Call RFCS-2022
Project number 101112657

REECOL Ecological rehabilitation and long term monitoring of post mining areas

Deliverable 4.1

Method for a steered succession of low-growing plants and its field testing

Author | beneficiary

Łukasz Pierzchała, Marcin Głodniok, Paweł Łabaj, Małgorzata Białowąs, Aleksa Warzecha | GIG-PIB
Bartłomiej Bezak | PGG
Valérie Bert | INERIS
Michal Řehoř, Lenka Antošová | VUHU
Christos Roumpos, Aikaterini Servou | PPC
Aleš Lamot, Matjaž Kamenik | PV

Version | Date VERSION 1 | 29.01.2026
Dissemination level PU

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

TABLE OF CONTENTS

List of Tables

List of Figures

1. EXECUTIVE SUMMARY

Post-mining areas with high potential for redevelopment require protection against the encroachment of invasive species and the spontaneous development of woody vegetation. The proposed reclamation method involves accelerating and directing succession processes towards low herbaceous vegetation. The goal is to quickly and low-costly greening areas covered with waste from hard coal mining. The solution developed involves the application of a soil additive that improves the growing conditions for vegetation directly on waste rock, and the sowing of species that spontaneously appear on non-reclaimed waste rock heaps. Laboratory tests and preliminary results of monitoring the effectiveness of the method in situ conditions, confirm the effectiveness of the proposed method. The proposed approach shows significant potential for implementation in other types of areas transformed by mining.

2. INTRODUCTION

As a result of task 3.2 for polish case study areas the criteria for the evaluation of redevelopment potential of post-mining and active mines owned by PGG S.A. were set. Despite of high redevelopment potential, due to the large supply, the most of post-mining area will be not reuse in near future. The surface of such terrain should be covered with low vegetation as soon as possible to reduce risk the spread of invasive plants and dense trees cover development. These processes decrease the economic values of post-mining terrains. The task 4.1 aims to provide innovative and cost-effective solutions for revegetation post-mining terrains with a high redevelopment potential. The results of the evaluation of the potential of this post-mining area for redevelopment (Task 3.2) showed that the area Sośnica heap area has high potential for economic redevelopment. However, due to the ongoing waste storage process in the part belonging to PGG, it is currently not possible to set experimental plots there. For this reason, the experimental plot for testing new methods of greening post-mining areas was located within the Północ Waste Heap. Due to the significant similarity in chemical composition and physical properties of the waste hard coal rock heap, it is possible to replicate the developed rehabilitation method in other post-mining areas belonging to PGG S.A. This also applies to areas with high potential for redevelopment. Evaluation if develop methods could be implemented in the other types of land degraded by mining in Czech Republic, Greece, Slovenia, and France was also caried out.

The report presents preliminary results on the effectiveness of rehabilitation method application on Jankowice Północ waste heap. The results of short-term and long-term monitoring of the effectiveness of the solution will be conducted and reported under WP 5. The cost-effectiveness of this method will be assessed in task 4.5.

According to technical annex description, the specific aims of Task 4.1 are:

- to elaborate the low-cost techniques for habitat condition improvments on hard coal mining waste heap by applying fertilizers, pH correction, utilizing high-value mineral potential of mine tailings and using organic waste in laboratory scale;
- to carry out the selection of the herbs and grass species with the ability to compete with trees and invasive plants;
- to build field plot were developed in laboratory scale rehabilitation techniques will be tested in real conditions (experimental field on study areas selected in 3.4);
- to evaluate if develop methods could be implemented in the other post mining sites (test on soil samples delivered by INERIS, VUHU, PV).

3. Task Implementation

To achieve the set objectives, the following research and development work was carried out:

- identification of factors limiting growing plant directly on surface of mine waste heap,
- elaboration methods to improve plants growth conditions on mine waste rock,
- assessment of the effectiveness of the reclamation method on a laboratory scale,
- development of seed mixture composition,
- development of guidelines for the application of the method in situ,
- application of the solution in situ,

- monitoring the effectiveness of the method,
- assessment of the possibility of applying the method in other mining areas.

4. Identification of factors limiting growing plant directly on surface of mine waste heap

The Północ Waste Heap covers areas of about 56 ha and is localized in the southwestern part of the Upper Silesian Coal Basin. This area is used to accommodate waste from the Jankowice mine, which is scheduled for closure in 2049. Flat top of the heap, where reclamation activities not yet been carried out, was selected to locate experimental and control plots (Fig. 1).

Fig. 1. Flat surface of the Północ waste heap.

To define optimal habitat conditions for the development of low vegetation, the ecosystems of low herbaceous ecosystems developed on native soil, located in proximity to the Północ waste heap, the reference study plot was also established. This community is characterized by significant species diversity, and full coverage with low vegetation (Fig. 2).

Fig. 2. The reference study-plot in low-herbaceous ecosystems.

Co-funded by the European Union

To identify factors limiting plant cultivation directly on the surface of the mine dump, soil samples were taken from the surface of the dump where the experimental plot was planned to be located and from the reference ecosystem. A composite soil sample consisted of nine random subsamples taken from a depth of 0 to 20 cm. The results of standards physical and chemical parameters of soil substrates are presented in the table below:

Table 1 Standards physical and chemical parameters of soil substrates.

Parameter	Północ waste heap	Reference ecosystem
pH	7,8	7,6
Soil salinity [mS/m]	0,2	0,18
Total soil organic carbon (TOC) [%]	19,48%	9,31%
Total nitrogen [%]	0,24%	0,23%
Total phosphorus [%]	0,05%	0,16%
Calcium [%]	0,29	1,04
Potassium [%]	1,62	0,3
Magnesium [%]	0,64	0,38
Total sulphur [%]	0,13	0,07
Granular composition - Content of skeleton particles	69%	21%

Comparison of the physicochemical parameters of the top layer of waste rock with native soil within the reference ecosystem showed that:

- The waste heap rock and reference soil indicate lightly alkaline reaction;
- Salinity in both samples is well below thresholds that may have a negative impact on vegetation (>4us/m, (Miller and Donahue, 1995);
- Organic carbon content shows much higher values than in the reference soil. However, it should be assumed that it is an organic compound difficult to mineralize by microorganisms (content of hard coal);
- The substrate within experimental plots has a similar total nitrogen content to that of the referent soil. Due to the hard coal content, it is most likely nitrogen compounds with low bioavailability for plants and microorganisms;
- The substrate has a much lower concentration of phosphorus. It may be the main reason for limiting the development of vegetation on this substrate. It is necessary to assess the availability of this element for plants and microorganisms;
- Due to the high calcium, magnesium, potassium, and sulphur content, plant growth limitation by these elements is unlikely (Liebenberg et al 2020, Yesmin et al 2020, Hazelton, P.; Murphy 1995);
- Content of skeleton particles 2mm is above 60% and it is much higher that in referene ecosystems. This could have negatively impact on the substrate water holding capacity.

Land surface quality standards specifying levels of contamination with trace elements that do not pose a threat to the environment or humans are defined in Poland by the Regulation on Soil Quality and Pollution Standards [Regulation 2016], the concentration of trace elements did not exceed the permissible limits for areas used for residential buildings (Grupe I), recreational and leisure areas (Group III, and industrial areas (group IV). Detailed results of analyses of substances in soil that have toxic, mutagenic, and carcinogenic properties, in relation to limit values that may pose a risk, are summarized in the table below.

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Table 2 Concentration of trace elements in soil substitutes in waste rock.

Trace element	Unit (Dry mass)	Value	Risk group		
			I	III	IV
As	[ppm (mg/kg)]	4	25	50	100
Ba	[ppm (mg/kg)]	366	400	1000	1500
Cd	[ppm (mg/kg)]	<1	5	10	15
Co	[ppm (mg/kg)]	13	50	100	200
Cr	[ppm (mg/kg)]	53	200	500	1000
Cu	[ppm (mg/kg)]	43	200	300	600
Hg	[ppm (mg/kg)]	0,17	5	10	30
Mo	[ppm (mg/kg)]	<1	50	100	250
Ni	[ppm (mg/kg)]	40	150	300	500
Pb	[ppm (mg/kg)]	37	200	500	600
Sn	[ppm (mg/kg)]	2,3	20	100	350
Zn	[ppm (mg/kg)]	95	500	1000	2000

These results confirm the commonly observed phenomenon that waste dumps from hard coal mining within mines belonging to PGG are not characterized by low levels of trace substances that could pose an environmental and health risk.

The results of the analyses indicate that the main cause of limited vegetation growth on waste rock dumps is the limited availability of phosphorus and, probably, nitrogen, as well as the low content of easily decomposable organic matter.

5. Elaboration methods to improve plant growth conditions

To enhance vegetation development directly on the surface of waste rock, a solution based on the application of a granular soil additive made from sewage sludge and ground waste rock was developed. As confirmed by the research presented in the previous chapter, hard coal waste rock is characterized by hight contain silica, potassium, CaO, MgO, which are valuable nutrients for plants. However, the availability of these elements will depend on the level of fragmentation of the rock material. The best source of macronutrients (phosphorus and nitrogen) is easily decomposable organic matter. Sewage sludge has a high phosphorus and nitrogen content, and the release of nutrients from it is much slower than when mineral fertilizers are used. Since the pH of the tested barren rock was favorable for plant growth, the soil additive being developed doesn`t need to have properties related to correcting the pH of the surface wase rocks.

This stage of work was focused on developing the right proportions of components to obtain a product with the appropriate properties for improving plant growth conditions and with favorable physical properties enabling its easy application in field conditions (granule stability).

