RFCS RESEARCH PROJECT

Recovery of degraded and transformed ecosystems in coal mining-affected areas

847205-RECOVERY-RFCS-2018

Deliverable 3.2

Artificial substitutes for soils in difficult terrains

European Commission

Research Fund for Coal & Steel

Authors

Ph.D Arkadiusz Bauerek, GIG Research Institute (Poland)

Ph.D Lukasz Pierzchała GIG Research Institute (Poland)

Msc. Eng. Angelika Więckol-Ryk GIG Research Institute (Poland)

Assoc. Prof. Alicja Krzemień, GIG Research Institute (Poland)

Prof. Jean Diatta, Poznan University of Life Sciences (Poland)

Dr Robert Frączek, Tauron Wydobycie (Poland)

Deliverable 3.2	
Due date of Deliverable	30.09.2022
Start - End Date of Project	01.07.2019 – 30.06.2023
Duration	4 years
Deliverable Lead Partner	GIG
Dissemination level	Public
Work Package	WP 3
Digital File Name	D3.2 Artificial substitutes for soils in difficult terrains
Keywords	Land rehabilitation, coal mining by-products, vegetation assessment, Janina Mine Waste Heap

Disclaimer

Table of contents

List of Figures

List of Tables

1 Executive summary

This Deliverable presents a novel approach to land rehabilitation of mining-affected areas in the case of coal mining waste heaps with intensive eroded slopes and high acidic character. An innovative approach to using industrial by-products and wastes was based on using "non-valuable" materials produced during the extraction and combustion of coal. All the materials were available "at hand" near the waste heap.

Several blends consisting of rock wastes, coal combustion by-products from coal power plants, and organic waste materials, including sewage sludge and spent mushroom compost, were tested as artificial soils for different plant communities. Before selecting appropriate mixtures, a set of waste samplings were collected, and laboratory tests were performed. Only three investigated wastes could be considered rich in organic matter. Organic matter is a critical parameter that decides soil substitutes' environmental and biological sustainability. The content of calcium and sulphur in the wastes and their further occurrence in the ready-to-use soil substitutes was of prime importance for the remediation of waste heaps, where the latter and its compounds cause excessive acidity, contrary to calcium, the addition of which significantly increases the pH value. Also, other important parameters of water leachates from by-products, organic materials and wastes used for composing soil substitute blends were tested. Finally, two germination and vegetation tests were performed using Sinapis alba and meadow plant communities. All the analysis and tests in laboratory conditions allowed the selection of the best three types of soil substitutes for dry meadow vegetation, mesic meadow vegetation, and wet and humid habitats.

In the next step, a concept of building a test polygon covering a fragment of the Janina Mine waste heap in Libiąż (4,000 m^2) with components was developed. The testing ground was geodetically divided into two sections, each measuring 40 m x 50 m. Subsequently, protection layers with a total thickness of 0.8 m were laid, following two approaches, i.e. two-layer cover and multi-layer cover. Later, three mixtures of soil substitutes were spread as strips of 16.5 m. Finally, the plantation of shrubs (approx. 400 seedlings), wetland vegetation (approx. 1,000 seedlings of Phragmites australis), and sowing of approx. 3 kg of the dry and mesic meadow vegetation seeds was carried out. In this Deliverable also, costs of reclamation can be found. In the last step, a species diversity assessment was undertaken. In-situ growth of some species after two years of vegetation showed outstanding development. At the same time, other plan communities have not adapted to artificial soil conditions (no successful planting in the second year).

The study has initiated the preliminary "ecosystem-services" concept by exhibiting the eco-friendly and suitability of elaborated soil substitutes for semi-natural meadow communities. It showed up-and-coming opportunities to use artificial soil substitutes to rehabilitate spoil tips addressing high acidic waste.

2 Introduction

Within Work Package 3, Task 3.2 assess a novel approach to land rehabilitation of coal mine waste heaps. For this purpose, the use of industrial by-products generated in coal mines and coal-fired power plants as the components for preparing artificial soils was investigated at a laboratory scale. Soil substitutes were tested for physicochemical parameters, and several of them were selected for the reclamation of the experimental land field of Janina Mine waste heap in Libiąż, property of Tauron Wydobycie S.A.

The primary purpose of artificial soils was to neutralise the high acidity of the waste rock stored in the Janina Mine waste heap and transform it into an eco-friendly status.

The specific objectives of Task 3.2 were:

a) The conversion of industrial by-products from local power plants and coal mining wastes with an amendment of industrial organic waste into usable soil substitutes for environmental reclamation of mining-affected areas.
b) Prepare a protective soil cover for the test polygon against acidification and contamination from stored mine wastes.
c) Introduction of four plants (meadow, xerophyte, bush and wetland wet terrains communities) proper for different conditions occurring on spoil tip and matching the local plant communities.
d) Observation of plant vegetation's natural processes and monitoring changes in physicochemical parameters of the soil substitutes and run-off water characteristics.

The results from this task will be considered for formulating alternative actions for land rehabilitation and ecological restoration in mining-affected areas in the case of 'difficult terrains'.

3 Characteristic of waste rock from Janina Mine waste heap AMD waters

The post-exploitation land, Janina Mine waste heap, is one of the biggest dumping sites of this kind, located in the Silesia Coal Basin in Poland (Figure 1). The waste heap contains almost 10 million tons of waste poor in carbonates and chemically unstable. It covers an area of 75 hectares, reaches 35 m in height, and is an excellent "field laboratory" for assessing land rehabilitation techniques.

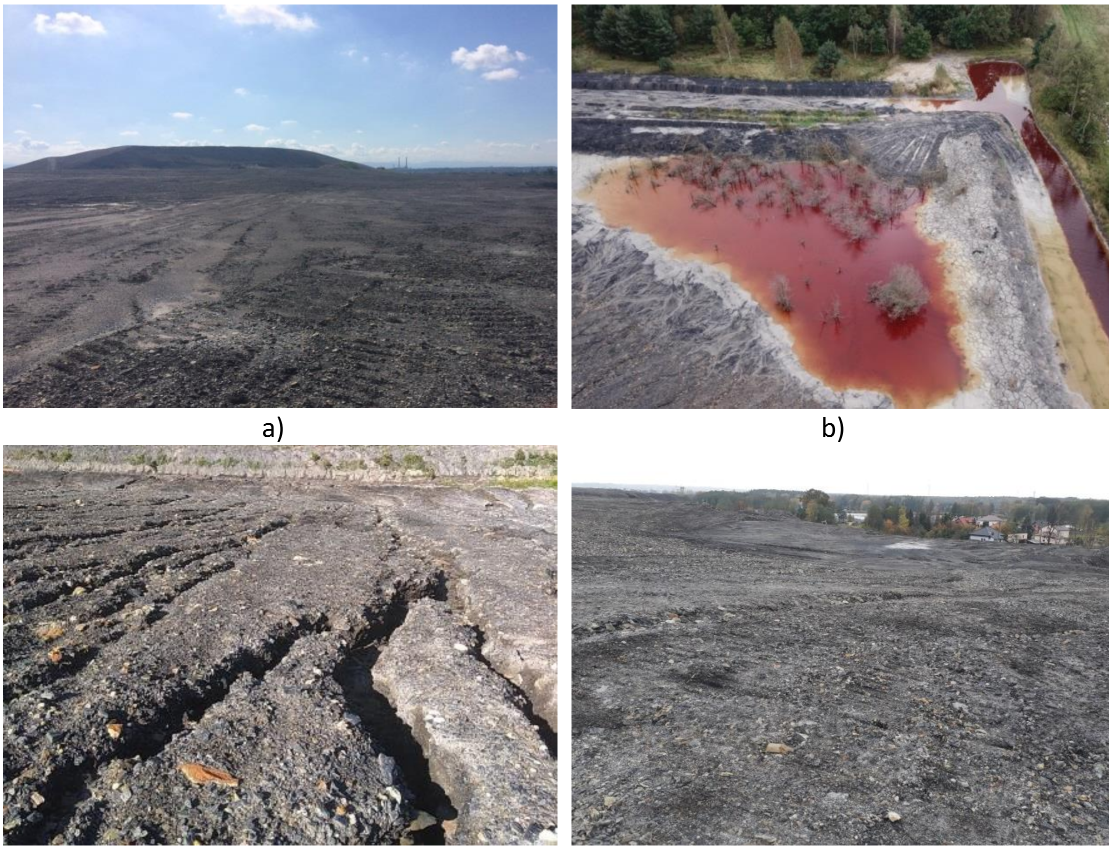
Figure 1 Western slope of Janina Mine Waste Heap

Eroded slopes and the highly acidic character of the terrain are challenging conditions for reclamation. The environmental impact of Janina Waste Heap includes:

- Surface and groundwater pollution–acid rock drainage is observed in the formulation of surface run-off during atmospheric precipitation.
- Air quality deterioration–spreading of suspended dust during dry and windy periods.
- Biodiversity loss - acid property of gangue is inconvenient as habitat for plant and animal = lost of areas with regulation (i.e. local climate regulation, and cultural function (interactions with a living system).
- Acid rock drainage from waste dumps contributes to the deterioration of the condition of surface water.
- Water erosion and waste mass displacements occur on the slopes of the waste heap, which generates costs associated with securing and reinforcing the waste heap.
- Wind erosion contributes to the negative impact which waste dumps have on the adjacent areas (including areas of single-family housing).

- Negative impact on the aesthetic value of the landscape.

The problem of pollution in a waste heap is caused by acid mine drainage (AMD) (US Environmental Protection Agency, 1994) responsible for the deterioration of surface and groundwater, soil and biodiversity in mining areas (Figure 2). AMD processes manifest in highly acidic run-off water (pH differs from 2,1 to 3,5) contaminated by metals: Al, As, Cd, Co, Fe, Mn, Ni and Zn (Gitari et al., 2008).



a) b) c) d)

Figure 2 Environmental impact of Janina Waste Heap: a) study area in Janina mine waste heap; b) acid mine drainage; c) slopes of the waste heap caused by water erosion

The concentrations of heavy metals and total sulphur of investigated waste rock from the Janina Mine waste heap were presented in Table 1.

Table 1 Total content of indicated elements from the Janina Mine waste rock (Klojzy-Karczmarczyk et al., 2016)

Parameter	Value ($mg \cdot kg^{-1}$)	
	aggregate 30-200 mm	aggregate 0-30 mm
S	162.8	6014.4
As	1.8	11.7
Cd	0.025	0.045
Co	14.3	20.60
Cr	60.0	1171.2
Cu	23.8	52.3
Hg	<0.01	0.01
Mo	<0.07	<0.03
Ni	79.6	91.9
Pb	17.1	49.3
Zn	37.6	48.1

The mining waste from the surface layer is a mixture of mineral crumbs (claystone, sandstone, quartz pebbles) of different fractions with black coal crumbs. Pyrite grains in various stages of weathering are abundant. The clay minerals, which total between 20% and 36%, and the amorphous substance (mainly carbon), with content of between 21.1 and 24%, determine the susceptibility to weathering processes of waste deposited under hypergenic conditions. From an environmental point of view, the most crucial factor is the presence of weathering-prone pyrite, whose proportion in the waste ranges from 1 to 2% and lacks carbonate minerals (Bauerek et al., 2017).

The surface run-off waters near the Janina mine spoil heap belong to acidic waters (pH 2.1 to 3.5). The hydrochemical character of the studied waters, presented in the rhombus diagram of Piper (Figure 3), indicates that they are of the sodium chloride-sulphate ($Cl\text{-}SO_4\text{-}Na$) or sodium sulphate-chloride ($SO_4\text{-}Cl\text{-}Na$) type (Figure 3). Analysis of the concentrations of the main components and parameters allows the separation of two different groups in the data population (Bauerek et al., 2017). The first includes waters with dissolved matter concentrations and specific conductivities averaging 4400 mg·l^{-1}and 5537 µS·cm^{-1}, identified as short retention (SR) surface run-off waters. The second group consists of stagnant (S) surface run-off waters, with almost three times higher mineralisation (average 12,688 mg·l^{-1}) and 2.5 times higher specific conductivity (average 13,963 µS·cm^{-1}).

