potential of a rhizobacterium on removal of heavy metals from aqueous solution and promoting plant root elongation under heavy metal toxic conditions. *Environmental Technology & Innovation, 22*, 101419. https://doi.org/10.1016/j.eti.2021.101419

Kwiatkowski, K., Krzysztoforski, J., Bajer, K., & Dudynski, M. (2013). Bioenergy from feathers gasificatione-Efficiency and performance analysis. *Biomass Bioenergy*, *59*, 402–411. https://doi.org/10.1016/j.biombioe.2013.07.013

Lacalle, R. G., Bernal, M. P., Álvarez-Robles, M. J., & Clemente, R. (2023). Phytostabilization of soils contaminated with As, Cd, Cu, Pb and Zn: Physicochemical, toxicological and biological evaluations. *Soil & Environmental Health*, *1* (2), 100014. https://doi.org/10.1016/j.seh.2023.100014

Liu, W., Qin, Y. P., Yang, X. B., & Zhang, G. Y. (2014). Experimental study for impact of volatile matter on spontaneous combustion characteristics of coal. *Journal of China Coal Society*, *39* (5), 891–896. https://doi.org/10.13225/j.cnki.jccs.2013.0493

Mohamed, E., Ren, J., Ren, H., Tao, L., & Mala, A. (2023). *Stabilization remediation of soil polluted by heavy metals using palygorskite modied with chlorides* (preprint). Research Square. https://doi.org/10.21203/rs.3.rs-2462204/v1

Moon, W. C. (2019). A review on interesting properties of chicken feather as low-cost adsorbent. *International Journal of Integrated Engineering*, *11* (2), 136–146. https://doi.org/10.30880/ijie.2019.11.01.015

Pueyo, M., López-Sanchez, J. F., & Rauret, G. (2004). Assessment of $CaCl_2$, $NaNO_3$ and NH_4NO_3 extraction procedures for the study of Cd, Cu, Pb and Zn extractability in contaminated soils. *Analytica Chimica Acta, 504* (2), 217–226. https://doi.org/10.1016/j.aca.2003.10.047

Radziemska, M., Gusiatin, Z. M., Cydzik-Kwiatkowska, A., Cerdŕ, A., Pecina, V., Bęś, A., Datta, R., Majewski, G., Mazur, Z., Dzięcioł, J., Danish, S., & Brtnicky, M. (2021). Insight into metal immobilization and microbial community structure in soil from a steel disposal dump that was phytostabilized with composted, pyrolyzed or gasified wastes. *Chemosphere*, *272*, 129576. https://doi.org/10.1016/j.chemosphere.2021.129576

Radziemska, M., Gusiatin, Z. M., Kumar, V., & Brtnicky, M. (2022). Co-application of nanosized halloysite and biochar as soil amendments in aided phytostabilization of metal(-oid)s-contaminated soil under different temperature conditions. *Chemosphere*, *288* (Part 1), 132452. https://doi.org/10.1016/j.chemosphere.2021.132452

Rascio, N., & Navari-Izzo, F. (2011). Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? *Plant Science*, *180* (2), 169–181. https://doi.org/10.1016/j.plantsci.2010.08.016

Santini, N. S., & Miquelajauregui, Y. (2022). The restoration of degraded lands by local communities and Indigenous peoples. *Frontiers in Conservation Science*, *3*, 873659. https://doi.org/10.3389/fcosc.2022.873659

Shackira, A. M., & Puthur, J. T. (2019). Phytostabilization of heavy metals: understanding of principles and practices. In S. Srivastava, A. K. Srivastava, & P. Suprasanna (Eds.), *Plant-metal interactions* (pp. 263–282). Springer. https://doi.org/10.1007/978-3-030-20732-8_13

Shahrokh, V., Martínez-Martínez, S., Faz, Á., Zornoza, R., & Acosta, J. A. (2023). Efficiency of large-scale aided phytostabilization in a mining pond. *Environmental Geochemistry and Health*, *45* (7), 4665–4677. https://doi.org/10.1007/s10653-023-01520-z

Shrivastava, M., Khandelwal, A., & Srivastava, S. (2019). Heavy metal hyperaccumulator plants: the resource to understand the extreme adaptations of plants towards heavy metals. In S. Srivastava, A. K. Srivastava & P. Suprasanna (Eds.), *Plant-metal interactions* (pp. 79–97). https://doi.org/10.1007/978-3-030-20732-8_5

Solcova, O., Rouskova, M., Sabata, S., Dlaskova, M., Demnerova, K., Bures, J., & Kastanek, F. (2024). Removal of heavy metals from industrial brownfields by hydrolysate from waste chicken feathers in intention of circular bioeconomy. *Environmental Advances*, *16*, 100521. https://doi.org/10.1016/j.envadv.2024.100521

Sumiahadi, A., & Acar, R. (2018). A review of phytoremediation technology: heavy metals uptake by plants. *IOP Conference Series: Earth and Environmental Science*, *142*, 012023. https://doi.org/10.1088/1755-1315/142/1/012023

Teodoro, M., Hejcman, M., Vítková, M., Wu, S., & Komárek, M. (2020). Seasonal fluctuations of Zn, Pb, As and Cd contents in the biomass of selected grass species growing on contaminated soils: Implications for in situ phytostabilization. *Science of The Total Environment*, *703*, 134710. https://doi.org/10.1016/j.scitotenv.2019.134710

Zhang, Y., Zhan, J., Ma, C., Liu, W., Huang, H., Yu, H., Christie, P., Li, T., & Wu, L. (2024). Root-associated bacterial microbiome shaped by root selective effects benefits phytostabilization by *Athyrium wardii* (Hook.). *Ecotoxicology and Environmental Safety*, *269*, 115739. https://doi.org/10.1016/j.ecoenv.2023.115739

Summary

Ash from gasification of poultry feathers for heavy metal immobilization under assisted phytostabilization in soils. The carried-out experiment aimed to assess the influence of ash derived from the thermochemical conversion of feathers (AGF) as a soil amendment, and *Dactylis glomerata* L. as a test plant in aided phytostabilization of soil strongly contaminated by Cu, Cd, Pb and Zn. The influence of AHG on the chemical properties of soil (pH as well as total and $CaCl_2$-extracted heavy metals) as well as the plant yield and concentration of heavy metals in the roots and shoots. The applied soil amendment influenced an increase in the pH values of soil (by 0.4 units) and a reduction in $CaCl_2$-extractable forms of Zn (25%), Cu (23%), Cd (20%) and Pb (12%), as well as total forms of Cu (35%), Zn (35%), Pb (20%) and Cd (17%) in the soil. The plant yield of the shoots of *Dactylis glomerata* L. following the application of AGF was 31% higher when compared to the control series. The roots of the tested plant in the AGF series contained higher values of the analyzed heavy metals in relation to the shoots, which was especially visible in the case of Pb (more than twice as high) and Cd (37%).