The experimental formulation was designed to contain 40% by weight of ground waste rock as the mineral additive. The components were subjected to dynamic mixing, followed by simultaneous homogenization and granulation within a controlled process to ensure uniform particle structure and consistency. During this operation, the organic phase (stabilized sewage sludge) provided both cohesion and plasticity, facilitating the formation of stable granules while enhancing the nutrient composition of the product (Fig. 3).

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Fig. 3. Equipment used for preparing soil improvers.

The resulting granulated material exhibited a grain size range of 2–4 mm, corresponding to typical parameters for agricultural and reclamation fertilizers. The granules were characterized by good mechanical integrity and uniform structure, suitable for subsequent laboratory analyses of their physicochemical properties, nutrient release dynamics, and potential application in soil improvement and post-mining land reclamation (Fig. 4).

Fig. 4. Granulated soil improver formed from stabilized sewage sludge and grounded minerock.

The target product was assessed for compliance with European legal requirements.

In accordance with Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance), *„fertilising product means a substance, mixture, micro-organism or any other material, applied or intended to be applied on plants or their rhizosphere or on mushrooms or their mycosphere, or intended to constitute the rhizosphere or mycosphere, either on its own or mixed with another material, for the purpose of providing the plants or mushrooms with nutrient or improving their nutrition efficiency". […] „Different product functions warrant different product safety and quality requirements adapted to their different intended uses. EU*

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

fertilising products should therefore be divided into different product function categories, which should each be subject to specific safety and quality requirements".

The used experimental fertilizer granules were produced from ground waste rock from a mine (40% by weight) and stabilized sewage sludge from a municipal wastewater treatment plant (WWTP). The sewage sludge selected for the experiment exhibited an appropriate organic matter content and a favorable nutrient profile, including essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). Moreover, the organic phase provided both cohesion and plasticity, facilitating the formation of stable granules while enhancing the nutrient composition of the product. The resulting granulated material exhibited a grain size range of 2–4 mm, corresponding to typical parameters for agricultural and reclamation fertilizers. Hence, the experimental fertilizer granules demonstrate potential for application in soil quality enhancement and the ecological restoration of post-industrial landscapes. In accordance with Article 4 of the mentioned Regulation, an EU fertilising product shall meet the requirements (according to Annex I) for the relevant product function category.

An analysis of the content of contaminants in the developed granulate vs. the requirements contained in the regulation showed that the developed fertilizer product meets the requirements for **inorganic soil improvers** in terms of the parameters specified in Annex 1 to the regulation (Table...). Currently, chromium measurements include total chromium, but for full compliance, the analysis must be supplemented with a measurement for chromium VI.

According to Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance) inorganic soil improver shall be a soil improver other than an organic soil improver, contaminants in inorganic soil improvers must not exceed the following permissible values:

- cadmium (Cd): 1,5 mg/kg dry mass,
- hexavalent chromium (Cr VI): 2 mg/kg dry mass,
- mercury (Hg): 1 mg/kg dry mass,
- nickel (Ni): 100 g/kg dry mass,
- lead (Pb): 120 mg/kg dry mass,
- inorganic arsenic (As): 40 mg/kg dry mass.

The copper (Cu) content in inorganic soil improvers must not exceed 300 mg/kg dry matter, and the zinc (Zn) content in inorganic soil improvers must not exceed 800 mg/kg dry matter.

The results show that developed product is in line with the regulations and will not cause additional contamination to soils (REGULATION (EU) 2019/1009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (for organic soil improver).

Table 3 Characteristics of the fertilizer product.

SPECIFICATION	UNIT	VALUE	
Total nitrogen	[%wag. (%m/m) s.m.]	1.43	-
Phosphorus P	[%wag. (%m/m) s.m.]	0.64	
Calcium Ca	[%wag. (%m/m) s.m.]	1.75	
Magnesium Mg	[%wag. (%m/m) s.m.]	0.73	
Potassium K	[%wag. (%m/m) s.m.]	1.15	
Total sulfur TS	[%wag. (%m/m) s.m.]	0.54	
Total carbon TC	[%wag. (%m/m) s.m.]	20.61	
Total organic carbon TOC	[%wag. (%m/m) s.m.]	19.97	

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

			INORGANIC SOIL IMPROVER[1]
Arsenic As	[ppm (mg/kg) s.m.]	<1.0	40
Barium Ba	[ppm (mg/kg) s.m.]	365	-
Cadmium Cd	[ppm (mg/kg) s.m.]	1.3	1.5
Cobalt Co	[ppm (mg/kg) s.m.]	9.5	-
Total chromium Cr_{tot}	[ppm (mg/kg) s.m.]	70	-
Chromium Cr (VI)	[ppm (mg/kg) s.m.]	n.d.	2.0
Copper Cu	[ppm (mg/kg) s.m.]	65	300
Mercury Hg	[ppm (mg/kg) s.m.]	0.24	1
Molybdenum Mo	[ppm (mg/kg) s.m.]	1.3	-
Nickel Ni	[ppm (mg/kg) s.m.]	33	100
Lead Pb	[ppm (mg/kg) s.m.]	35	120
Tin Sn	[ppm (mg/kg) s.m.]	6.4	-
Zinc Zn	[ppm (mg/kg) s.m.]	223	800
pH of the water extract		7.7	-
temperature of measurement	[°C]	20	-
Conductivity	[mS/cm]	1,07	-

Source: Own elaboration; also based on (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance)

6. Assessment of the effectiveness of the reclamation method on a laboratory scale

Thise stage of work involved determining the appropriate dose of developed soil additive.

The seed germination test on *Sinapis alba* (Diclotyledonae) and *Festuca rubra* (Monocotyledonae) were used to assess the influence of different doses of soil improvement for vegetation development on waste rock material. *Sinapis alba* is often used in phytotests standardization method. *Festuca rubra* is a plant that often spontaneously spreads on uncultivated coal spoil heaps. The growth of *Sinapsis alba* was tested on unsifted mining waste to simulate the growth conditions at the dump site. Due to the significant proportion of particles larger than 2 mm in the waste rock, it was necessary to select containers of appropriate depth and surface area to obtain comparable results. At the same time, the containers could not be too large to ensure that the experiment could be conducted in a single series in the one phytotron. The mining waste in the pots was at least 5 cm thick. It allowed to test the germination process and initial plant growth on the surface of the spoil heap. The same amount of waste material previously collected from the test surface was placed in each container (1kg). The containers used measured 18 cm x 23 cm (area 414 cm²). On each repetition, 2 g of *Sinapis alba* and 1 g of *Festuca rubra* seeds were sown.

The results of stimulating plant growth through soil additives were compared to growth in native soil from the reference ecosystem. Three repetitions of each treatment were performed. Test duration was 14 days. All tests were carried out in a phytotron in controlled conditions. Plants were watered every 2 days, and a constant temperature were kept 22 Celsius degrees. The fertilizer dose was determined by weight share (%) in relation to the weight of waste material/native soil placed in the pot. The length of the stems and the coverage of the area with vegetation were determined.

[1] Based on Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance)

The results on *Sinapis alba* and *Festuca rubra* test showed quite significant variation between the replications within groups where waste rock was used. This was most likely due to the use of unsifted mining waste and was a deliberate experimental treatment.

The highest average length for the stem and the average plant cover of *Sinapis alba* and *Festuca rubra*) were obtained in a control sample with native soil. In the case of waste without soil improvement, growth in both species was significantly limited. In the case of the best improvement in growth parameters was achieved hen using a soil improver in an amount of 2% relative to the weight of the waste rock were applied. Festuca rubra showed the longest average stem length when using a soil additive of 3.5% and the highest average coverage at 2%.

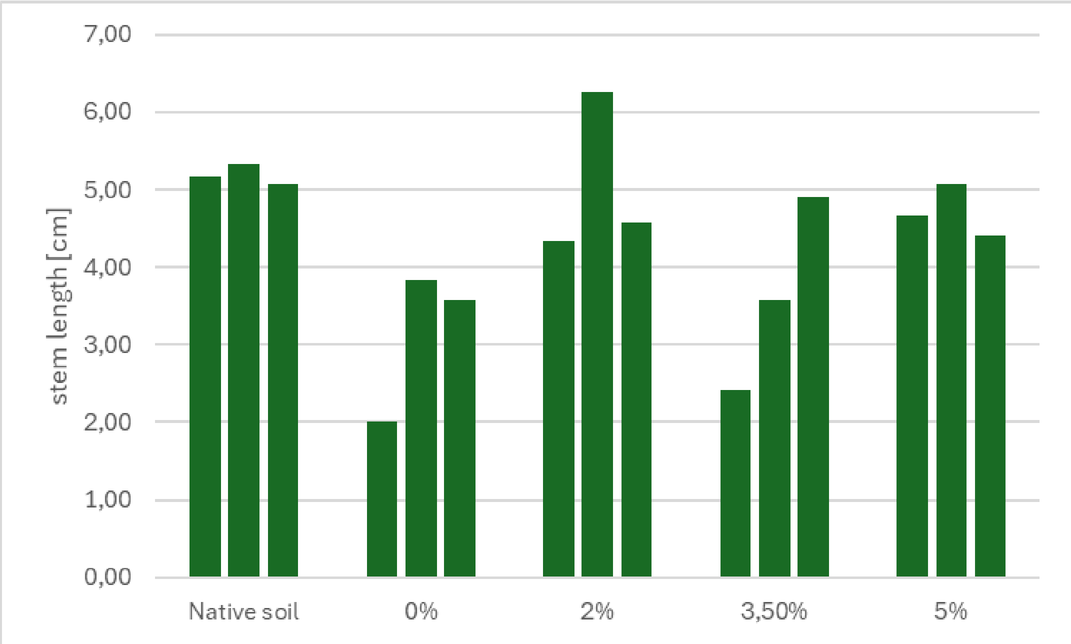

Fig. 5. Stem length of Sinapis alba on the native soil and waste rock with various percentages of soil improver (0%, 2%, 3,5% 5%).