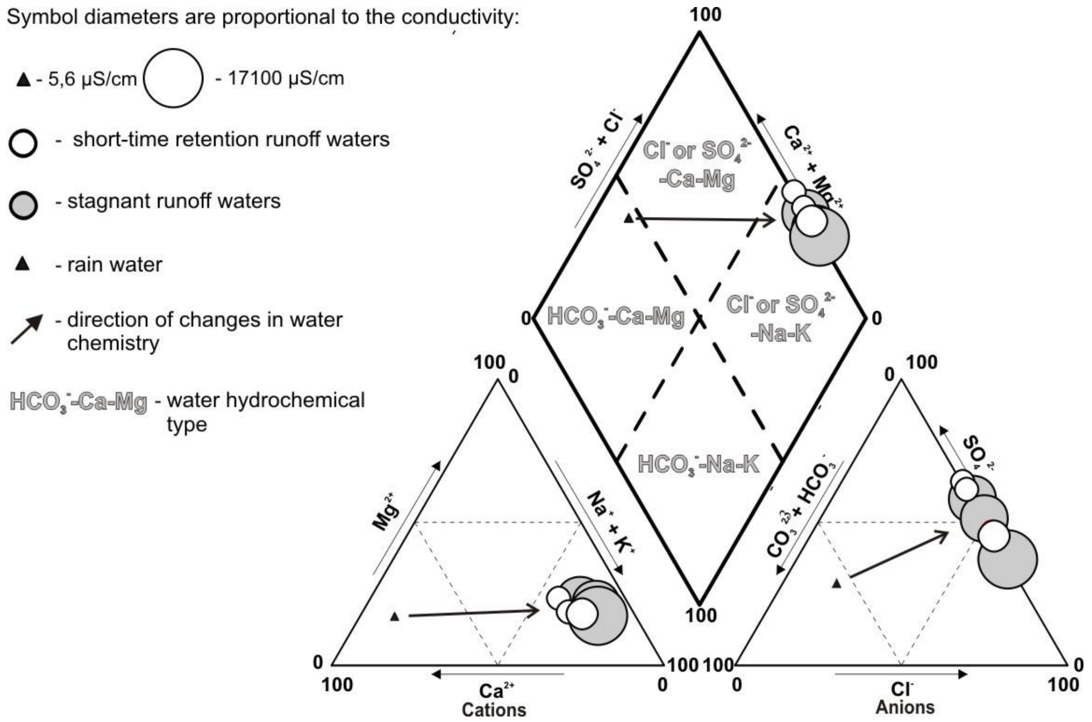


Figure 3 Chemical composition of analysed rainwater and run-off waters (Bauerek et al., 2017)

For short-retention waters, the pH range is from 2.6 to 3.5 (average 2.9), and for stagnant waters, from 2.1 to 2.8 (average 2.4). However, the characteristic parameter differentiating the groups mentioned above of surface run-off waters is acidity. On average, the total acidity in stagnant waters (1,200 to 3,050 mg·l-1 CaCO3) is four times higher than that of short-retention waters (109 to 890 mg·l^{-1} $CaCO_3$).

On average, stagnant waters have 2.6 times more SO_4^{2-} (3500-5800 mg·l^{-1}), 3.2 times more Cl^- (2300-5400 mg·l^{-1}) and 2.7 times more Na^+ (1500-3730 mg·l-1) than short-retention waters.

4 Methodology of waste sampling and lab-testing

4.1 Mine waste sampling

The team of the Environmental Monitoring Department from GIG collected samples of mining waste from the heap of the Janina mine. Twenty-five samples were taken from where the testing ground will be established. Five boreholes were made and five samples were collected from each, in the following intervals 0-0,2 m; 0,2-0,4 m; 0,4-0,6 m; 0,6-0,8 m; 0,8-1,0 m. Waste samples have been tested for pH assessment because the waste will come into contact with artificial soils and plant roots.

Sample collecting was conducted using a MAKITA electric hammer with a set of cylindrical knock-in samplers Eijkelkamp (Figures 4 and 5).

Figure 4 Point of mine waste sampling on Janina Mine

Figure 5 Mine waste profile from Janina Mine spoil heap

4.2 Testing of mine wastes, industrial by-products, organic materials and soil substitutes

The wastes and soil substitutes were assayed for pH and electrical conductivity (EC) in aqueous solutions at the ratio of 1:2.5 (w/v). Photometric and conductometric methods measured pH and electrical conductivity (EC).

The content of dry matter (DM) in wastes and soil substitutes was determined by the gravimetric method by drying samples to a constant weight at 105°C. The amount of organic matter (OM) in the samples was determined by measuring the loss-on-ignition of dry matter at 550°C. Total ash was assessed by incinerating the respective samples at 815°C and weighting the post-combustion residues.

The content of calcium (Ca), potassium (K), magnesium (Mg), phosphorus (P) and sodium (Na) was assayed employing the X-ray fluorescence method with wavelength dispersion WDXRF (Rigaku ZSX Primus, Inc., Wilmington, USA). The content of trace metals, i.e. cadmium (Cd), chromium (Cr), cuprum (Cu), nickel (Ni), lead (Pb), and zinc (Zn), were determined by inductively coupled plasma atomic emission spectroscopy method (ICP-OES) after sample digestion in *aqua regia* (Perkin Elmer Optima 5300, Perkin Elmer Inc., Waltham, MA. USA). The total content of sulphur (S) was determined with infrared spectroscopy (IR) using an ELTRA CHS instrument by Eltra GmbH, Haan, Germany, whereas the nitrogen content by the Kjeldahl method.

All physical and chemical analyses were conducted in an accredited Laboratory of Solid Wastes Analysis and Laboratory of Water and Wastewater Analysis (GIG Research Institute, Katowice, Poland).

4.3 Leachates and waters - sampling and testing methods

Measurements of pH and electrical conductivity (EC) of unfiltered groundwater were performed with the integrated meter WTW MultiLine P4 in the field (Figure 6). Then the water samples were filtered through a 0.45 µm filter and collected into polyethylene bottles.

Figure 6 Sampling of groundwater from testing-ground

Laboratory tests of groundwaters and eluates from industrial by-products (soil components) and soil substitutes were performed by the accredited Laboratory of Water and Wastewater Analysis which is part of the Department of Environmental Monitoring in Central Mining Institute (Katowice, Poland).

The methods used for testing were as follow:

- potentiometric (pH value);
- conductometric (electrical conductivity);
- ion chromatography (chloride, sulphate, nitrate, phosphate);

- emission spectroscopy - ICP-OES (metals);
- high-temperature combustion with IR detection (TOC, total nitrogen);
- flow spectrophotometric (FIA - flow injection analysis) (ammonia);

The water extracts from by-products were tested to determine the potential release of contaminants from reactive materials into the aquatic environment. Leachates were obtained based on 24-hour static tests, and the chemical composition of the leachates was determined using the same methods as for the water samples.

4.4 Statistical analyses of data

The normal distribution of data was confirmed using the Shapiro-Wilk test. The relationship between the *Sinapis alba* germination and physical-chemical parameters of soil substitutes was analysed using Pearson's linear correlation coefficient with Statistica 13.0 (StatSoft, Poland). Principal Component Analysis (PCA) was applied to determine conditions that influence the development of native meadow vegetation on soil substitutes. The analysis was performed by using the CANOCO package. Variables data were transformed using log(x+1) before the analysis response (Lepš and Šmilauer, 2000).

5 Determination of waste mining pH

The samples collected at the specific depths and borehole sites (see Figure 4) were analysed for pH and electrical conductivity (EC). The data from these tests are reported in Table 2.

Table 2 Electrical conductivity and pH values of mining wastes from the surface layer of Janina Mine spoil heap

Borehole	Depth (m)	EC ($mS \cdot cm^{-1}$)	pH
1	0.0-0.2	7.06±0.72	2.42±0.12
2	0.2-0.4	6.32±1.64	2.52±0.35
3	0.4-0.6	3.49±0.96	2.80±0.56
4	0.6-0.8	6.13±1.77	2.99±0.82
5	0.8-1.0	3.02±0.81	3.09±0.78

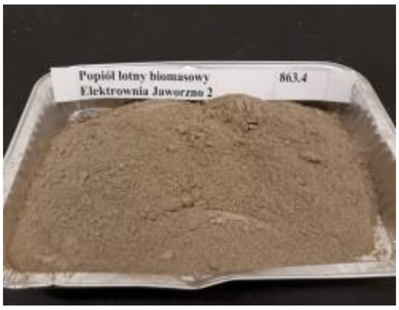
According to Bruce and Rayment (1982), the results were evaluated based on criteria. The pH value of all collected wastes was substantial acidic (average value 2,70) and varied from 2.17 to 4,02. It was also noticed that more acidic wastes are from the surface layer (0,0 – 0,2 m) – pH 2,42, compared to wastes from deeper layers. For example, the average pH value of wastes collected from the deepest layer (0,8 – 1,0 m) was slightly higher – pH 3.09. This phenomenon is due to more effective and intensive pyrite (FeS_2) oxidation in the upper layer of wastes with higher oxygen availability.

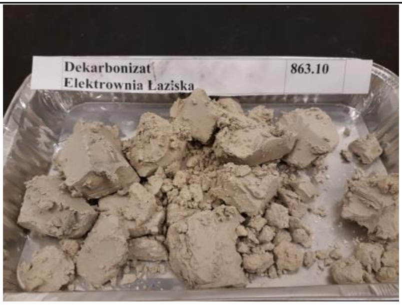
The values of the salinity (expressed by electrical conductivity, EC) varied from 3.02 to 7.06 $mS \cdot cm^{-1}$and may be classified into two groups (Miller and Donahue, 1995):
- slightly saline range (2 – 4 $mS \cdot cm^{-1}$) for the borehole sites 3 and 5, and
- moderately saline range (4 – 8 $mS \cdot cm^{-1}$) for the borehole sites 1, 2 and 4.

6 Selection of soil substitutes

Four coal combustion by-products from industrial power plants located in Upper Silesia in Poland and two by-products from TAURON Wydobycie S.A. coal mines were used in the current investigation. Additionally, two organic waste materials, including sewage sludge and spent mushroom compost, were obtained from a sewage treatment plant in Jaworzno city and a mushroom farm in Kryry. The list of selected materials tested as components for artificial soil preparation is presented in Table 3.

Table 3 Set of wastes and substrates for soil substitutes

No	Wastes and substrates	Description	Symbol	Origin
1		Fly ash (Charcoal combustion)	CFA	Power plant Jaworzno 3
2		Fly ash (Plant biomass combustion)	BFA	Power plant Jaworzno 2
3		Energetic slag	ES	Power plant Łaziska

4		Decarbonisation lime	DL	Power plant Łaziska
5		Aggregate (0-2 mm) clay shale 0.0 – 2.0 mm	AG	ZG Sobieski Mine
6		Sealing material TAURONIT U –	SL	ZG Sobieski Mine
7		Sewage sludge	SWS	Waste water plant Chrzanów
8		Spent mushroom compost	CM	Kryry location

6.1 Physicochemical parameters of waste components

The selected wastes are generated in coal mines, coal-fired power plants, agriculture industries, and residues from wastewater plants differing in chemical composition, consistency and structure. A sum up of selected waste parameters is given in Table 4.

Table 4 Physicochemical characteristics of investigated wastes

Parameter		Wastes*							
		CFA	BFA	DL	AG	SL	SWS	CM	ES
pH	-	12.0	13.1	9.6	7.6	8.0	7.5	7.1	9.8
EC	$mS \cdot cm^{-1}$	3.60	39.4	1.57	0.50	0.90	12.18	7.76	0.35
Dry matter	%	100.0	99.7	50.8	90.1	72.6	16.6	34.7	77.6
Organic matter		3.28	0.52	7.02	15.9	35.6	64.33	60.4	4.38
Total ash		96.7	99.5	93.0	84.1	64.4	35.67	39.5	95.6
Ca		2.27	9.65	32.0	0.43	0.34	4.45	8.22	2.74
N		< 0.15	< 0.15	0.32	0.18	0.40	4.61	2.36	< 0.15
K		2.05	5.53	0.04	2.32	1.69	0.0.37	1.03	2.14
Mg		1.15	2.43	5.44	0.24	0.57	0.74	0.42	1.69
P		0.10	1.07	0.01	0.02	0.03	2.73	0.78	0.11
Na		1.22	0.75	0.01	0.09	0.08	0.10	0.13	0.32
S		0.16	0.98	0.24	3.95	0.63	1.87	1.97	0.32
Cd		1	9	< 1	4	< 1	29	< 1	1
Cr	$mg \cdot kg^{-1}$	88	54	1	22	76	74	7	53
Cu		86	173	3	85	31	269	29	46
Ni		67	28	9	26	33	42	7	47
Pb		94	176	4	213	53	300	2	3
Zn		139	610	36	1281	141	2710	183	22

CFA–fly ash from coal combustion; BFA–fly ash from plant biomass combustion; DL–decarbonisation lime; AG–aggregate; SL–sealing material; ES–energetic slags; SWS–sewage sludge; CM–mushroom compost.

The wide range of data illustrated in Table 4 shows the heterogeneity of the wastes and their chemical composition. Among all investigated wastes, only CFA, BFA, and AG were extremely low in water content (90-100 % of dry matter), with SL and ES containing 72.6% and 77.6% of dry matter, respectively, and DL 50.8%.

Among all investigated wastes, only three, i.e., SL, SMC and SWS, could be considered rich in organic matter, ranging between 35.6 and 74.8%. The AG, with 15.9% organic matter, could be involved as a moderate source, but its physical and mineralogical composition may act as a strongly limiting factor. Organic matter is a critical parameter that decides soil substitutes' environmental and biological sustainability.

The content of calcium and sulphur in the wastes and their further occurrence in the ready-to-use soil substitutes are of prime importance for the remediation of waste heaps, where the latter and its compounds cause excessive acidity, contrary to calcium, the addition of which significantly increases the pH value. The highest calcium content was observed in DL compared to the low range in SL and AG. Three of the eight investigated wastes exhibited sulphur content above 1.8%, i.e., SWS, and SMC, whereas the sulphur content in the remaining wastes did not exceed 1.0 %. The chemical forms of sulphur in those wastes may affect their utility for incorporation in the development of soil substitutes.

Another critical feature expected from the wastes is adequate concentrations of plant nutrition nutrients such as N, P, K and Mg. N is responsible for biomass build-up (Heaton et al., 2004; Lee et al., 2017), P for good development of plant root systems (Shen et al., 2018; Wissuwa et al., 2005), K for internal water management in plants (Grzebisz et al., 2013) and Mg for photosynthesis activity (Guo et al., 2016; Hermans and Verbruggen, 2005). The research proved that only SWS contained much more N (5.1%) than the other wastes, where the low N content varied in the range of 0.15 – 0.4%. It is worth mentioning that natural soil ecosystems are typically poor in nitrogen content, so the developed soil substitutes should comply with this rule. Nevertheless, a slightly enhanced N level may be expected as a „starter" for boosting plant growth at the anthropogenic (artificial) ground.