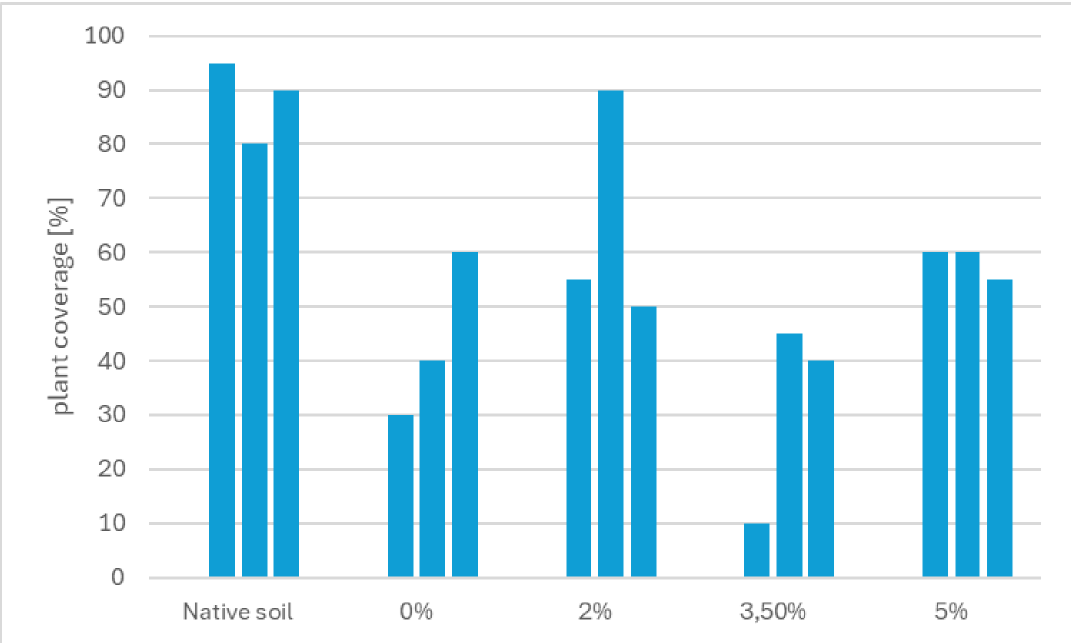

Fig. 6. Coverage of Sinapis alba on the native soil and waste rock with various percentages of soil improver (0%, 2%, 3,5% 5%).

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

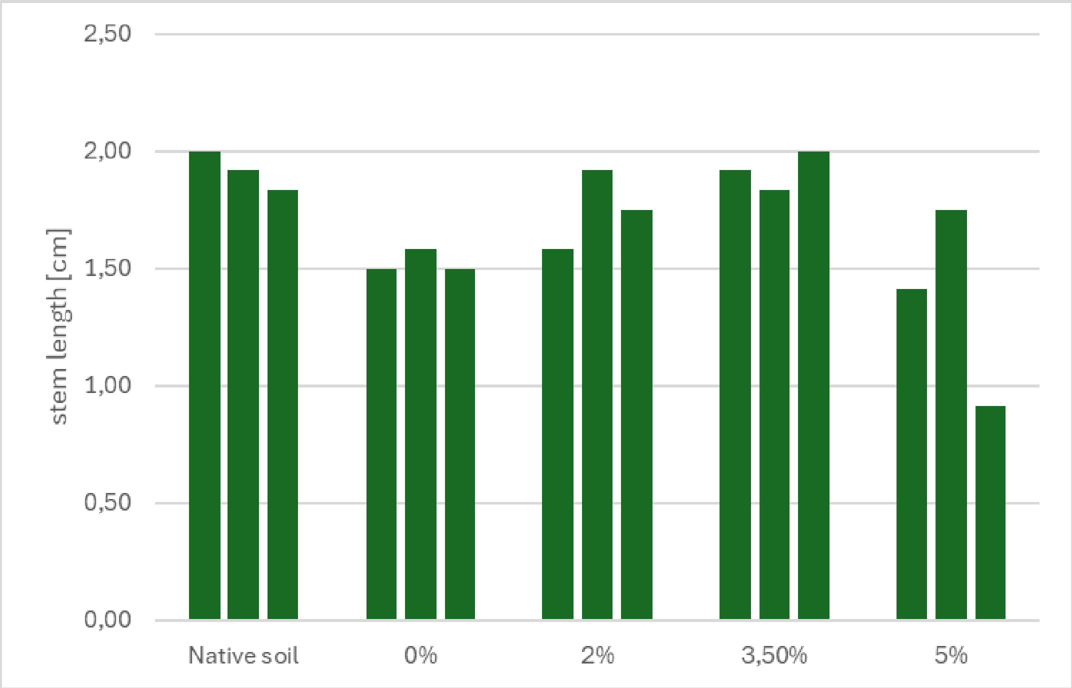

Fig. 7. Stem length of Festuca rubra on the native soil and waste rock with various percentages of soil improver (0%, 2%, 3,5% 5%).

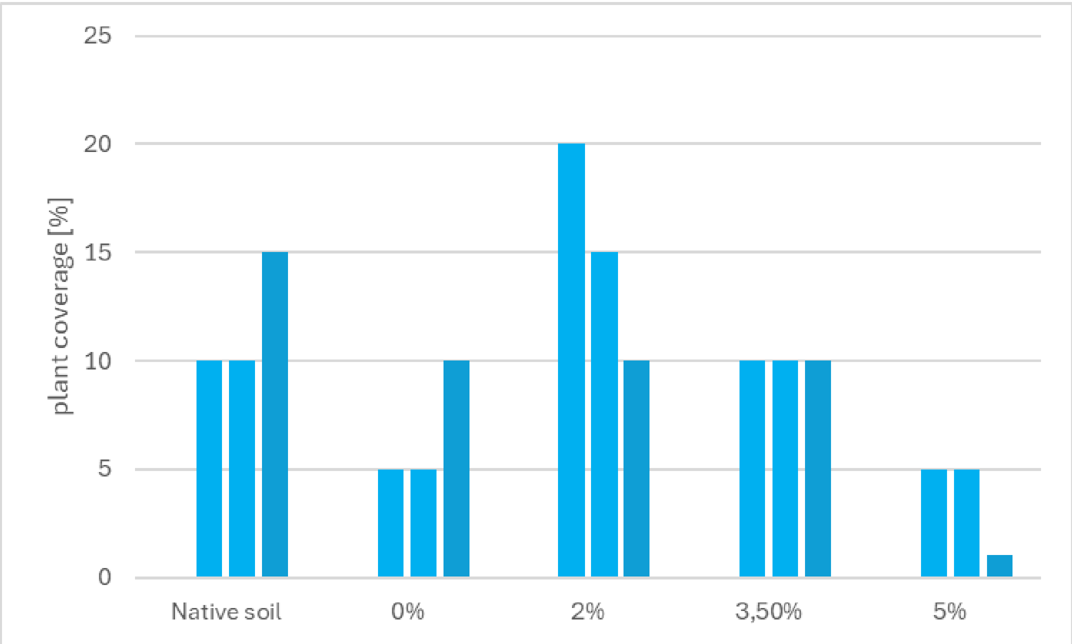

Fig. 8. Coverage of Festuca rubra on the native soil and waste rock with various percentages of soil improver (0%, 2%, 3,5% 5%).

Water-holding capacity is the ability of soil to retain water against gravity (measure of the amount of water that can be absorbed, fixed or held). The native soil showed a water holding capacity of approximately 68%. The waste was characterized by almost half the capacity to be absorbed, fixed or held the water. The addition of fertilizer at a rate of 2% has a positive effect on increasing WHC (an increase of approximately 6%) Further increases in dosage do not significantly increase WHC values.

Table 4 Water-holding capacity the native soil and waste rock with various percentages of soil improver.

Samples	WHC [%]
Native soil	**67,46**
0%	35,41
2%	**41,49**
5%	39,22
10%	42,92

7. Development of seed mixture composition

The process of spontaneous succession on un-reclaimed waste rock dumps depends on the availability of plant species diasporas capable of colonizing these specific habitats. Seeds usually reach the surface of the dump site carried by the wind. It is therefore largely a random process. This creates the risk of invasive vegetation colonizing the surface of the spoil heap. In the case of the developed method, it was decided to develop a reclamation mixture consisting exclusively of native plant species, which will accelerate and direct succession towards low herbaceous vegetation. The aim is to quickly establish vegetation cover that will also reduce the risk of woody vegetation encroachment.

Considering the identified habitat conditions and the intended function of the post-mining area the target plant community should:

- be adapted to difficult habitat conditions (low requirements),
- has resistance to climate variability (drought-resistant species),
- limiting the spread of invasive species and controlling the succession of woody vegetation,
- low maintenance requirements,
- potential to provide ecosystem services.

The following criteria were used when selecting species for the reclamation mixture:

- spontaneous occurrence on waste heaps,
- low biogenes and water requirements,
- high competitiveness,
- preferably flowering plants that provide pollinators with nectar and pollen,
- availability and low cost of purchasing seeds.