Regarding P concentrations, only three of the wastes recorded values higher than 1.0%, two typically organic, i.e. SWS and SMC, and one common mineral from biomass combustion, BFA. Moreover, BFA was characterised by the highest K content, and it was also observed that DL contained the highest magnesium concentration.

The patterns of metal distributions among the wastes are similar but disparate depending on the metal types. Higher copper (Cu) content was observed at ashes BFA and CFA and for the sewage sludge SWS. As in the case of copper (Cu), zinc (Zn) was also found from moderately high concentrations for CFA and SMC to very high levels for BFA and AG. Excessive content of Zn was observed only for SWS (1704.0 $mg \cdot kg^{-1}$). The high and extreme Zn contents of these wastes may be a potential source of soil substitutes. According to the Polish regulations, the permissible range of pollutants in organic-mineral fertilisers must not exceed 100 $mg \cdot kg^{-1}$ (DM) for chromium, 5 $mg \cdot kg^{-1}$ (DM) for cadmium, 60 $mg \cdot kg^{-1}$ (DM) for nickel and 140 $mg \cdot kg^{-1}$ (DM) for lead. The excessive concentrations of Cd were observed only for SWS and BFA.

On the other hand, the content of Ni was lower than the Polish limit value only for two of all wastes, such as DL (9 $mg \cdot kg^{-1}$) and SMC (7 $mg \cdot kg^{-1}$). The excessive values for Pb were noticed for BFA, AG and SWS. The concentration of Cr in all studied wastes can be considered at an acceptable level (< 100 $mg \cdot kg^{-1}$).

The parameters of water leachates from materials (by-products, organic materials and wastes) used for composing soil substitute blends are presented in Table 5.

Table 5 Chemical composition of leachates from by-products and organic materials

Parameter		Wastes*							
		CFA	BFA	DL	AG	SL	SWS	CM	ES
pH	-	11.9	12.8	9.70	7.50	7.80	7.50	7.10	9.8
EC	$mS \cdot cm^{-1}$	3.60	39.40	1.57	0.50	0.90	12.20	7.70	0.35
Ca^{2+}	$mg \cdot l^{-1}$	612	540	3.35	25.9	40.5	642	1100	43.4
Mg^{2+}		0.26	<0.12	347	19.2	29.7	251	289	9.03
Na^{+}		184	175	5.52	33.4	101	167	223	12
K^{+}		29.8	11800	1.35	11.9	17.3	228	1870	6.57
NH_4^{+}		21.1	1	0.5	4.5	3.2	1980	239	0.3
NO_3^{-}		0.32	0.86	40	0.3	0.17	<0.5	4.2	0.35
N_{tot}		16.5	0.97	9.42	3.57	2.53	1540	187	0.31
PO_4		0.011	<0.1	<0.01	<0.01	<0.01	77	170	0.13
P_{tot}		<0.03	<0.07	<0.03	<0.010	<0.010	36.5	57.4	0.053
SO_4^{2-}		1010	7460	581	192	250	5030	3200	112
Cl^{-}		20	4720	10	6.6	87	185	394	7.2
Cu		<0.005	<0.01	<0.005	<0.003	<0.005	0.042	0.32	<0.003
Fe_{tot}		0.006	<0.02	0.0047	0.0032	0.02	11.5	10.8	0.0086
Mn		<0.003	<0.003	<0.003	0.14	0.14	1.66	2.77	0.0014
Zn		<0.01	0.029	<0.01	0.015	0.011	0.31	0.79	<0.01
As		<0.03	<0.02	<0.005	<0.005	<0.005	0.14	0.050	<0.01
Cd		<0.001	<0.001	<0.001	<0.0005	<0.001	<0.002	0.0029	<0.0005
Cr		0.69	0.45	<0.003	<0.003	<0.003	0.007	0.019	<0.003
Ni		<0.005	<0.005	<0.005	<0.003	<0.005	0.71	0.082	<0.003
Pb		<0.005	<0.01	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005

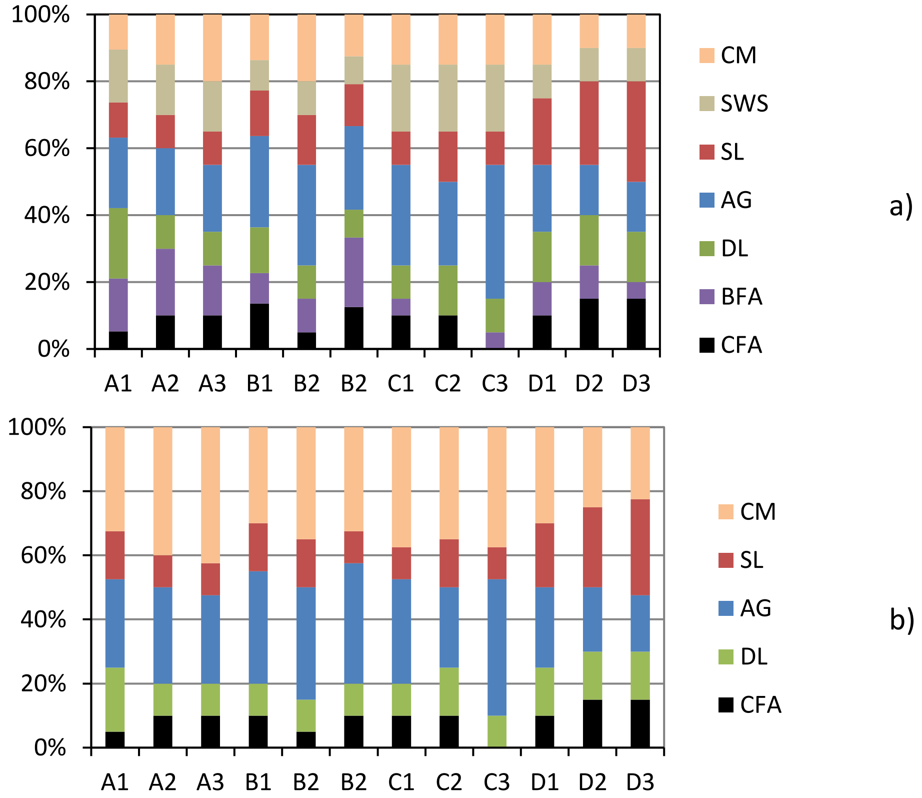
The chemical parameters of aqueous leachates from waste materials varied widely. The analysis showed that the pH of SMC (pH 7.1), SWS (pH 7.5), SL (pH 7.8) and aggregate AG (pH 7.5) was neutral or slightly alkaline in comparison to other industrial wastes (pH range between 9.7 and 12.8). The electrical conductivity (EC) of BFA (39.4 $mS \cdot cm^{-1}$) was significantly higher compared to other mineral wastes, ranging between 0.35 for EC and 3.6 $mS \cdot cm^{-1}$ for CFA, and relatively higher than organic wastes, i.e. 12.2 and 7.7 $mS \cdot cm^{-1}$ for SWS and CM, respectively. The reason for that was very high concentrations of soluble particles and mineral elements in BFAs, such as chlorides (4720 $mg \cdot l^{-1}$) and sulphates (7460 $mg \cdot l^{-1}$). The calcium (Ca2+) content in mineral wastes ranged from 3.35 to 612 $mg \cdot l^{-1}$ and amounted to 642 $mg \cdot l^{-1}$ in SWS and 1110 $mg \cdot l^{-1}$ for CM. The low calcium concentrations in aqueous extracts from DL were due to the presence of Ca^{2+} as insoluble carbonate ($CaCO_3$). However, the magnesium (Mg2+) concentration in DL leachates was very high (347 $mg \cdot l^{-1}$) compared to other samples.

Sodium concentrations ranged from 5.52 $mg \cdot l^{-1}$ (DL) to 223 $mg \cdot l^{-1}$ (CM), whereas potassium from 1.35 $mg \cdot l^{-1}$ (DL) to 1870 $mg \cdot l^{-1}$ (CM). High total phosphorus (Pt) values, i.e. 36.5 mg·l^{-1} and 57.4 mg·l^{-1}, were observed only for organic wastes SWS and CM, respectively. The total nitrogen concentration (N_t) of 1540 mg·l^{-1} for SWS and 187 mg·l^{-1} for CM was also relatively higher than in coal by-products which ranged between 0.97-16.50 mg·l^{-1}.

The concentrations of trace elements such as Fe, Mn, As, and Ni was higher in organic wastes (SWS and CM) compared to industrial by-products. However, the contents of Cr in fly ashes, i.e. 0.69 and 0.45 mg·l^{-1} for CFA and BFA, respectively, were higher than in SWS 0.007 mg·l^{-1} and SMC 0.019 mg·l^{-1}.

6.2 Preparation and characteristics of soil substitutes

Soil substitutes A1-D3 (n=36) differed in waste type and percentage share (Figure 7). The experiments were run at three operational stages: I, II and III.



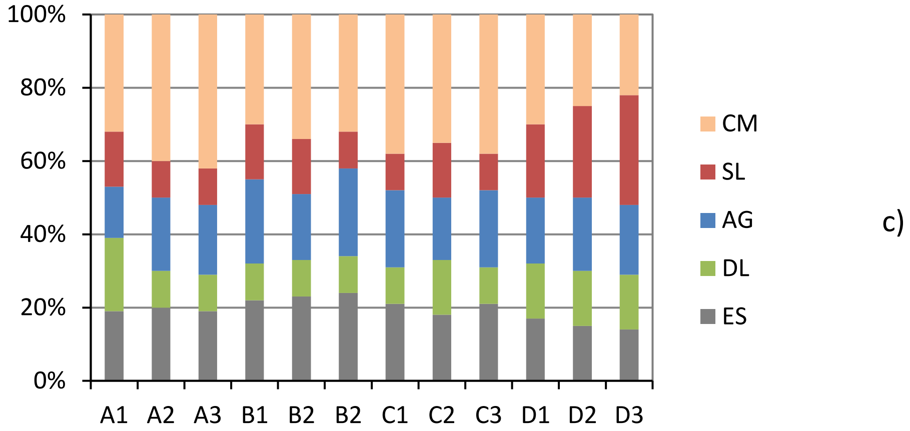


Figure 7 Composition of soil substitutes A1-D3 a) stage I, b) stage II, c) stage III

Figure 8 Preparation of soil substitutes in laboratory condition

Soil substitutes were developed as follows: dry and moderate fertility for low vegetation of dry and poor habitats (A1-A3), mesic and low fertility for low vegetation of fresh habitats (B1-B3), mesic and moderate fertility for woody and shrub-like vegetation (C1-C3), humid and low fertility for vegetation of wet and humid habitats (D1-D3).

For the soil substitutes, two parameters were considered decisive for optimal seed germination and further plant growth: pH and electrical conductivity. As reported in

Table 6 and based on the general classification, the pH of the soil substitutes showed three primary ranges moderately alkaline (pH 8.0-8.4), strongly alkaline (pH 8.5-9.0) and very strongly alkaline (pH >9.0).

Table 6 Set of values for pH and electrical conductivity EC ($mS\cdot cm^{-1}$) for the respective soil substitutes

Soil substitutes	pH			EC, $mS\cdot cm^{-1}$		
	STAGES					
	I	II	III	I	II	III
A1	9.1(a)	8.3(c)	8.3(c)	10.0(e)	8.01(e)	6.73(d)
A2	9.4(a)	8.1(c)	8.2(c)	11.7(e)	7.54(d)	6.67(e)
A3	9.1(a)	8.1(c)	8.2(c)	10.2(e)	7.61(d)	6.63(d)
B1	9.0(b)	8.2(c)	8.2(c)	6.9(d)	6.21(d)	5.39(e)
B2	8.8(b)	8.1(c)	8.3(c)	8.4(e)	6.66(d)	5.98(d)
B3	9.6(a)	8.2(c)	8.3(c)	11.0(e)	6.93(d)	5.66(d)
C1	8.5(b)	8.2(c)	8.2(c)	6.2(d)	6.57(d)	5.90(d)
C2	8.3(c)	8.2(c)	8.4(c)	4.7(d)	8.85(e)	6.19(d)
C3	8.3(c)	8.0(c)	8.2(c)	6.2(d)	6.71(d)	6,30(d)
D1	9.0(b)	8.3(c)	8.6(b)	6.7(d)	6.87(d)	5.80(d)
D2	9.2(a)	8.2(c)	8.8(b)	6.8(d)	6.05(d)	5.28(d)
D3	8.7(b)	8.2(c)	8.4(c)	5.1(d)	5.73(d)	5.71(d)

(a) very strongly alkaline, (b) strongly alkaline, (c) moderately alkaline; (d) moderately saline, (e) intensely saline (Bruce and Rayment, 1982; Hazelton and Murphy, 2016)

The highest pH values (8.3-9.6) were measured at stage I, but results of the soil substitutes from Stages II and III were in ranges of 8.0-8.3 and 8.2-8.8, respectively. According to (Hazelton and Murphy, 2016), the optimal pH range for various plants is from 5 to 8.

Data of EC varied within an extensive range, from 4.7 to 11.7 $mS\cdot cm^{-1}$. It corresponds to two classifications (Miller and Donahue, 1995); moderately saline in the range of 4 to 8 $mS\cdot cm^{-1}$ (sprouting, biomass and yields of many plants are restricted) and strongly saline from 8 to 16 $mS\cdot cm^{-1}$ (only tolerant plants develop satisfactory biomass and results). Characteristics of primary nutrients in soil substitute development in stages I-III were presented in Tables 7, 8 and 9.