The list of low vegetation species appearing spontaneously on waste rock dumps was determined based on scientific publications in this field (Rostański, Stawowczyk 2006, Włoch *et al.* 2013; Kompała-Bąba *et al.* 2019; Bak *et al.* 2024). Finally, considering the criteria adopted for the reclamation mixture, 20 species of herbaceous plants and 5 species of grasses were selected for the preparation of the reclamation mixture (Fig. 9). The species of herbaceous plants included in the mixture are:

- *Achillea millefolium*
- *Anthemis tinctoria*
- *Artemisia vulgaris*
- *Centaurea jacea*
- *Centaurea stoebe*
- *Cichorium intybus*
- *Crepis biennis*
- *Dactylis glomerata*
- *Daucus carota*
- *Echium vulgare*
- *Elymus repens*
- *Festuca_rubra*
- *Festuca_ovina*
- *Glebionis segetum*
- *Hypericum perforatum*
- *Leucanthemum vulgare*
- *Lolium perenne*
- *Lotus corniculatus*
- *Matricaria chamomilla*
- *Melilotus albus*
- *Oenothera biennis*
- *Pastinaca sativa*
- *Plantago lanceolata*
- *Poa compresa*
- *Poa nemoralis*
- *Reseda luteola*
- *Tanacetum vulgare*

The mass proportion of individual seeds in the mixture was calculated in relation to the number of seeds of a given species per gram and the target proportion in the plant community.

Fig. 9. Seed mixture for post-mining spoil heaps reclamation.

8. Development of guidelines for the in-situ application

8.1 Determining the dosage and method of application of soil improver

Based on the comparative evaluation, the 2% fertilizer dose was experimentally determined to be the most appropriate level for further use. It provides:

- Optimal nutrient enrichment without excessive salinity,
- Good structural stability of the soil matrix.

Therefore, the 2% addition of the developed fertilizer is recommended as the optimal dosage for soil improvement and reclamation applications, ensuring both agronomic efficiency and environmental safety. The laboratory test surface area used for determining the reference fertilizer dose(20g) was therefore 414 cm². Target field plot surface area: 40 m × 40 m. Thus, the target plot area is approximately 38,647 times larger than the laboratory test surface. If 20 g of fertilizer were applied to the 23 × 18 cm sample, the proportional mass of fertilizer required for the 40 × 40 m plot is approximately 773 kg, which was rounded to 800 kg. Thus, the final field application rate corresponded to 0.5 kg of fertilizer per square meter of experimental plot surface area.

Manual application was selected to maintain precise control over spreading uniformity, especially considering the granular structure of the material. After application, the fertilizer layer should be lightly incorporated into the topsoil (preferably to a depth of 1-2 cm) to enhance soil–fertilizer contact and minimize nutrient losses through surface runoff or volatilization. Mixing can be done by manually raking the surface or by a tractor-mounted spring-tooth harrow.

8.2 Substitution of Ground Waste Rock with Fly Ash in Field Trials

During the preparatory phase of the experimental work, unforeseen technical challenges were encountered in the comminution (grinding) process of the waste rock material. The laboratory ball mill, although effective for small-scale processing, proved insufficient to produce the required quantity of finely ground material (grain size 0–0.2 mm) needed for the planned field-scale applications. The high hardness and heterogeneity of the waste rock led to prolonged milling times and significant wear of the grinding media, which ultimately limited the achievable production capacity.

To ensure continuity of the research and to allow the commencement of field testing within the scheduled timeframe, it was decided to introduce a substitute material characterized by comparable chemical and physical properties. After evaluating several alternatives, fly ash derived from the combustion of hard coal was selected as the most suitable replacement.

The selected fly ash exhibited a similar mineral composition (predominantly silica, alumina, and calcium oxide), fine particle size distribution, and pozzolanic reactivity, closely matching the expected behavior of the ground waste rock in the fertilizer matrix. Moreover, both materials share a comparable alkaline reaction and low organic content, making the substitution scientifically justified for the purpose of assessing the fertilizer's performance and soil interaction under field conditions.

The use of fly ash as a substitute allowed for the continuation of experimental validation of the developed fertilizer formulations without compromising the overall objectives of the project. All modifications were thoroughly documented, and the substitution was considered temporary, intended solely for field-scale verification until enough ground waste rock could be prepared for subsequent experimental series.

For the experimental field trials, a batch of fertilizer was produced in accordance with the formulation developed by the Central Mining Institute – National Research Institute (GIG-PIB) in cooperation with Jastrzębskie Wodociągi S.A. The production was carried out at the facilities of Jastrzębskie Wodociągi S.A., which possesses all legally required permits and authorizations for the manufacturing of fertilizer products derived from stabilized sewage sludge and mineral additives, including fly ash.

The production process was conducted under controlled technological conditions, ensuring compliance with the standards defined in both Polish and European Union regulations governing the recovery and utilization of waste-derived materials in agricultural applications (in particular, the EU Fertilising Products Regulation (EU) 2019/1009 and relevant national legislation on the use of sewage sludge in the environment).

The selected formulation, hereinafter referred to as the GIG-PIB fertilizer, represents a product of integrated waste management and circular economy principles. It combines organic matter from municipal wastewater treatment plant sludge with inorganic and mineral components such as fly ash, which acts as a structural stabilizer and source of calcium and trace elements. The resulting material demonstrates stable physicochemical characteristics, low heavy metal content, and nutrient availability consistent with the requirements for safe application in soil improvement and land reclamation projects.

All stages of the production and material handling were documented and monitored to ensure reproducibility of the fertilizer's composition and quality parameters. The produced fertilizer batch was subsequently used as the test material for further laboratory and field-scale performance evaluation.

A sample of the fertilizer material containing fly ash as a mineral component was subjected to a series of laboratory tests to assess its physicochemical properties and agronomic effectiveness. The performance of this formulation was experimentally compared with the fertilizer variant based on ground waste rock, previously tested at an application rate of 2% (reference dose).

The comparative laboratory experiments demonstrated that the fly ash–based fertilizer exhibited equivalent effectiveness to the waste rock–based formulation in terms of nutrient availability, soil pH stabilization, and stimulation of microbial activity. Both materials produced comparable improvements in soil structure and fertility indicators, confirming that the use of fly ash as a substitute mineral component did not adversely affect the overall functionality or efficiency of the fertilizer product.

These findings validate the feasibility of using fly ash as an alternative raw material in the fertilizer formulation, ensuring similar agronomic performance under controlled experimental conditions.

9. Determining the method of application of the seed mixture

To establish a wildflower meadow on native soils, typically 4-5 grams of seeds mixture per square meter is used. Due to limited water and nutrient resources, to reduce competition between plants, it was decided to reduce the amount of seeds in spring sowing to approx. 3 g per square meter. The developed seed mixture consisted of 67% herbaceous plant species and 33% grass species. A total of 4 800 g of mixture is needed to sow 1,600 m2 of experimental plots. The remaining number of seeds, approx. 2 g per m2, is intended for

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

sowing in the fall. Sowing in autumn provides better conditions for plant germination due to the lower risk of water shortages. The spring sowing date was determined based on an analysis of rainfall during spring periods in previous years. An analysis of sum of monthly precipitation has shown that the most favorable month for sowing is May.

It is characterized by higher precipitation than March and April and an increase in rainfall in recent years (2018-2024) compared to the previous period (1991-2017).

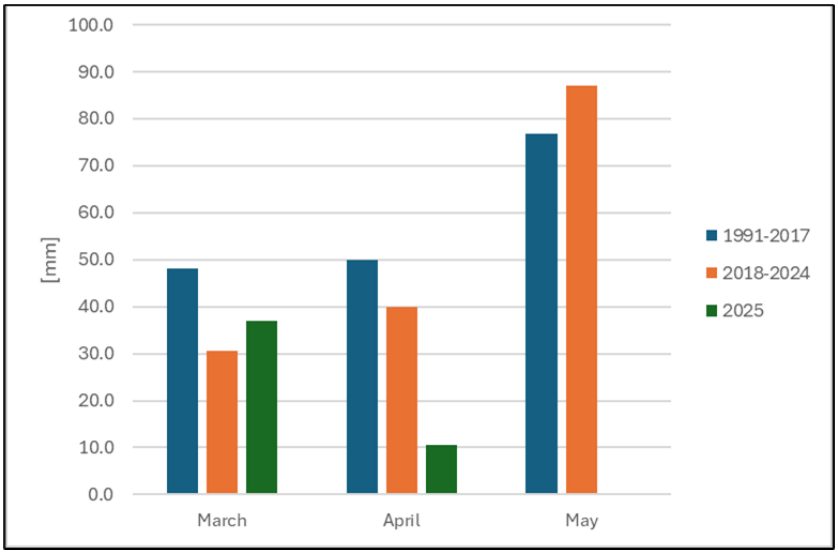

Fig. 10. The analysis of sum of monthly precipitation.

10. Application of the solution on the experimental plot

On 29.04.2025, a soil improver was applied to the research area. To ensure uniform application, the test plot was divided into four equal areas. A weighed amount of the additive was applied manually to each section of the plot.

Fig. 11. Application of soil improver within the research plot – application.

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Fig. 12. Application of soil improver within the research plot – outcome.

Seeds were sown one week after the application of the soil additive. This allowed the soil improver to penetrate the substrate and release biogenic substances in the plant root zone.

Due to the relatively small area of the research plot, seeds were sown manually. The seed mixture was mixed with dry sand. This allowed for even sowing of seeds in the research area.

Fig. 13. Manual sowing of seeds on the study-plot area.

To ensure that the plants take root at a greater depth, the seeds were raked in after sowing.

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Fig. 14. Raking seeds after sowing.

11. Monitoring the effectiveness of the method

To compare the effectiveness of the reclamation measures implemented, it was decided to establish additional control plots within the mining waste dump, where vegetation develops through spontaneous succession. The study plot was established on the flat part of the Sośnica waste heap in Gliwice. Vegetation development is shaped by natural processes for at least 10 years (Fig. 15).

Fig. 15. The part of Sośnica waste heap where vegetation develops through spontaneous succession.

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

At this stage of the work, the monitoring of the effectiveness of reclamation activities (experimental plot) was carried out regarding the observation of habitat parameters and the characteristics of vegetation on:

- Waste heap surface without reclamation (without treatment)
- Herbaceous plant communities on native soil (reference ecosystem)
- Waste heap undergoing spontaneous succession

The key characteristics of each study plots are summarised in the table below.

Table 5 Characteristics of study plots.

ID	Plot types	Dimension	Slope	Geographical coordinates (central point; WGS 84)
1	Waste heap surface rehabilitated by directed succession (experimental plot)	40m x 40m	< 5° (5.23%)	N50°03'38.99" E: 18°34'25.65
2	Waste heap surface without reclamation (without treatment)	20m x20m	< 5° (5.23%)	N: 50°03'38.17" E: 18°34'24.08"
3	Herbaceous plant communities on native soil (reference ecosystem)	20mx20m	< 5° (5.23%)	N: 50°03'38.17" E: 18°34'24.08"
4	Waste heap undergoing spontaneous succession	20m x 20m	< 5° (5.23%)	N: 50°16'24.04" E: 18°44'12.01"

The plot sizes were selected to allow for subsequent analysis of satellite data. Data from the Sentinel-2 mission were used, enabling the determination of NDVI index values, which can be used to monitor vegetation cover. Within each study plot, four 10m x 10m sub-plots were set. On each sub-plots plant species' percentage cover was evaluated.

The largest number of plant species was observed within the study area (26). Species diversity was greater than in the reference ecosystem (17 species) and in the vegetation developed through spontaneous succession (19 species). Waste heap surface without reclamation (without treatment). On the waste heap surface without reclamation, 13 species were identified. However, some of them appeared periodically and disappeared after periods of drought and heat.

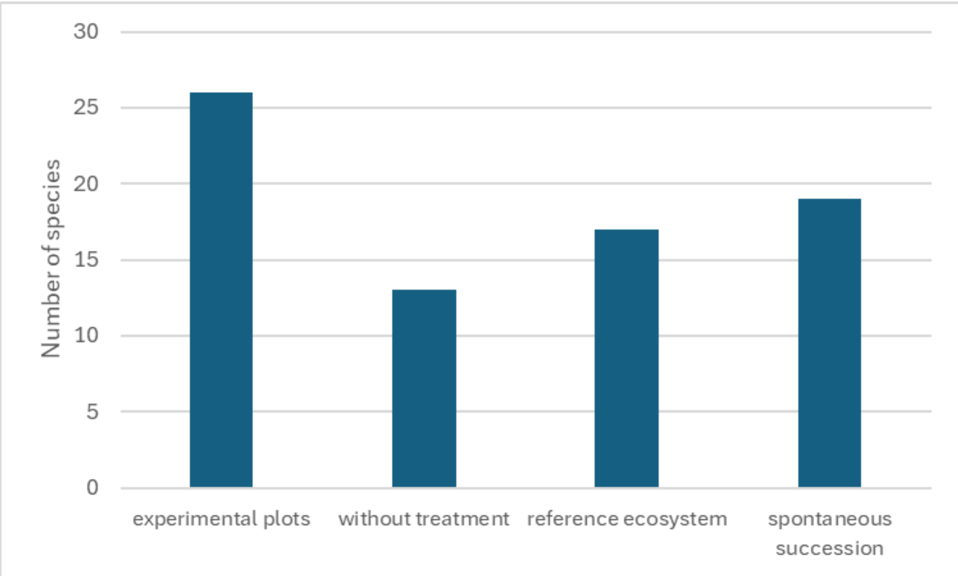

Fig. 16. Number of plant species in individual study areas.

The reference ecosystem was characterized by the highest vegetation cover. Due to full coverage of the area and overlapping cover of individual species, total plant cover exceeds 100%. The ecosystem undergoing spontaneous succession showed average total plant coverage at the level of 38%. 4 months after application, average total plant coverage on the experimental plot reached 20% and was about 5 times higher than in the case of surface area without treatment (4%). The contribution of invasive species was highest in the spontaneous succession study plot (about 9%). A small contribution of invasive species was recorded both on the experimental plot and on the reference plot.

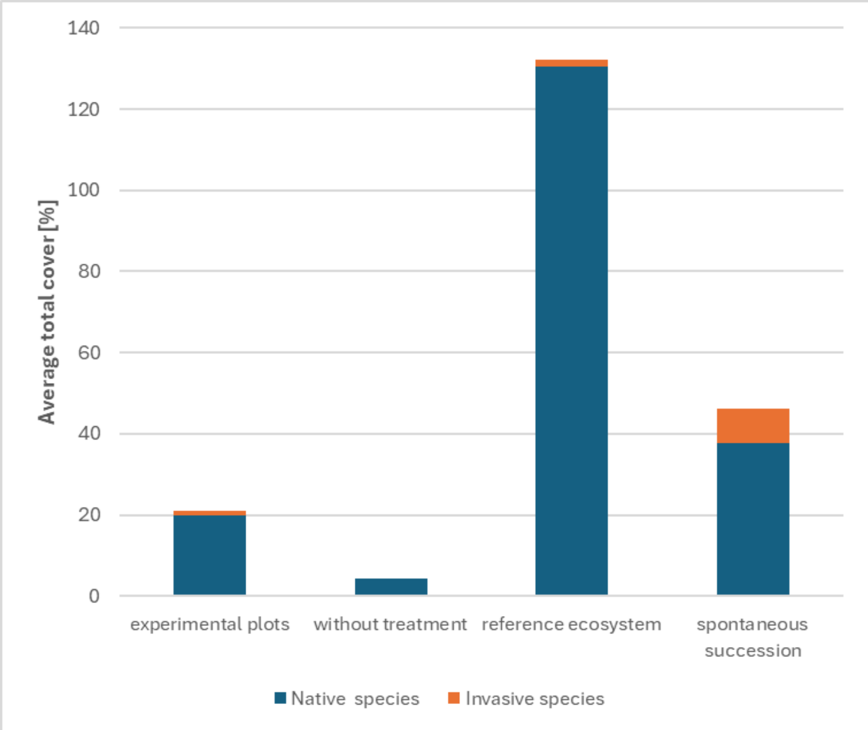

Fig. 17. Contribution of native and invasive species in each study plot.

In the experimental plot, a gradual increase in vegetation cover is observed on all sub-plots. This indicates the resilience of developing vegetation to difficult habitat conditions, including periods without rain and heat waves.

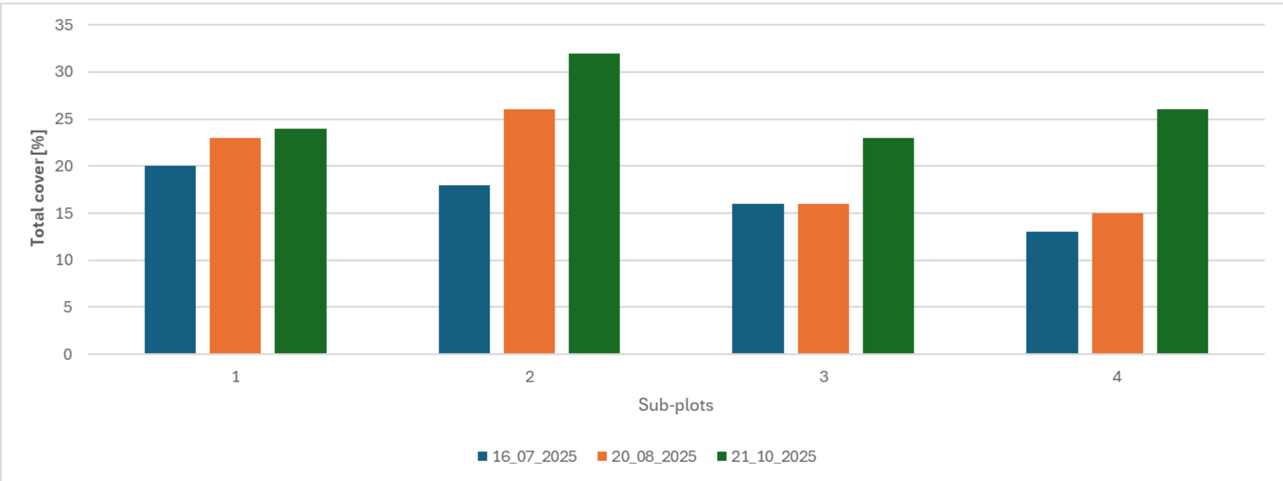

Fig. 18. Changes in plant cover within the experimental plot.

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Fig. 19. Vegetation within the experimental plot (Photo: Ł. Pierzchała, August 22, 2025)..

To determine the impact of experimental treatments on soil parameters, soil samples were collected from each study-plots in the middle of the growing season (22.07.2025) (Fig. 20).

Fig. 20. Soil sampling from research areas.

Preliminary results of soil physicochemical parameter analyses showed:

- The substrate within waste rock dumps is characterized by a slightly higher pH value than the native soil (slightly alkaline reaction).
- Within the same waste rock heap (Janina-Północ), the substrate may show differences in total nitrogen and phosphorus content.
- The total nitrogen and phosphorus content does not reflect the availability of these elements to vegetation.
- Determination of available phosphorus, the Olsen method allows for the assessment of the effectiveness of rehabilitation measures.
- The available phosphorus on the experimental plot showed a lower concentration than in native soils, but significantly higher concentration than in untreated waste rock and spoil heaps undergoing spontaneous succession.