Table 7 Characteristic of primary nutrients in soil substitutes development in stage I

Soil substitute	Parameter (%)							
	TOC	Ca	N_t	K	Mg	P_t	S_t	Na
A1	16.2	8.39	0.40	2.54	1.61	0.41	3.10	0.18
A2	18.7	6.07	0.40	2.27	1.24	0.25	3.76	0.15
A3	17.5	5.97	0.49	2.76	1.28	0.44	3.16	0.26
B1	16.4	6.10	0.37	3.17	1.36	0.47	2.97	0.35
B2	22.9	5.42	0.44	2.40	1.08	0.33	3.78	0.16
B3	14.9	4.93	0.37	2.81	1.71	0.38	3.42	0.24
C1	20.7	4.82	0.56	1.98	0.97	0.28	4.26	0.14
C2	23.9	6.50	0.48	1.47	1.16	0.23	3.42	0.19
C3	22.5	4.70	0.47	1.94	0.83	0.27	5.51	0.12
D1	19.1	6.11	0.38	2.19	1.16	0.27	3.15	0.23
D2	20.6	7.67	0.46	2.13	1.47	0.29	1.54	0.45
D3	25.0	6.13	0.51	1.78	1.31	0.23	1.21	0.22

Table 8 Characteristic of primary nutrients in soil substitutes development in stage II

Soil substitute	Parameter (%)							
	TOC	Ca	N_t	K	Mg	P_t	S_t	Na
A1	35.6	7.23	0.50	1.54	1.16	0.15	3.76	0.06
A2	36.0	5.37	0.56	1.78	0.90	0.18	4.20	0.10
A3	34.7	5.34	0.62	1.77	0.90	0.18	3.80	0.12
B1	41.5	4.63	0.32	1.77	0.87	0.13	3.91	0.10
B2	36.8	4.9	0.53	1.69	0.78	0.12	4.47	0.07
B3	41.2	4.47	0.47	1.78	0.83	0.14	4.45	0.10
C1	42.7	5.85	0.48	1.69	0.92	0.13	4.21	0.19
C2	30.5	6.9	0.61	1.64	1.23	0.19	2.80	0.18
C3	37.8	4.58	0.56	1.71	0.68	0.14	5.61	0.03
D1	35.6	5.52	0.35	1.65	1.03	0.13	3.20	0.09
D2	40.1	5.37	0.43	1.68	0.96	0.14	2.98	0.16
D3	39.9	4.95	0.49	1.67	0.96	0.13	2.70	0.14

Table 9 Characteristic of primary nutrients in soil substitutes development in stage III

Soil substitute	Parameter (%)							
	TOC	Ca	N_t	K	Mg	P_t	S_t	Na
A1	23.74	8.23	0.51	1.63	1.38	0.20	2.66	0.19
A2	22.23	5.51	0.56	1.96	1.02	0.21	3.28	0.20
A3	23.05	6.33	0.60	1.86	1.11	0.21	3.46	0.22
B1	22.61	5.32	0.44	1.86	1.01	0.14	3.69	0.19
B2	22.95	5.88	0.46	1.86	1.08	0.18	3.41	0.19
B3	20.27	6.00	0.45	1.98	1.09	0.17	4.12	0.19
C1	22.68	6.18	0.50	1.88	1.08	0.19	3.32	0.19
C2	24.55	6.95	0.51	1.79	1.26	0.17	3.18	0.18
C3	22.51	6.07	0.52	1.90	1.09	0.20	3.56	0.18
D1	24.61	6.88	0.48	1.71	1.22	0.16	3.61	0.17
D2	26.24	5.92	0.48	1.69	1.19	0.13	3.21	0.17
D3	27.90	5.38	0.48	1.74	1.13	0.13	3.41	0.16

The content of total organic carbon (TOC) in stage II ranged from 30.5 to 42.7 % and was higher compared to stage I (14.9-25.0 %) and stage III (20.27-27.90 %). It was observed that the content of potassium in stage I (1.78-2.81 %), excluding soil substitute C2 (1.47 %), was much higher compared to stage I (1.54-1.78 %) and stage III (1.63-1.98 %) similar to the content of phosphorus, i.e., stage I (0.23-0.47 %), stage II (0.12-0.18 %) and III (0.14-0.21 %). It indicates that these amounts may be sufficient for supporting plant growth and further green biomass production. However, a higher concentration of K and Na may be responsible for the strong salinity of soil substitutes, may reduce the sprouting and biomass yields and exhibit a series of harmful effects on plant growth. The levels of nitrogen ranged from 0.32 to 0.62% and were comparable in all stages, s well as the other nutrients such as magnesium (0.68–1.71%) and sodium (1.08–1.71%) exhibited values indicating that these amounts may be sufficient for supporting plant growth and further green biomass production. The sulphur content in the soil substitutes ranged from 1,21 to 5,61%, whereas the concentration of Ca varied from 4.47 to 8.39%. Wastes with high Ca contents are expected to counteract acidity, whereas those with notable S levels should enhance the acidification of soil at the dumping site.

It should be pointed out that the reported concentrations of primary nutrients (N, P, K, Ca, Mg, Na) deal with the vegetation of the so-called natural ecosystems since its physical requirements for nutrients is low.

6.3 Phytotoxicity test

6.3.1 Test with *Sinapis alba* germination

White mustard *(Sinapis alba)* was used as the typical plant for seed germination test to assess the suitability of each soil substitute for vegetation development.
Additionally, one reference soil (S0), i.e., a garden soil rich in organic matter with optimal parameters (N, P, K), was used to control the germination potential of *Synapsis alba* seeds. The pH and electrical conductivity of the S0 soil were 5.5 and 443 $\mu S \cdot cm^{-1}$, respectively. The content of organic matter in S0 was 89%, and the concentration of nitrogen (N), phosphorus (P) and potassium (K) amounted to 0.91, 0.11 and 0.12%, respectively.

Seed germination assays were carried out on plastic sprouting bowls that contained 1 kg of soil substitute (Figure 9). In each sprouting bowl, 50 seeds of *Sinapis alba* were placed at equal distances at a depth of 1 cm. The tests were performed in laboratory conditions under constant temperature (22°C), controlled humidity (30-40%), and light. Each sprouting bowl was watered once daily (50 ml/day) and exposed to white light for 12 hours daily. The sprouting rate was counted after 20 days.

Figure 9 Soil substitutes with *Sinapis alba* seeds during laboratory phytotoxicity tests

Since white mustard is very sensitive to soil conditions and salinity, the results observed in Figure 3 supported the hypothesis that salinity could be primarily responsible for the lack of or inefficient sprouting process. Based on the response of white mustard, for EC, the value of 6.50 $mS \cdot cm^{-1}$ could be considered the threshold for plants susceptible to saline media. Hence, soil substitutes characterised by EC ≤ 6.50 mS·cm^{-1} should give successful germination. Phytotests with white mustard showed that the most promising results were obtained at stage III. The sprouting in reference soil S0 ranged from 84 to 94 %, confirming that quality seeds were used and tests were carried out appropriately for white mustard development.

The results of the germination of the *S. alba* are presented in Figure 10. The soil substitutes with low water storage capacity and moderate content of nutrients showed the best sprouting for A3 in stage III (26%) compared with the A2 (12%) and A1 (0%). Soil substitutes with low water retention and low content of nutrients showed good germination for B3 at stage III (52%). The most promising soil substitute with moderate water retention ability and low nutrient content was C3 at stage II (46%). Germination of white mustard in soil substitutes with moderate water retention and a moderate range of nutrients showed good results at stages I and II, i.e., 58 and 56% for D2, respectively and 66% for D3.

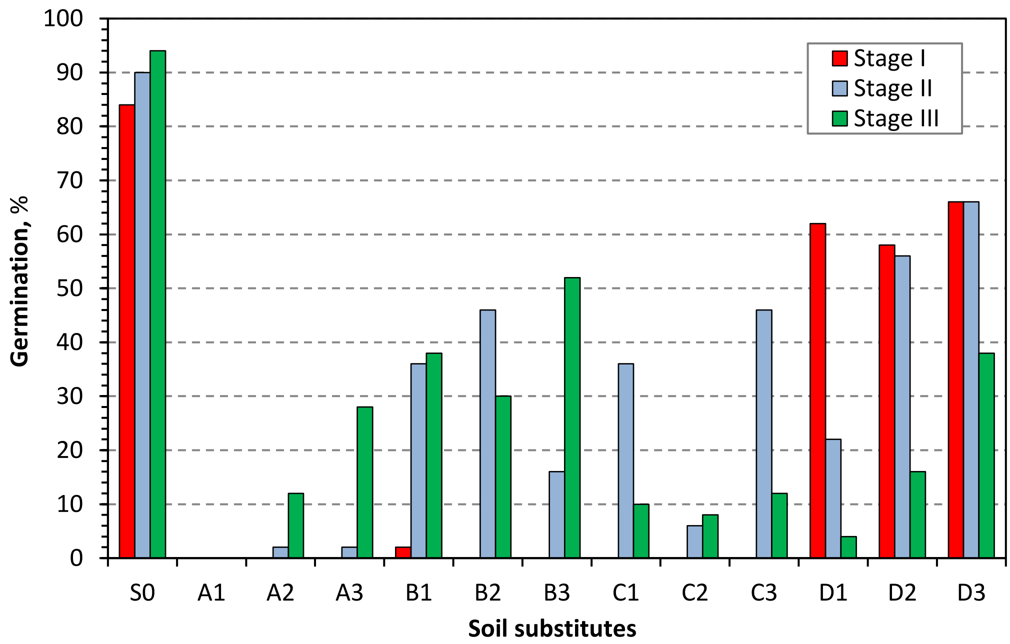


Figure 10 Germination of *Sinapis alba* in the soil substitutes (A1-D3) and control soil (S0)

The relationships between parameters reported in Tables 3 and 6 have shown various interactions. The increase of calcium concentration (5.32-8.23%) in the soil substitutes (stage III) has induced a decrease in S content (2.66-4.12%) but simultaneously raised pH and EC. Therefore, it should be hypothesised that only S caused a pH decrease and was not directly and solely responsible for controlling the salinity of soil substitutes. Chemically, calcium reacts with sulphate ion (SO_4^{2-}) to form some compounds reducing the chemical reactivity of SO_4^{2-}.

According to the linear correlation, the coefficients between soil substitutes' physical and chemical parameters and the *Sinapis alba* germination (GER, %) have revealed a negative correlation with EC (r = -0.46). Water content (W), OM, pH, EC and concentration of other main chemical elements in soil substitutes: Ca, N, K, Mg, P, S and Na did not correlate with *Sinapis alba* germination (Table 10), nor did the content of trace elements.

Table 10 Linear correlation coefficients between physical and chemical parameters (%) of soil substitutes and the *Sinapis alba* germination

Parameter	pH	W	OM	Ca	N	K	Mg	P	S	Na	EC	GER
pH	1.00	0.06	-0.35	0.47	-0.25	-0.02	0.51	0.06	-0.49	0.49	-0.25	0.12
W		1.00	-0.16	0.30	0.52	-0.41	-0.14	-0.25	0.02	-0.04	-0.43	-0.05
OM			1.00	-0.40	0.16	-0.65	-0.69	-0.72	0.28	-0.62	-0.26	0.32
Ca				1.00	0.04	0.05	0.68	0.25	-0.56	0.44	0.14	-0.20
N					1.00	-0.42	-0.30	-0.27	0.11	-0.19	-0.17	-0.12
K						1.00	0.54	0.90	-0.12	0.55	0.58	-0.26
Mg							1.00	0.62	-0.66	0.66	0.43	-0.24
P								1.00	-0.22	0.58	0.55	-0.31
S									1.00	-0.66	0.03	-0.24
Na										1.00	0.05	0.10
EC											1.00	-0.46
GER												1.00

W - water content (%); OM organic matter (%); EC-electrical conductivity ($mS \cdot cm^{-1}$); GER– *Sinapis alba* germination (%)

6.3.2 Tests with meadow vegetation

At stage III of the experiment, seeds of semi-natural meadow communities were additionally used. They are represented by plant species typical for meadow communities in Central Europe. Species with low (dry meadow) and middle soil moisture requirements (mesic meadow) were used, taking into consideration habitat conditions on waste heaps slopes (Table 11). Then, 3 g of the mesic and dry meadow seed mixture were sown into all types of soil substitutes (1kg in plastic sprouting bowls, n=24). The tests were performed from 11 May to 26 June in outdoor conditions without artificial application of water and light. At the end of the tests, the percentage coverage of developed meadow vegetation was evaluated.