The results of the physicochemical parameters of the substrate/soil are presented in the table below. A detailed analysis of the impact of the effectiveness of the developed reclamation method on the physicochemical parameters and biological indicators of soil quality will be presented in D5.3 related to long- and short-term monitoring.

Table 6 Results of physicochemical parameters of the substrate/soil within the study plots.

Study-plot	pH	Total N (mg/kg)	Total P (mg/kg)	P2O5 Olsen (mg/kg)
experimental plots	7,9	**5215**	**570**	**56,3**
without treatment	8,1	**6461**	**500**	13,3
reference ecosystem	**7,1**	4082	**1920**	**306,3**
spontaneous succession	7,9	3209	440	17,0

The comparison of satellite data was also carried out with in situ measurements and observations. The comparison was based on the analysis of NDVI index values recorded between March and September. NDVI calculations were performed using Sentinel-2 satellite mission data for the following acquisition dates: 2025-03-07, 2025-03-17, 2025-03-22, 2025-04-16, 2025-04-26, 2025-05-01, 2025-05-21, 2025-05-31, 2025-06-05, 2025-06-15, 2025-06-30, 2025-07-15, 2025-07-15, 2025-07-30, 2025-08-06, 2025-08-14, 2025-08-26, 2025-09-05, 2025-09-28. For each image, the mean positive NDVI value was determined for the two plots located on the Północ waste heap, as well as for comparative objects—the reference study plot and a section of the Sośnica waste heap characterized by spontaneous vegetation succession.

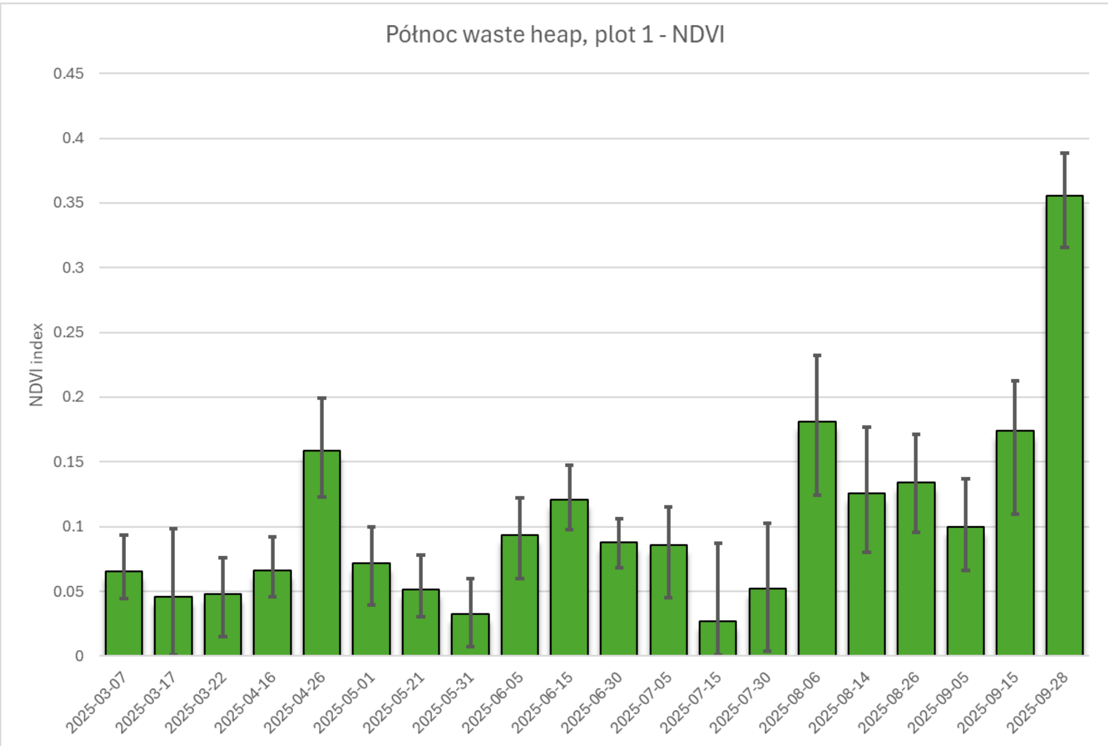

Fig. 21. NDVI results – Północ waste heap, plot 1.

For plot 1 located in the Północ waste heap, mean NDVI values ranged from 0.02 to 0.35. From March to July, the mean NDVI value amounted to 0.07, whereas in August and September, a distinct increase was observed, reaching an average value of 0.18 (mean for August and September).

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

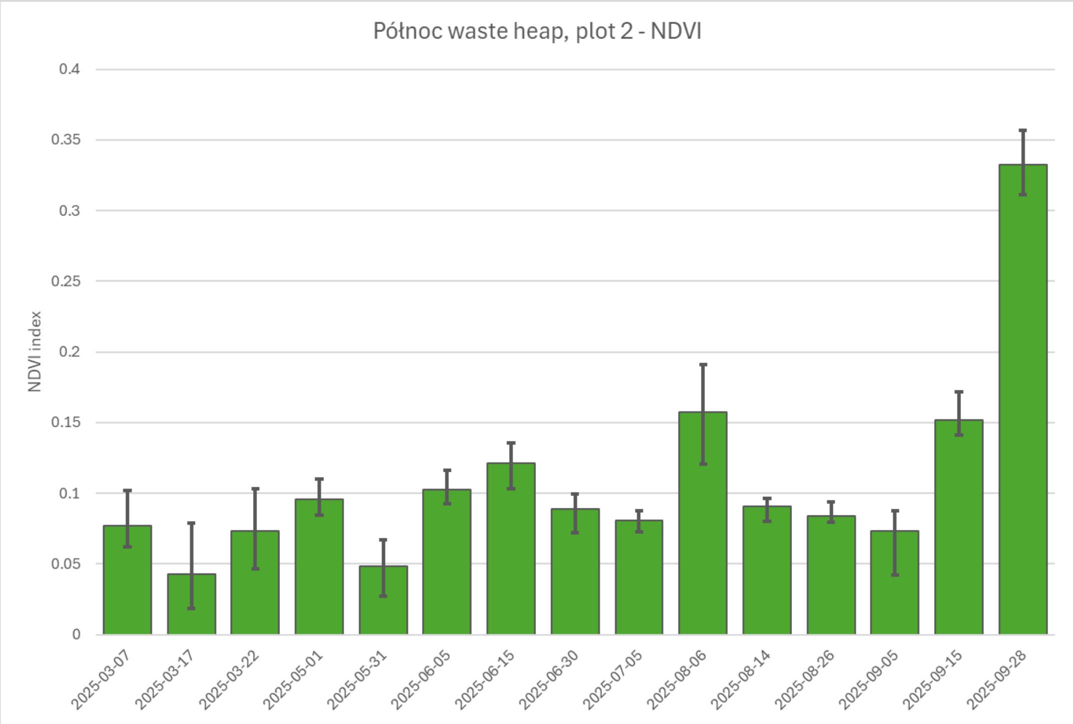

Fig. 22. NDVI results – Północ waste heap, plot 2.

In the case of plot 2 located in the Północ waste heap, mean NDVI values ranged from 0.04 to 0.33, also showing an upward trend. Between March and July, the mean NDVI value equaled 0.08, while in August and September it reached 0.15, indicating an increase of 0.07.

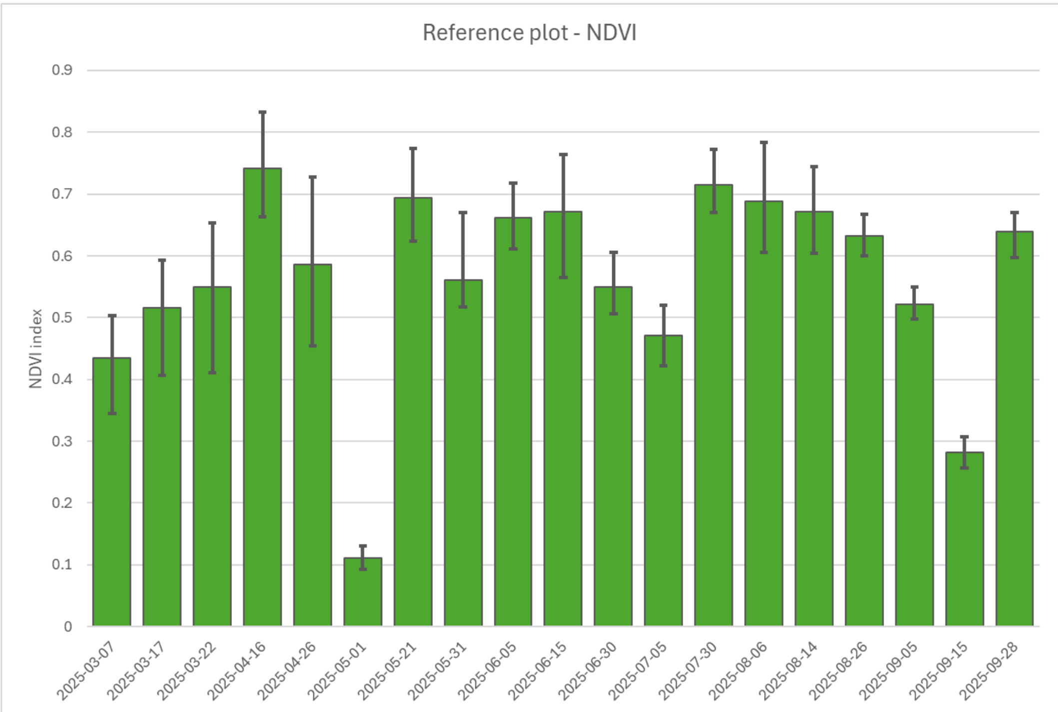

Fig. 23. NDVI results – Reference plot.