Table 11 Species composition of mesic and dry meadow seed mixture

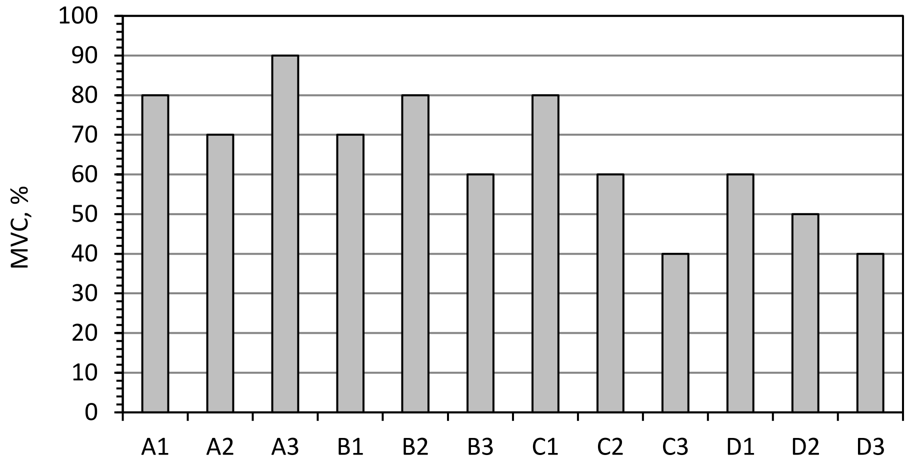
Type of plant communities	Species composition
Dry meadow	*Euphorbia cyparissias, Tussilago farfara, Hypericum perforatum, Artemisia vulgaris, Papaver rhoeas, Vicia cracca, Securigera varia, Vicia villosa Vicia grandiflora, Centaurea scabiosa, Knautia arnvensis, Echium vulgare, Cichorium intybus, Achillea millefolium, Centaurea jacea, Verbascum thapsiforme, Anthemis tinctoria, Saponaria officinalis, Agrimonia eupatorium, Verbascum nigrum, Succisa pratensis, Leontodon hispidus, Tripleurospermum inodorum, Cynoglossum officinale, Tragopogon pratensis.*
Mesic meadow	*Leucanthemum vulgare, Lotus corniculatus, Lychnis flos-cuculi, Securigera varia, Ranunculus acris, Ranunculus polyanthemos, Knautia arvensis, Vicia cracca, Vicia grandiflora, Tragopogon pratensis, Achillea millefolium, Centaurea phrygia, Centaurea jacea, Daucus carota, Leontodon hispidus, Stachys officinalis, Sanguisroba officinalis, Tripleurospermum inodorum, Campanula patula.*

These plants were less sensitive to the harmful effects induced by salinity which, in the case of white mustard, significantly limited and even hampered the first sproutings and their further growth. Additionally, both the mesic and dry meadow plants belong to the typical plant species for meadow communities in Central Europe which may be developing a dynamic green biomass production, intensifying the rhizosphere activity and finally increasing carbon dioxide assimilation. The phytotoxicity tests with meadow vegetation were conducted as follows:

The weight of 3 g of the mesic or dry meadow seed mixture was sown into four types of soil substitutes (1kg in plastic sprouting bowls). The tests were performed in three repetitions in outdoor conditions without artificial application of water and light. After 45 days, the percentage of meadow vegetation cover (MVC) was evaluated based on the following equation:

$$MVC = \frac{area\ covered\ by\ plant\ species}{total\ area\ for\ cover} \times 100$$

The results of the tests with meadow vegetation for soil substitutes (A1-D3) prepared during stage III were presented in Figures 11 and 12.



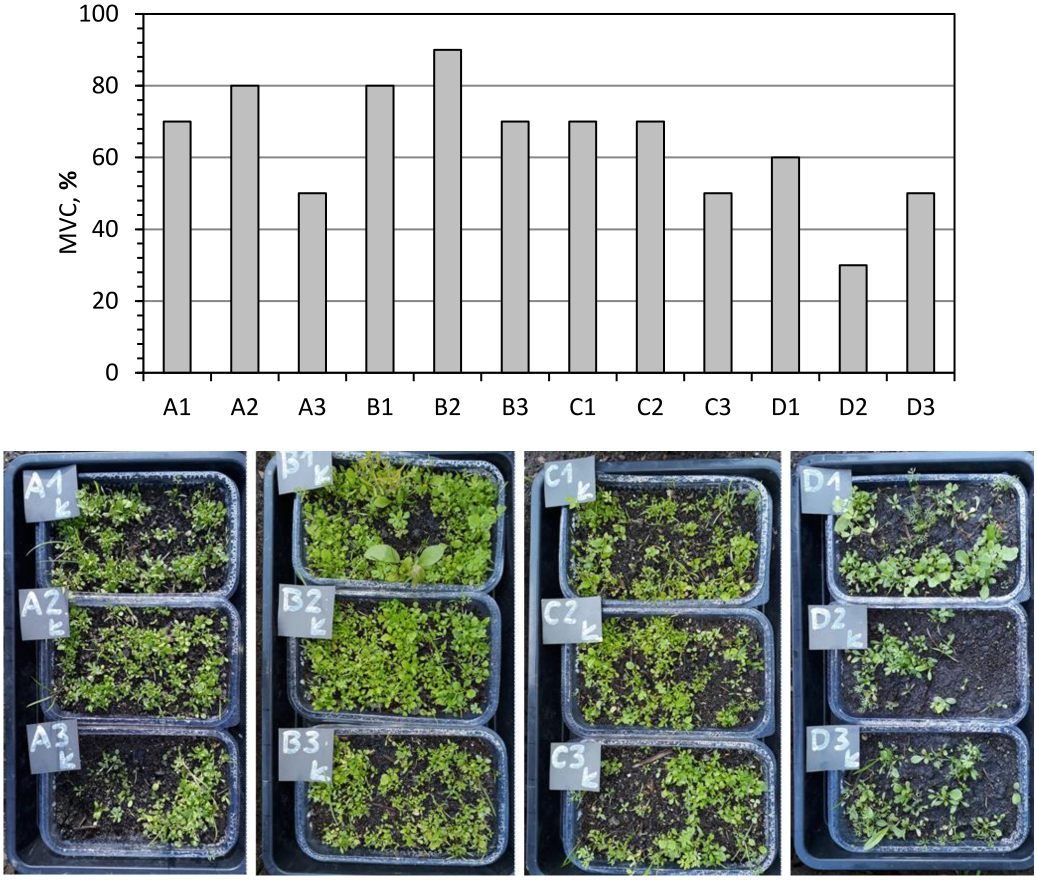
a)

b)

Figure 11 Development of mesic meadow vegetation at the soil substitutes: a) the percentage of vegetation (MVC, %); b) photography of observed results

The number of mesic meadow species (Figure 11) varies between 5 (for A1, B1, C2, C3, and D5) through 6 (for A2, B2, B3, C1 and D2) to finally, the highest number of species, i.e. 7 for D1, which means that the adaptation and tolerance processes were significantly increased. As proof of adaptation to new growth environments, the vegetation cover varied greatly, from 40 to 90%.

The number of dry meadow species also fluctuated in an extensive range, from 4 (A2, D3) through 5 (A1, B3, C1, C3, D1, D2) to 6 (A3, B2, C2), reaching even 8 for B1 (Figure 12). The coverage was much more disparate: from 30 to 90%, whereas 30% applied to only a single case (D2).



a)

b)

Figure 12 Development of dry meadow vegetation at the soil substitutes: a) the percentage of vegetation (MVC, %); b) photography of observed results

PCA (Table 12) was performed to evaluate the influence of the physical and chemical parameters of the soil substitutes on the development of meadow vegetation. The first ordination axis of the PCA model (axis 1) accounts for 65.2% of the total variation of vegetation. This axis has a positive correlation with the content of OM (r=0.60) and a negative correlation with the concentration of P (r=-0.45). The cover of mesic meadow species (Mes_Mea %) and dry meadow species (Dry_Mea %) negatively correlates with this axis. The second axis (axis 2) explains 19.5% of response variables variation and shows a gradient in soil pH values. This axis has a positive correlation with the cover of mesic meadow species and a negative correlation with dry meadow species cover (Figure 13).

Table 12 Values of the correlation coefficient between soil physical and chemical parameters and axes 1 and 2 of the PCA model

Parameter	pH	P	S	EC	Ca	OM
	-	%		mS/cm	%	
Axis 1	**0.49**	**-0.45**	0.04	-0.11	-0.17	**0.60**
Axis 2	**0.45**	0.08	0.24	0.07	0.23	0.05

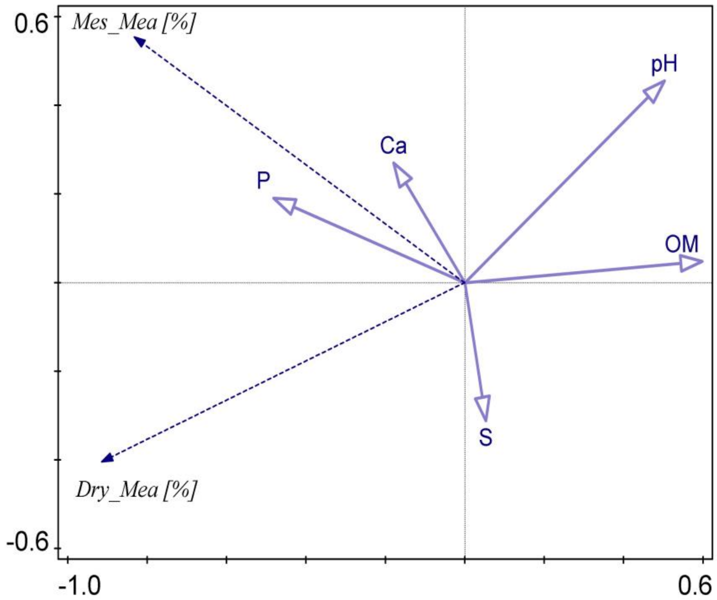


Figure 13 Principal Component Analysis (PCA) for cover mesic meadow (Mes_Mea %) and dry meadow species (Dry_Mea %) with relation to soil physical and chemical parameters

Soil organic matter plays a significant role in terrestrial ecosystems. It maintains the soil structure, improves water infiltration, increases the water holding capacity and reduces the risk of soil erosion. In addition, its decomposition provides nutrients for plants (Krull et al., 2009). The significant components of soil organic matter are humic substances and fulvic acids. The results of (Asik et al., 2009) and (Çelik et al., 2010) study have shown positive effects the humic substances on seed germination, seedling growth, root initiation, root growth, shoot development and the uptake of macro- and microelements. Soil humic substances may also mitigate abiotic stress conditions caused by unfavourable pH and high salinity. The organic matter content also increases the P sorption capacity of the soil (Kang et al., 2009), which could cause decreasing phosphorus availability for plants in the soil substitutes with higher organic matter contents. P constitutes an essential element for seed germination, seedling establishment, and plant growth (John et al., 2016; Malhotra et al., 2018; Neitzke, 2002; Venterink and Güsewell, 2010) at the same time, affecting the variety of meadow species (van Dobben et al., 2017; Venterink and Güsewell, 2010; Weigelt et al., 2005).

The species characteristic for mesic meadows has shown increasing coverage with higher P concentration, which proved its role in soil fertility and plant growth.

The pH of soil substitutes has significantly influenced the development of semi-natural meadow communities, making it the primary factor affecting habitat conditions for many meadow species (Venterink and Güsewell, 2010). Soil substitutes for establishing semi-natural meadow communities were characterized by alkaline conditions (pH 8.16-8.78) and Ca content between 5.23 to 8.23%. Such calcareous conditions often exhibit a high concentration of bicarbonate in the soil solution and induce low availability of Fe and Zn (George et al., 2011). On the other hand, high pH has shown a negative effect on developing dry meadow communities, contrarily to Ca manifesting a positive impact on mesic meadow communities. It could be associated with a decrease in the negative influence of S. The habitats with high content of Ca are characteristic of the type of meadow communities that are considered the wealthiest and most endangered ecosystems of the natural environment of Europe (Boroń et al., 2019). Generally, a significant decrease in semi-natural meadow areas has been observed over the past few decades (Tokarczyk, 2017).

Based on the phytotoxicity tests, three types of soil substitutes, i.e., A3 for dry meadow, B2 for mesic meadow vegetation and D2 for wet and humid habitats, were selected for land test in the experimental polygon. Soil substitutes differed regarding waste components' type and percentage share (Figure 14).

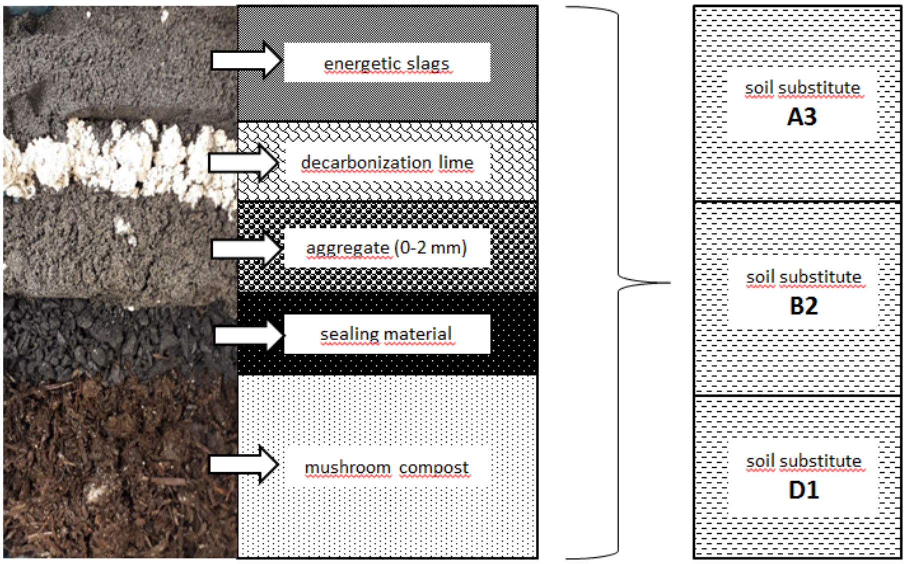


Figure 14 Composition of soil substitute blends used in experimental polygon

7 Preparation of soil substitutes

The concept of making an experimental reclamation, covering a fragment of the Janina Mine waste heap in Libiąż (4000 m^2) with the use of components, forming layers, was presented in Figure 15.

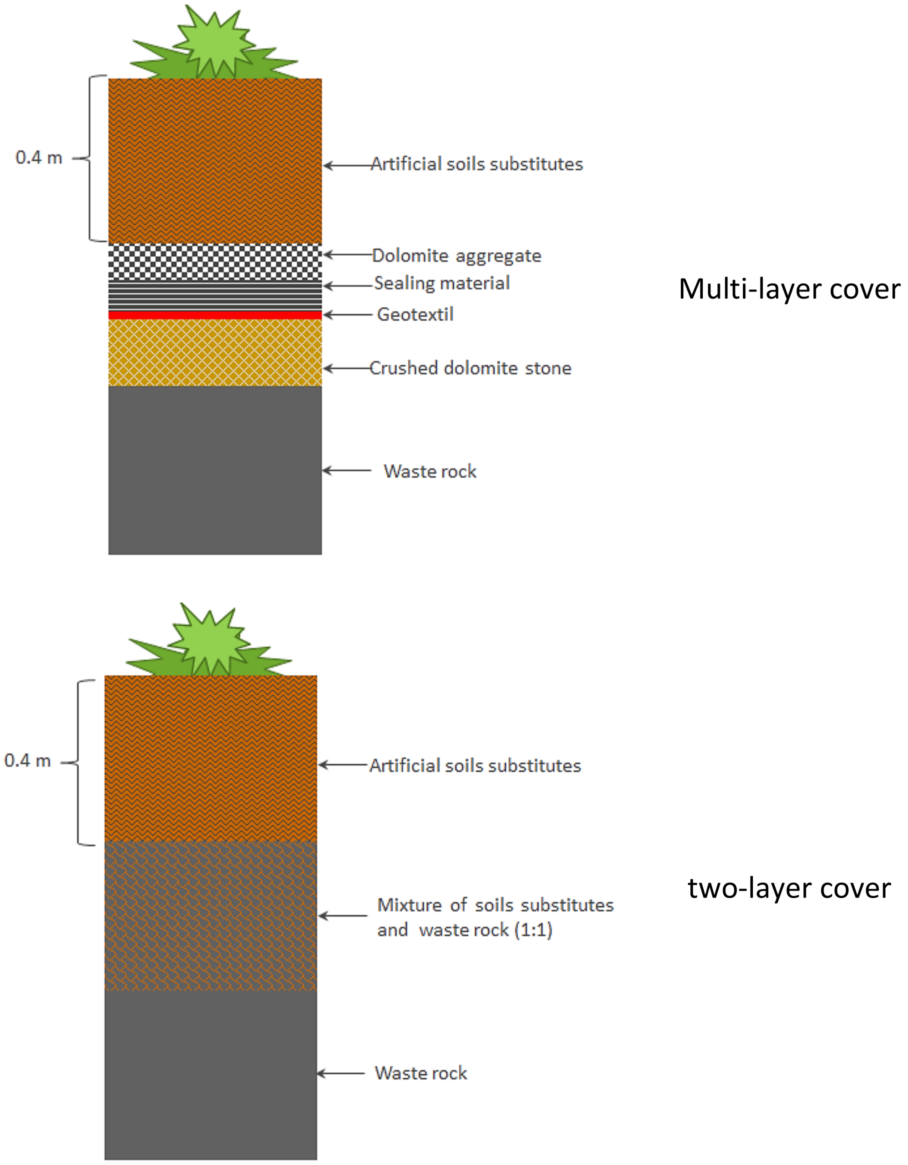


Figure 15 Model profiles of tested coverings on the spoil heap of the Janina Mine

7.1 Formation of the testing ground

At this stage, the testing ground was geodetically divided into two sections, each measuring 40 m x 50 m (Figure 16). Subsequently, protection layers with a total thickness of 0.8 m were laid, following the sequence and thicknesses shown on the profiles (Figure 15). Later, three mixtures of soil substitutes were spread on the soil, thus prepared in 16.5 m wide strips.

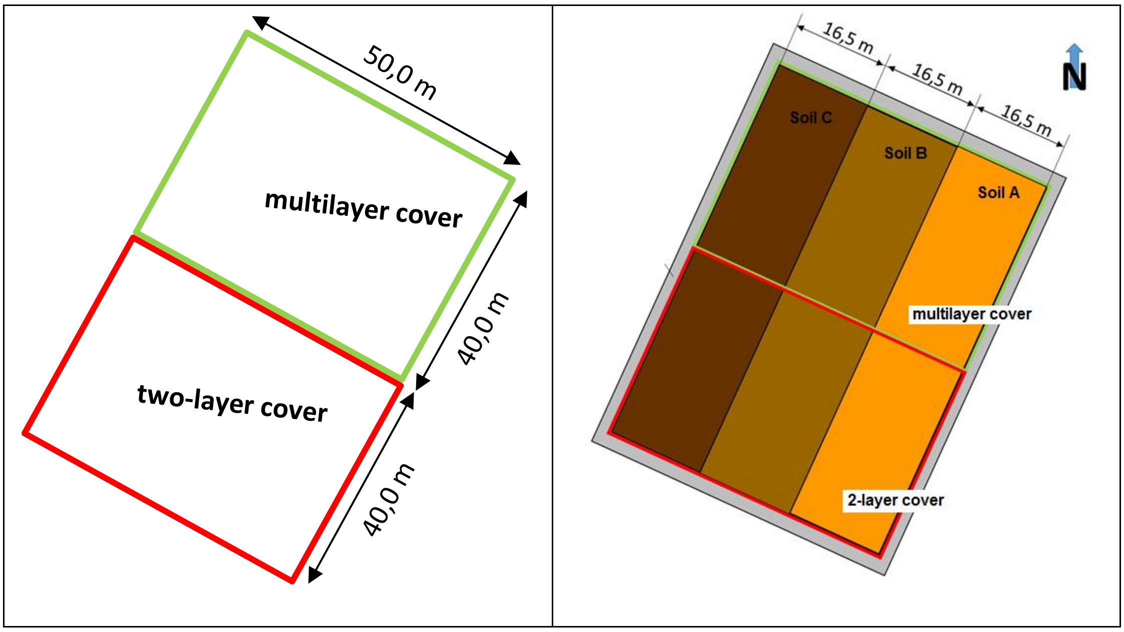


Figure 16 Organization of the testing polygon, taking into account the 2-type of cover and three types of soil substitutes

The training ground was bounded by embankments and fenced to maintain the layers' stability. Its surface was levelled and prepared for sowing plants and planting shrubs.

The first works on the construction of the Janina Mine testing polygon were started in October 2020 and finished in late November 2020. Documentary photographs illustrating the structure of the experimental field are presented in Figure 17.

Figure 17 Field works on the Janina waste heap

7.2 Planting works in experimental polygon

The plantation of shrubs (approx. 400 seedlings), wetland vegetation (approx. 1000 seedlings of *Phragmites australis*), and sowing of approx. 3 kg of the dry and mesic meadow vegetation seeds was carried out in November 2020. The shrub plantation was adapted to the local condition of the test site. The average height of shrubs species at the beginning of the experiment ranged from 0.25 to 0.4 m (Table 13).

Table 13 Plants used in soil covers B in experimental polygon

Species	Soil	Height (cm)	Units
Wild privet (*Ligustrum vulgare*)	B2	40±5	120
Common dogwood (*Cornus sanguinea*)	B2	35±5	120
Sea-buckthorn (*Hippophae rhamnoides)*	B2	25±5	120
Common hawthorn (Crataegus monogyna*)*	B2	25±5	120

Figure 18 presents the planting works in the Janina waste heap for biological reclamation.

Figure 18 Planting the Janina waste heap for biological reclamation

7.3 Material costs of reclamation by a two-layer cover and multi-layer cover method

The construction of the testing ground also provided information on the material costs of heap reclamation using two methods, i.e. the two-layer method and the multi-layer method. The costs indicated are current as of 30.10.2020. (1 Euro=4,62 PLN), according to the current exchange rate provided by the National Bank of Poland.

A comparison of material costs used to reclaim the surface of the heap at the testing ground is shown in Table 14 and Figure 19.

Table 14 Comparison of the costs of materials used for reclamation by two methods

Method	Materials	Part costs Euro/2000 m^2	Unit costs Euro/m^2
Multi-layer cover	Soil substitute for surface layer*	1 891	4,95
	Dolomite aggregate 0-31,5 mm	2 132	
	Sealing material	133	
	Geotextile	1 164	
	Dolomite aggregate 31,5-63 mm	4 586	
2-layer cover	Soil substitute for the surface layer and mixed with wastes	2836	1,42

* The costs of the soil substitutes include mining waste materials (see Fig. 14)

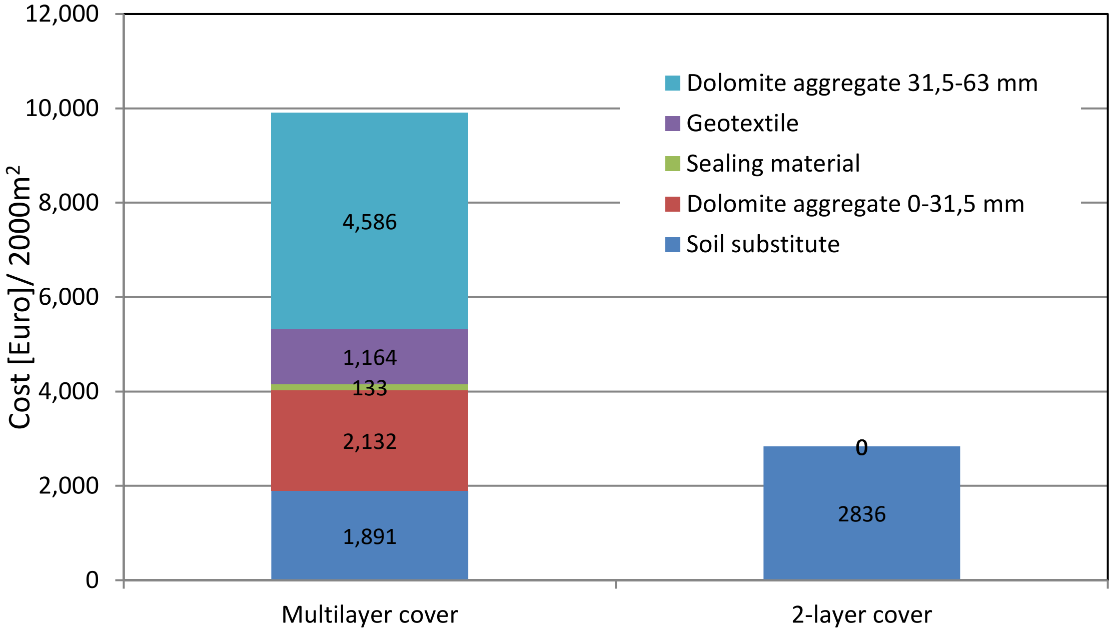


Figure 19 Comparison of reclamation materials costs for multi-layer and two-layer methods

The data presented in Table 14 and Figure 19 show that the costs of materials used for reclamation by the two methods differ significantly. Using the example of the Janina mine waste heap, reclamation of challenging terrains using the multi-layer method is 3.5 times more expensive than reclamation using the two-layer method.

8 Species diversity assessment for post-mining rehabilitation

8.1 Vegetation characteristics of plant communities

In-situ growth of *Phragmites australis* after two years of vegetation showed outstanding development (Figure 20).

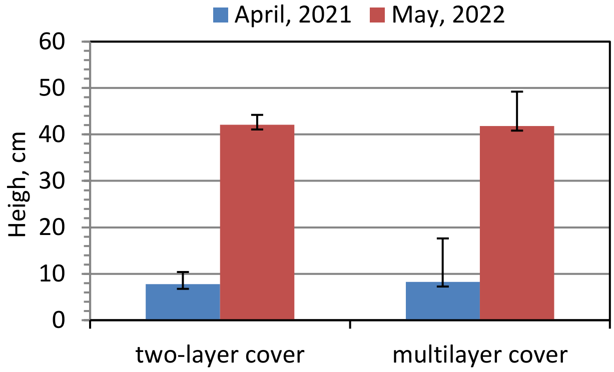


Figure 20 The average height of *Phragmites australis* after two years of vegetation

The average height of the *Phragmites australis* individuals in April 2022 was five times higher compared to April 2021. It ranged from 7.7 to 42.1 cm for a two-layer cover and from 8.25 to 41.8 cm for a multi-layer cover. There was no difference between average height at two-layer cover and multi-layer cover.

The vegetation communities using artificial soil cover D1 were observed from April 2021 to August 2022. The results of the plant vegetation of *Phragmites australis* are presented in **Error! Reference source not found.** 21.