The NDVI values for the reference plot varied from 0.11 to 0.74, with a mean of 0.56. In this case, no increase in NDVI values was observed in August and September.

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

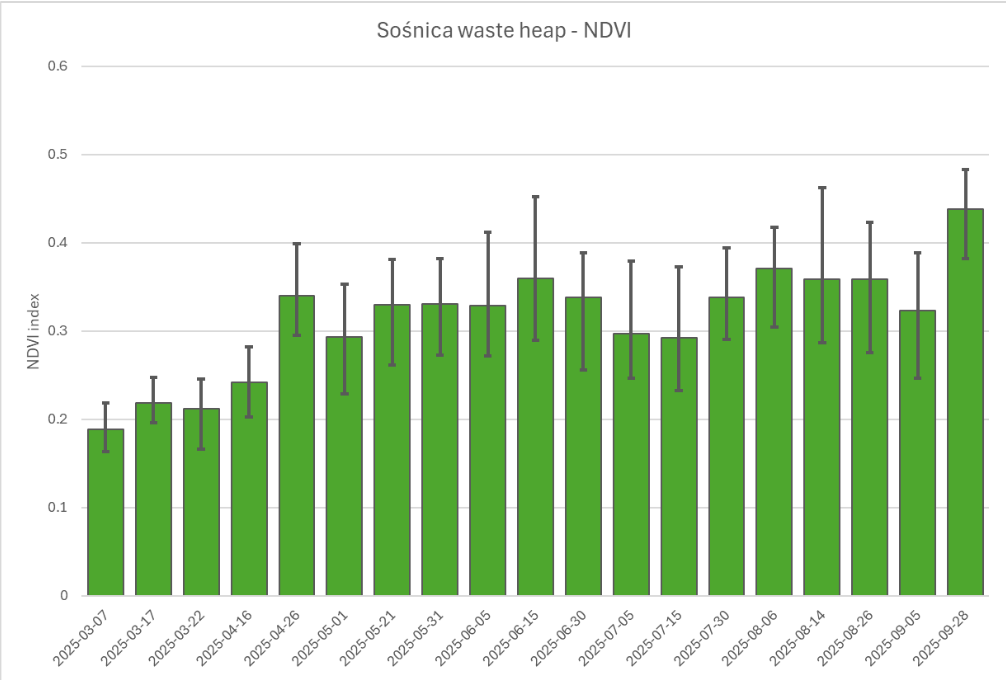

Fig. 24. NDVI results – Sośnica waste heap.

For the section of the Sośnica waste heap undergoing natural plant succession, NDVI values ranged from 0.19 to 0.44 and exhibited a gradual increase throughout the entire analyzed period. August and September were characterized by slightly higher values. Between March and July, the mean NDVI was 0.29, and in August and September it increased to an average of 0.36, corresponding to a change of +0.07. The magnitude of this increase was equivalent to that observed for the plot 1 plot 1 in the Północ waste heap and lower than that recorded for plot 2.

A comparative analysis was also carried out between mean NDVI values derived from satellite imagery and measurements obtained using an unmanned aerial vehicle (UAV) equipped with a multispectral camera. Only measurements conducted within six days of the satellite overpass were included.

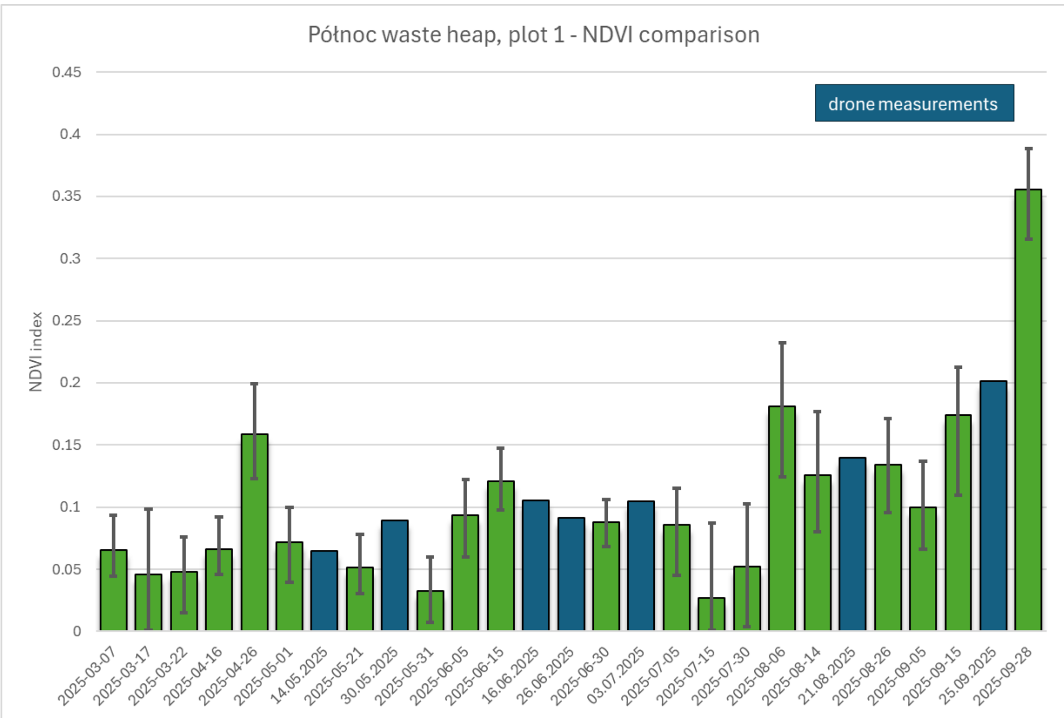

Fig. 25. NDVI results – comparison between drone and satellite data.

The results indicate a high degree of consistency between NDVI values obtained from UAV data and those derived from satellite imagery. Despite the high spatial variability of NDVI values in UAV data—attributed to its higher spatial resolution (10 cm per pixel)—the mean values calculated for the plot 1 plot 1 in the Północ waste heap were only slightly different from those obtained from Sentinel-2 data. This confirms that both methods are suitable for effective environmental monitoring applications.

12. Assessment of the possibility of applying the method in other mining areas

The possibility of supporting plant growth through the application of soil improvers based on sewage sludge and coal mining by-products has been preliminarily tested on degraded soils from other case study areas. INERIS, VUHU, PV, and PPC provided soil samples from selected degraded areas for laboratory testing. A description of the degraded areas selected for testing can be found in the table below.

Table 7 List of degraded soils for laboratory testing.

Partner	Samples number	Type of degradation	Description
INERIS	1	Contaminated area covered by wildflower meadow vegetation (Wildflower meadow plot)	Contaminated parts of the wasteland basins - Area of wildflower meadow dominated by a grass species *Arrhenatherum elatius* (False oat grass)(Giant hogweed is absent).
INERIS	2	Contaminated area covered by invasive vegetation (Giant hogweed plot)	Contaminated parts of the wasteland basins - area covered by alien species.
VUHU	5	Spontaneous succession on phytotoxic area	Practically phytotoxic succession area. The soil here is strongly contaminated with coal slime and coal matter. Therefore, the analysis showed practically no acceptable nitrogen and very low phosphorus content. The organic matter content is high, about 5%; however, it is likely not oxidizable carbon Cox, but coal matter.
PV	1	Biomass plantation	The farming area is subject to subsidence due to underground mining. Now covered with grass and planted with quick-growing willows for biomass production.
PV	2	Area without topsoil	A deforested hilly area with the topsoil removed (stripped), currently with very little or no vegetation on the surface
PV	3	Reclamated area covered by grassy vegetation	Former industrial area for mine infrastructure, later used as a settling pond for byproducts of Šoštanj thermal power plant. Now covered with grass vegetation.
PPC	4	Dumping area cover by native vegetation without topsoil (truffle)	Dumping area of the Ptolemais mine - reclaimed area - virgin inclined soil, type of native vegetation, without topsoil, where truffles have been planted by grafting on oak
PPC	6	Dumping area covered by aromatic plants	Dumping area of the Amyntaion mine aromatic plants - oregano
PPC	8	Non-reclaimed dumping area	Dumping area of the Amyntaion mine - not yet to be cultivated

The effectiveness of the developed soil improver was assessed based on stimulating plant growth (*Sinapis alba*) through soil additive aplication. Test duration was 14 days. The tests were carried out in a phytotron in controlled conditions. Plants were watered every 2 days, and a constant temperature was kept (22 Celsius degrees). The fertilizer dose was determined by weight share (%) in relation to the weight of soil placed in the pot. The length of the stems, the coverage with vegetation, and biomass of above-ground parts were determined.

Fig. 26. Laboratory tests of Synapsis alba growth stimulation.

In the case of degraded soils provided by INNERIS the results on *Sinapis alba* growth test showed:

- A slight negative impact of soil contamination on the growth conditions of indicator plant species (soil without treatment),
- Slightly lower the plant coverage and plant biomass on soil occupied by Giant hogweed than soil covered by meadow vegetation,
- That the application of the soil additive improved growing conditions on both soils, except for the 5% dose on the soil occupied by Giant hogweed.

Preliminary results indicate that to improve the conditions for the growth of desirable vegetation on the contaminated soils, it is recommended to use soil improvers. However, the dosage and probably also the composition of the improver must be selected according to the specific factors causing soil degradation.