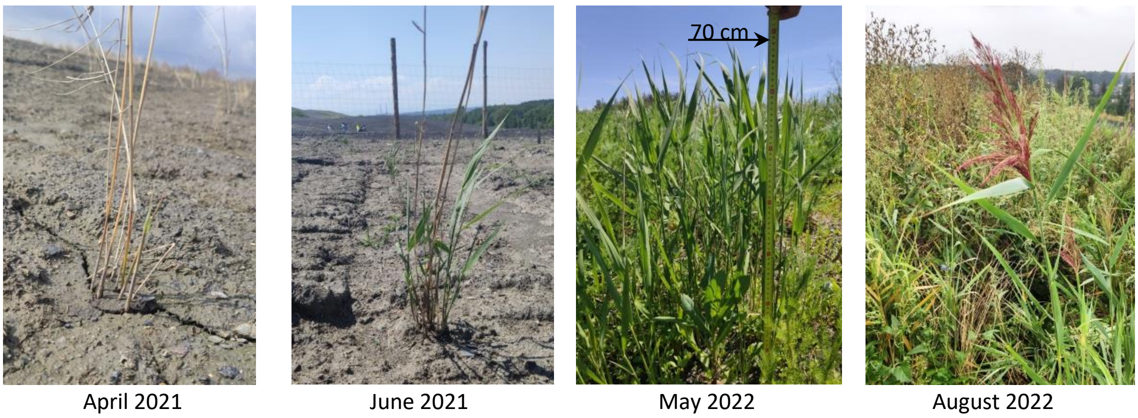


Figure 21 *Phragmites australis* communities in the first and after two years of vegetation in soil cover D1

In this study, we observed the vegetation characteristics (height) of four species of plant communities and their response to artificial soil properties. The data gathered throughout phytotests with shrub plant communities showed a promising opportunity for implementing the tested soil cover B2 as biological reclamation of the coal mine-affected areas.

The most significant plant growth was recorded for *Ligustrum vulgare* from 16.0 to 48.4 cm in the two-layer cover area and from 15.7 to 50.7 cm in the multi-layer cover. A visible increase in multi-layer soil cover, ranging between 36.1 and 41.17 cm, was observed for *Hippophae rhamnoides*. The average plant height of *Crataegus monogyna* did not change noticeably and was 50.2 cm. Unfortunately, it has been noticed that *Cornus sanguinea* has not adapted to artificial soil conditions (no successful planting in the second year). The results of measurements of height plant communities are presented in Figure 22.

a)
b)

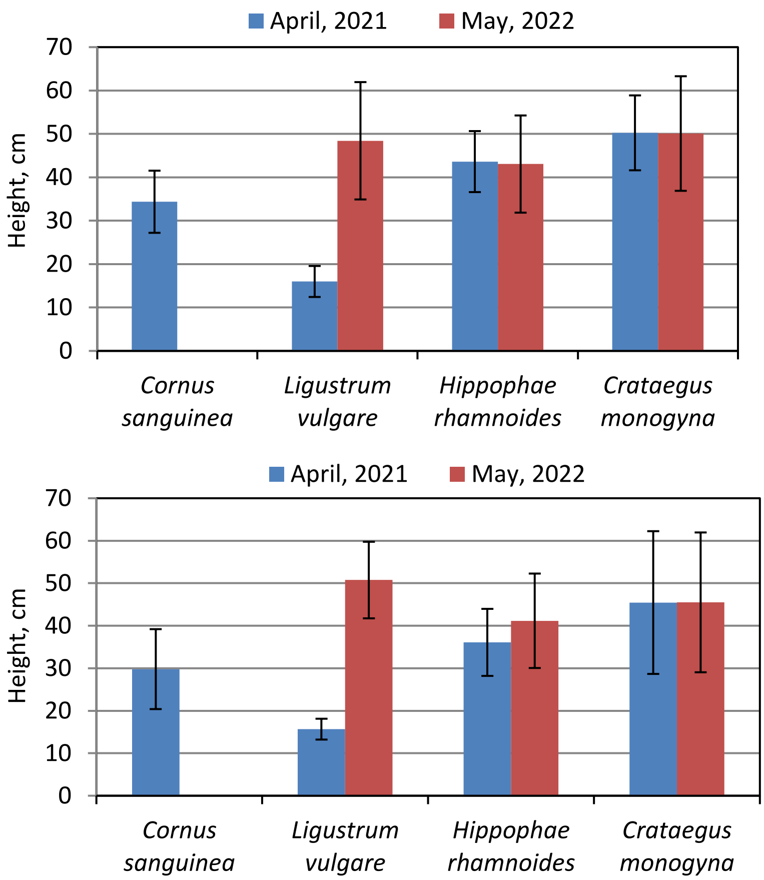


Figure 22 The average height of *plant communities* after two years of vegetation using soil cover B2: a) two-layer cover, b) multi-layer cover

Figure 23 presents the results of shrub communities' plant vegetation in soil B2 in April 2021 and May 2022. After two years of investigation, no visible symptoms of reduction in leaf size, chlorosis, discolouration or necrosis were observed.

a) b) c)

Figure 23 Plant species in the first and second year of vegetation in soil B2: a) *Hippophae rhamnoides,* b) *Ligustrum vulgare,* c) *Crataegus monogyna*

8.2 Vegetation characteristics of meadow vegetation

The standard methods for plant communities research were used to analyse the developed meadow vegetation. The study area was divided into four sections based on types of soil (A and B) and ground formation, two-layer and multi-layer covers. In each section 3, subplots were set (12 subplots in total) (Figure 24). Detailed lists of vascular plant species in the study plots of 1 m^2 were made in June 2021 and June 2022. Each plant species' percentage cover was evaluated using the following scale: 1%, 5%, 10%, 20%... 100%. Recorded plant species were classified into the following plant community types: dry meadow, mesic meadow, segatal and ruderal vegetation due to their preference to occur in specific habitats.

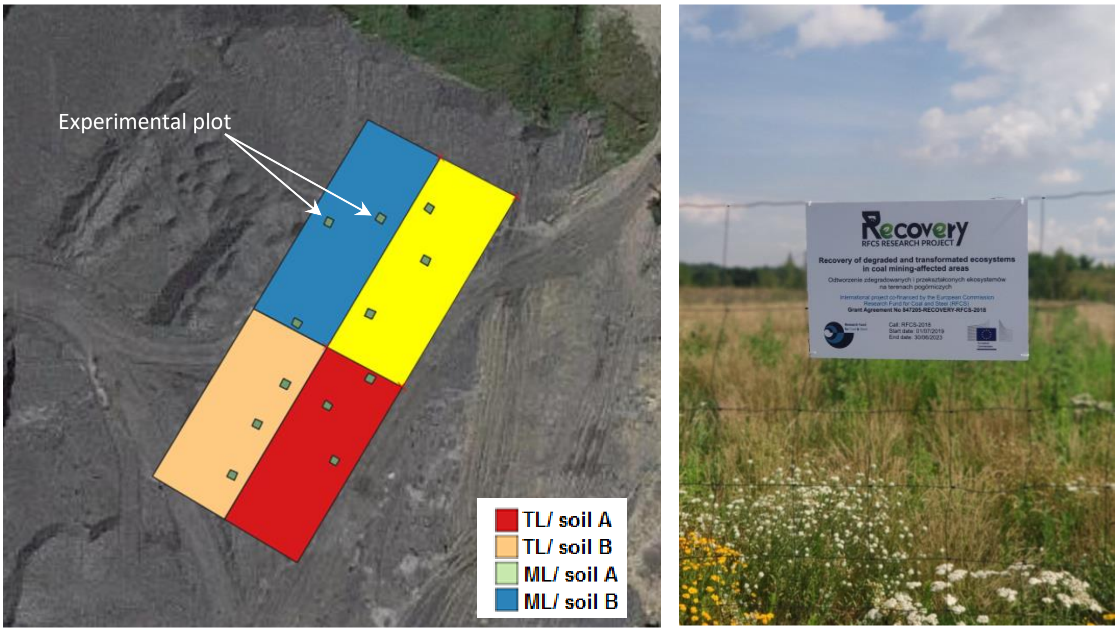


Figure 24 Location of the experimental plots in the study area: TL-two layer soil cover, ML-multilayer soil cover

a) b)

Figure 25 Examples of the experimental plots in the study area: a) in 2021, b) in 2022

The highest cover of the species characteristic for mesic meadow vegetation was observed on each section of the study plot (Figure 26 a,b). This vegetation also has the most significant coverage increase between 2021 and 2022. Both types of soil (A and B) on a 2-layer section have a lower cover or mesic meadow plant species that mulita layers cover (Figure 26 a,b).

The presence of species characteristic of dry meadow vegetation was highest on the two-layer ground formation with A type of soil. The cover of species with broad ecological amplitude (other) and species characteristics for ruderal and segetal vegetation is typical for the early stages of plant community development. These species can mainly spread over long distances and fast-cover open areas, and the presence of this species is shrinking in later stages of vegetation succession.

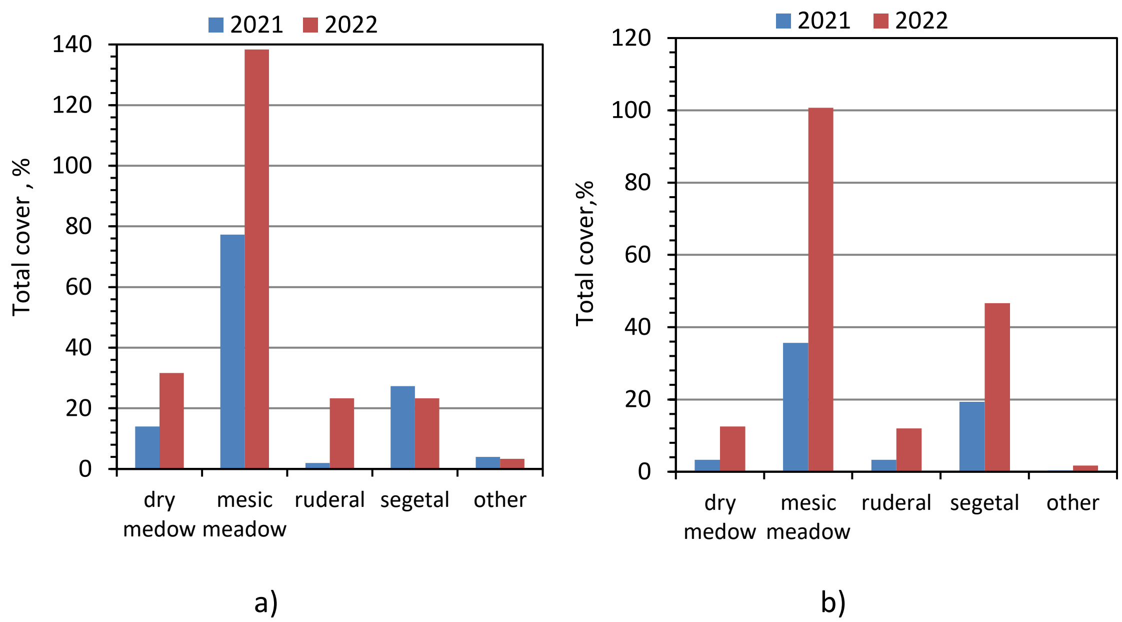


Figure 26 Cover of species characteristics for each habitat for the multi-layer section in 2021 and 2022 a) soil cover A, b) soil cover B

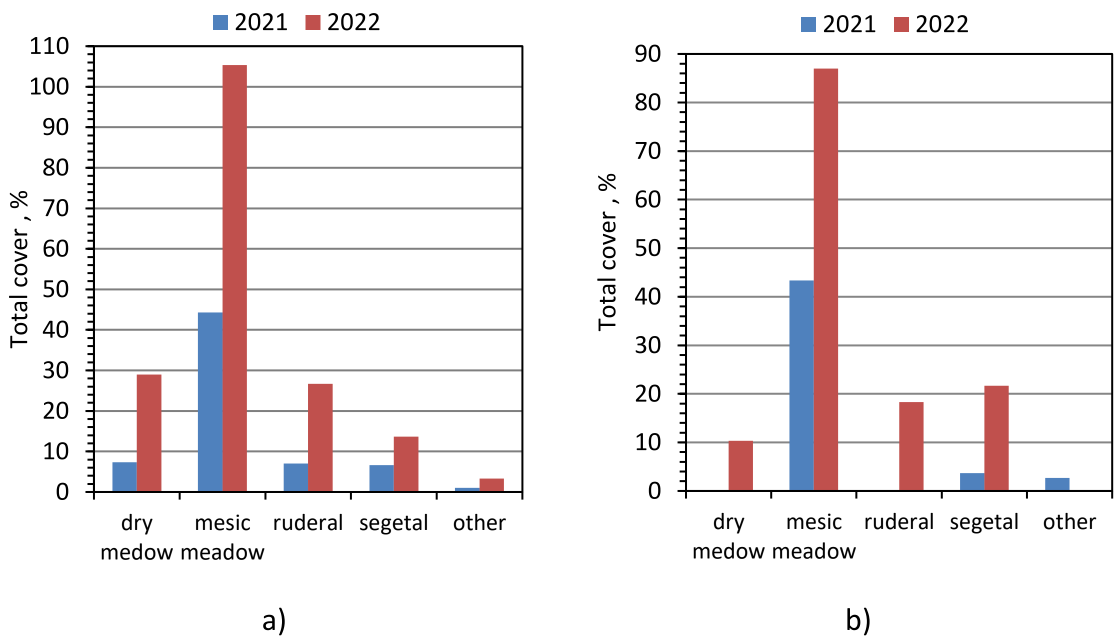


Figure 27 Cover of species characteristics for each habitat for the two-layer area in 2021 and 2022 a) soil cover A, b) soil cover B

The developed vegetation with the presence of vegetation with various flower species has high esthetic values (Figure 28) and delivers habitats for diverse communities of insects (Figure 29).

a)

b
)

Figure 28 Development of meadow vegetation using soil covers at Janina Mine waste heap (a) mesic meadow vegetation on soil B2, (b) dry meadow vegetation on soil A3

Figure 29 Example of fauna observed on experimental polygon after reclamation

Covered by density vegetation, the experimental polygon positively affects the local landscape (Figure 30).

a) b)

Figure 30 Development of meadow vegetation using soil covers at Janina Mine waste heap (a) experimental polygon before reclamation (b) experimental polygon after 18 months of reclamation

8.3 Physicochemical properties of selected soil substitutes

Between April and August 2022, depth measurements of the groundwater table were carried out in six piezometers: TL-1, TL-2 and TL-3 for two-layer cover and ML-1, ML-2 and ML-3 for multi-layer cover. The location of the piezometers on the testing ground is presented in Figure 31. The average depths of the groundwater table below the ground are summarised in Table 15.