The results of *Sinapis alba* growth test on phytotoxic soil, where vegetation develops through spontaneous succession (VUHU study case), indicated:

- high inhibition of plant growth,
- improvement in growth conditions after applying both doses of soil fertilizer, with the lower dose showing better results.

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

The results obtained indicate that in the case study, it is possible to use soil additives to improve vegetation growth conditions and accelerate natural succession processes.

In the case of soils provided by PV the results on *Sinapis alba* growth test showed:

- Very good plant growing conditions on soils within energy crop plantations,
- Deterioration of plant growth conditions within energy crop plantations, as a result of soil additive application- no need to fertilize the soil,
- Significant reduction in plant growth conditions on areas without topsoil,
- Positive effect of low doses of soil additive application on plant growth conditions in areas without topsoil,
- Good growing conditions on soils covered by grassy vegetation (reclamated area),
- Positive effect of low and higher doses of the soil improver on the plant growth on reclamated area covered by grassy vegetation.

The results indicate the high potential of soil additives in the reclamation of areas without topsoil and in improving the condition of vegetation in already reclaimed areas covered with grass vegetation. On soils without plant cover, fertilizer doses cannot be too high. This is probably due to the lack of sufficient microorganisms in the soil capable of decomposing organic substances. Excess organic matter can also negatively affect plant growth conditions.
Probably due to the earlier use of high fertilization, further enrichment of energy crops with nutrients is not currently recommended. Due to the high demand of energy crops for biogenic substances, this may become necessary in subsequent growing seasons.

The results of *Sinapis alba* growth test on soil samples from the dumping area of coal mines in Greece showed:

- Very good plant growing conditions on soils within the area covered by aromatic plants,
- Deterioration of plant growth conditions within the area covered by aromatic plants, as a result of soil additive application- no need to fertilize the soil,
- Impaired plant growth conditions within uncultivated parts of the dumping area,
- A slight positive effect of a higher dose of soil additive application on plant growth in the case of the Ptolemais dumping area covered by native vegetation without topsoil,
- Negative impact of soil additive application on plant growth conditions within the Amyntaion mine non-reclaimed dumping area.

The results obtained confirm the correctness of the reclamation carried out within the area covered by aromatic crops. At present, further improvement in vegetation growth is not necessary here. In the case of areas that have not been reclaimed, the use of soil conditioners to improve vegetation growth conditions requires further detailed research (adjusting the composition and dosage of soil improver to the factors causing soil degradation). The possibility of supporting plant growth has been observed in the case of dumping area covered by native vegetation without topsoil.

Detailed test results using *Synapis alba* are summarized in the table below.

Table 8 Result of laboratory test results of Synapsis alba growth stimulation.

Partner	Sample point	Dose of soil improver	Plant coverage (%)	Mean steam lenght (*cm)*	Biomass of above-ground parts (g)	Effect of soil improver
INERIS	1	0%	80	10,1	4,3	control
INERIS	1	2%	100	15,9	5,2	positive
INERIS	1	5%	100	16,1	4,7	positive
INERIS	2	0%	70	12,2	3,6	control
INERIS	2	2%	100	16,8	5,2	positive
INERIS	2	5%	60	12	2,9	negative
VUHU	5	0%	5	0,6	0,5	control
VUHU	5	2%	50	5,9	1,9	positive
VUHU	5	5%	30	5,8	1,5	positive
PV	1	0%	90	12,2	3,6	control
PV	1	2%	50	7,6	2,0	negative
PV	1	5%	20	2,1	1,0	negative
PV	2	0%	15	3,6	3,4	control
PV	2	2%	25	7,0	4,4	positive
PV	2	5%	25	3	4,1	positive
PV	3	0%	75	11,2	4,6	control
PV	3	2%	75	11,5	3,8	neutral
PV	3	5%	90	12,9	5,1	positive
PPC	4	0%	60	15,5	5,7	control
PPC	4	2%	60	16,2	5,7	positive
PPC	4	5%	75	14,5	6,4	positive
PPC	6	0%	100	10,5	4,0	control
PPC	6	2%	50	6,7	2,9	negative
PPC	6	5%	20	2,9	2,8	negative
PPC	8	0%	60	8,3	3,7	control
PPC	8	2%	45	8,7	4,5	negative
PPC	8	5%	40	10,6	4,7	negative

Research Fund for Coal & Steel

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

13. CONCLUSIONS AND RECOMMENDATIONS

In the case of waste rock from hard coal mining, the main cause of unfavorable conditions for plant growth is a shortage of available phosphorus. The percentage of this element in waste rock does not determine the ability of plants to uptake this element. Similarly, high organic matter content does not have a positive effect on the availability of biogenic substances. It is related to the content of hard coal that does not undergo decomposition. The composition of glanumromeric waste has a negative impact on water retention capacity, which, combined with the dark color of the rock waste, causes the surface of the landfill to dry out quickly on hot sunny days.

The use of soil additives based on sewage sludge, a by-product of coal mining and combustion, allows both the supply of available forms of nutrients to plants and the improvement of the substrate's ability to store water. Exposing the surface of the spoil heap to a lack of water requires special attention when selecting plant species. These must be species with low requirements in terms of water conditions and availability of nutrients. The dose of soil improver should provide the amount necessary for plant growth, but should not lead to excessive fertility of the habitat. This could lead to accelerated succession of woody vegetation and cause the risk of invasive vegetation encroachment. These are negative processes, particularly in the context of the future redevelopment of post-mining areas. Appropriate selection of low vegetation species and introduction of sowing immediately just after completion of the waste heap formation, allows for limiting the risk of unwanted plant species encroaching. Due to the lower amount of rainfall in the spring months, the fall season is a more favorable time for sowing. The timing of the application should be adjusted to local climatic conditions. In the case analyzed, due to the observed decrease in rainfall in the spring months, the fall season is a more favorable sowing time. Autumn sowing allows plants to develop roots better and reduces the risk of dying during heat waves and droughts in the summer. To better root the vegetation after sowing, it is necessary to rake it.

Preliminary assessment of rehabilitation method application on experimental plots indicates the correctness of the assumptions based on laboratory tests. The experimental plots achieved significantly greater vegetation coverage than the area without experimental treatment. The positive effect of the soil improver applied on the available phosphorus content is maintained for up to several months after its application. The vegetation within the research plot showed an increase in coverage throughout the growing season. No vegetation cover decline was observed during periods of heat and drought. An increase in vegetation cover is expected in the next growing season. The analysis of the NDVI index results indicates that it is possible to monitor plant growth based on remote sensing. The observed increase in NDVI is lower than might be expected from the field observations of vegetation cover. However, NDVI values are influenced by many factors, including meteorological conditions and the averaging effect caused by the large pixel size of satellite images. It can be expected that as vegetation cover within the plots increases, a stronger correlation between vegetation cover and NDVI values will be observed. In the next monitoring season, the analysis should include the largest possible number of satellite data and, if possible, synchronize drone measurements with satellite overpasses. The assessment of the applicability to other types of degraded land showed a wide range of applications for the proposed approach to improving plant growth conditions on post-mining areas. However, the dosage and probably also the composition of the soil improver must be selected according to the specific factors causing soil degradation. Due to the innovative approach and positive results obtained, the method of reclamation of coal waste rock heaps using the developed soil improver and a mixture of low pioneer vegetation seeds has been submitted for intellectual property protection (patent application).

Research Fund for Coal & Steel
Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

REFERENCES:

Bakr, J., Kompała-Bąba, A., Bierza, W., Chmura, D., Hutniczak, A., Błońska, A., ... & Woźniak, G. (2024). Taxonomic and functional diversity along successional stages on post-coalmine spoil heaps. *Frontiers in Environmental Science*, *12*, 1412631.

Hazelton, P.; Murphy, B. Interpreting Soil Test Results. In What Do all the Numbers Mean; CSIRO Publishing: Victoria, Australia, 2007.

https://www.carbonbrief.org

Kompała-Bąba, A., Bierza, W., Błońska, A., Sierka, E., Magurno, F., Chmura, D., ... & Woźniak, G. (2019). Vegetation diversity on coal mine spoil heaps–how important is the texture of the soil substrate?. *Biologia*, *74*(4), 419-436.

Liebenberg, A., van der Nest, J. R., Hardie, A. G., Labuschagne, J., & Swanepoel, P. A. (2020). *Extent of soil acidity in no-tillage systems in the western Cape province of South Africa. Land, 9 (10), 361*.

Miller, R.., Donahue, R., 1995. Soils in our Environment: An Introduction to Soils and Plant Growth. 7th Revised edition. Prentice-Hall.

Regulation (eu) 2019/1009 of the European Parliament and of the council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (for organic soil improver).

Regulation of the Minister of Environment on the manner of conducting assessment of pollution of the ground surface. *J. Laws Repub. Pol.* 2016, 1–86. [In Polish]

Rostański, A., Stawowczyk, E. (2006). Wpływ zabiegów rekultywacyjnych na skład flory spontanicznej zwałowisk po górnictwie węgla kamiennego. *Zeszyty Naukowe. Górnictwo/Politechnika Śląska*, 105-119

Woch, M. W., Radwanska, M., & Stefanowitz, A. M. (2013). Flora of spoil heaps after hard coal mining in Trzebinia (southern Poland): effect of substratum properties. Acta Botanica Croatica, 72(2), 237-256.

Yesmin, R., Hossain, M., Kibria, M. G., Jahiruddin, M., Solaiman, Z. M., Bokhtiar, S. M., ... & Abedin, M. A. (2021). Evaluation of critical limit of sulphur in soils for wheat (Triticum aestivum L.) and mustard (Brassica napus L.). Sustainability, 13(15), 8325.