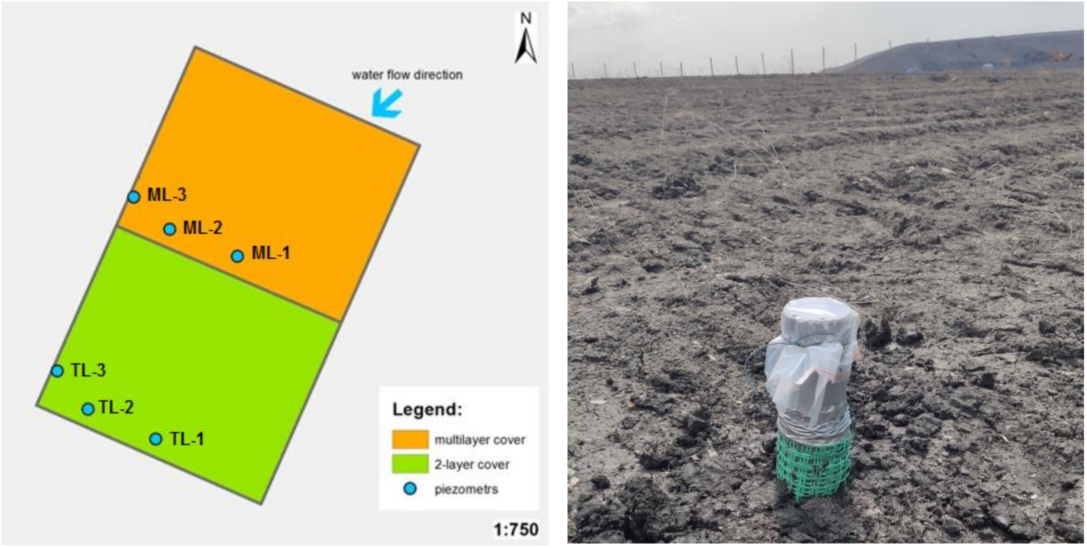
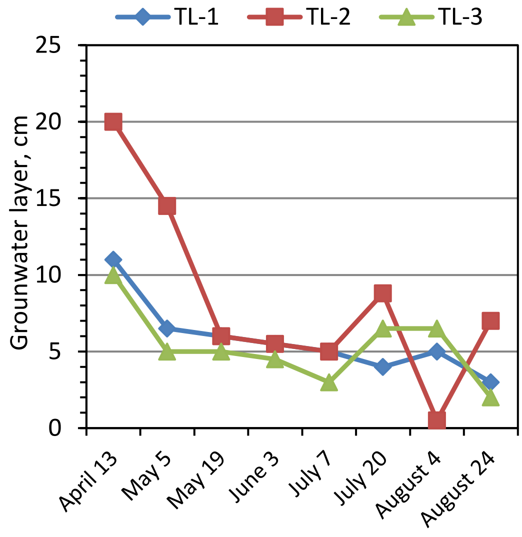


Figure 31 Location of piezometers on the experimental polygon

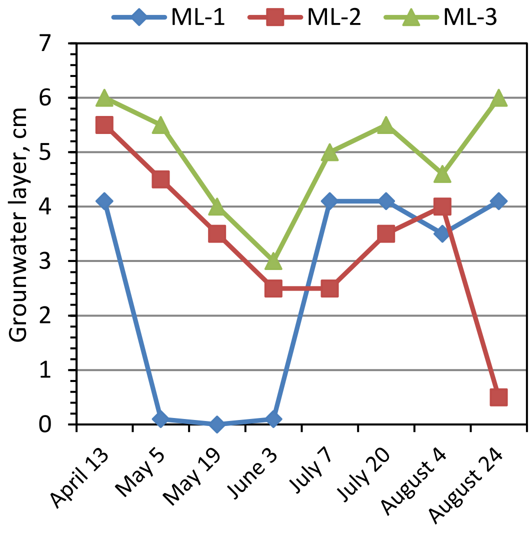
Table 15 Characteristic piezometers and depths to the groundwater table

Piezometer	layer cover	Soil cover	Depth of ground water table below ground surface (cm b.g.s.)
TL-1	two-layer cover	D1	32.3
TL-2		B2	45.2
TL-3		A3	39.7
ML-1	Multi-layer cover	D1	28.6
ML-2		B2	28.2
ML-3		A3	26.9

The study results indicated that the groundwater table level in the area with a 2-layer cover is more profound than in the area with a multi-layer cover (Figure 32).



a)



b)

Figure 32 The measured height of groundwater layer in piezometers from April to August 2022 a) two-layer cover, b) multi-layer cover

The average thickness of the groundwater layer in piezometers TL-1, TL-2 and TL-3 were 5.7, 9.8 and 5.3 cm, respectively. The average thickness of the groundwater layer in piezometers located in multi-layer cover was 2.6, 3.1 and 4.8 cm for ML-1, ML-2 and ML-3, respectively.

The physicochemical parameters of investigated soil covers after vegetation were presented in Table 16. The analysis was conducted in three repetitions.

Table 16 Physicochemical parameters of investigated soil covers in experimental polygon

Parameter	Soil cover								
	A3			B2			D1		
DM, %	96.90	96.98	97.27	97.21	96.63	96.71	96.57	96.34	96.63
OM, %	24.44	24.66	21.51	23.82	27.48	24.73	28.26	27.86	27.00
Ca, %	3.62	3.71	3.85	4.32	3.42	3.58	3.26	3.52	3.29
K, %	1.81	1.81	1.83	1.73	1.73	1.73	1.69	1.69	1.68
Mg, %	0.62	0.63	0.7	0.62	0.59	0.63	0.60	0.59	0.60
Na, %	0.15	0.16	0.16	0.13	0.14	0.13	0.11	0.14	0.13
N_t, %	0.60	0.49	0.53	0.45	0.45	0.48	0.49	0.46	0.47
P_t, %	0.17	0.14	0.16	0.14	0.13	0.14	0.14	0.15	0.15
S_t, %	2.62	2.41	2.20	2.15	1.78	2.08	1.89	2.03	2.32
pH	7.5	7.7	7.8	7.7	7.7	7.7	7.7	7.7	7.6
EC, $mS \cdot cm^{-1}$	3.39	2.66	2.71	2.52	2.65	2.64	2.01	2.57	2.56

The obtained results indicated that the content of main macronutrients in soil substitutes A3, B2, and D1 showed outstanding results for vegetation plan communities and varied in the order of Ca>K>Mg>Na>N>P>S. Macronutrients play an essential role in plant metabolism by enhancing growth and yields and protecting plants from stress and disease. The deficiency and excess macronutrients may reduce plant growth (McCauley et al., 2011). The concentration of organic matter (OM) was within the range of 25.51-28.26 %, and the highest amount of OM was observed for soil D1. However, soil D1 was characterised by lower concentrations of potassium (1.69-1.68 %) compared to soils A3 and B2 (1.73-1.83 %). Furthermore, the calcium levels were also the lowest in soil D1 (3.29-3.52 %), although these differences may be due to laboratory measurement errors.

It is reasonable to state that after 18 months of starting vegetation, the soils cover is characterised by neutral pH (7.6-7.8) and lower electrical conductivity (2.01-3.39 $mS \cdot cm^{-1}$) compared to the results achieved in laboratory conditions, i.e., pH from 8.2 to 8.6 and EC from 5.80 to 6.63 (see Table 6). After this time, the concentration of sulphur decreased (on average) from 3.49 to 2.16 %. A twofold reduction of the average concentration was also observed for calcium from 6.36 to 3.69 % and magnesium from 1.14 to 0.62 %.

9 Conclusions & lessons learnt

The primary purpose of this research was to outline a novel approach to using industrial by-products generated in coal mines and coal-fired power plants as the components for artificial soils. The study included the following by-products: fly ashes from coal and biomass combustion, aggregate from mine waste processing, sealing material and energetic slag. Additionally, sewage sludge and spent mushroom compost were tested and incorporated into vegetation testing in the lab stage as substrates enriching with organic matter.

Under laboratory conditions, a phytotoxicity test using white mustard (Sinapis alba) seeds showed good germination results for three soil substitutes that did not contain fly ash from biomass combustion. It is essential to know that by-products from combustion increase salinity, which could harm plant germination. The phytotoxicity test using Sinapis alba is an effective method for soil toxicity verification impacting vegetation development. On the other hand, a test using meadow species is needed to select the most suitable soil substrates for diverse vegetation development. During seed composition selection, the knowledge of local plant communities is necessary. Only native and resistant plant species that form valuable and diverse communities should be considered.

Results revealed that the amounts of organic matter and nutrients (N, P, K, Ca, Mg) in soil substitutes were sufficient to support plant growth. Moreover, the concentrations of trace elements (As, Cd, Cr, Cu, Ni, Pb and Zn) in soil substitutes did not exceed the permissible limits for soils classified as wooded, shrubby, and green areas. During soil substrate development, the range of substances that could cause environmental risk must be identified and checked against local legal conditions to ensure that final products are environmentally friendly and could be used in reclamation processes.

Based on the data gathered throughout phytotests in an experimental polygon (Janina Mine waste heap in Libiąż), the results showed a promising opportunity for implementing the tested soil covers in the acidic and highly eroded coal mine-affected areas. The current preliminary study shows that using waste materials to develop soil substitutes is eco-friendly and suitable for meadow communities. Covered by dense vegetation, the experimental polygon with various flower species has high esthetic values and delivers habitats for diverse insect communities.

Two methods of reclamation of a mine waste heap were tested during the trial: 2-layer technology and multi-layer technology). It was demonstrated that the costs of materials/components used in the 2-layer technology (layer of soil substitute and a layer of mixture soil substitute and mine waste 1:1) are 3.5 times lower than the costs of materials used in the multi-layer technology (soil substitute, aggregates, sealing material, geo-fibre). No differences were found in the conditions and density of the plants growing on the two sides of the testing ground, which differed in the reclamation technology used.

The semi-natural meadow vegetation grown on testing ground is an ecosystem with the ability to deliver ecosystem services such as pollination, herbs for traditional medicinal use, nutrient cycling, nutrient and water retention, biomass production, recreation and climate regulation. The field experiment was crucial to verify in natural conditions both the developed soil substrate and composition of species appropriate for the hard coal mine heap condition.

Data from the current preliminary study showed that using waste materials to develop soil substitutes, which are eco-friendly and suitable for semi-natural meadow communities, is possible. Further research is needed to evaluate the long-term development of semi-natural meadow communities in such types of reclaimed coal-mine-affected areas. The mining waste heaps seem to offer suitable locations for developing these semi-natural communities.

The study's results in managing the industrial by-products may be applied when developing innovative environmentally friendly methods of reclaiming coal mine-affected areas.

Regarding the laboratory tests, the main lessons learnt were as follows:

- It is essential to explore the local market for suppliers of by-products from coal combustions, coal mines, and organic matter-rich material before developing soil substitute mixtures.
- The first stage of laboratory testing of components can be limited to testing the aqueous extracts prepared for waste according to EN 12457-4:2002 Characterization of waste - Leaching - Compliance test for leaching of granular waste materials and sludges - Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction).
- The parameters for the aqueous extract tested in the first stage can be limited to pH, electrolytic conductivity, primary ions and main heavy metals.
- Waste with the lowest possible pH and electrolytic conductivity should be qualified for further testing and analysis. This condition is usually met by power plant slags, which are in contact with process waters during manufacturing.
- When preparing substitute mixtures, it is crucial to limit the number of components providing the ones that ensure:
  - ✓ proper soil structure - skeleton-building components (energy slags, fine aggregate)
  - ✓ fine-fraction components that retain water - decarbonization lime and sealing material (from coal dressing plants),

  - ✓ organic carbon-rich and structure-enhancing ingredients (spent mushrooms compost).
- The use of sewage sludge, due to its smear-like consistency and high nitrogen content, is not required and may even be inadvisable. A disproportionate share hinders soil homogenization and can cause excessive growth of inoculated plant biomass.
- Fly ashes from coal and biomass combustion should also be avoided in the composition of soil substitutes. This component causes high pH and salinity in the soil substrate mixture. The soil substrate's high pH and conductivity indicate unfavourable conditions for plant growth.

Regarding the polygon test construction phase as well as the plant introduction, the main lessons learnt were as follows:

- The construction of a reclamation layer using the 2-layer technology is logistically easier but requires very precise homogenisation of soil substitute with mine waste in a 1:1 ratio.
- In areas in the temperate transitional climate zone (cold winter, warm summer), the testing ground and plant sowing should be constructed in late autumn, avoiding the negative impact of extreme summer weather events (drought, heavy rainfall) on an unplanted reclaimed area with young germinating vegetation.
- Agrotechnical treatments should be carried out perpendicular to the slope to reduce erosion.
- In the case of planting shrub seedlings, the use of fencing against animals is necessary.
- Agro-fibre should be spread around planted young shrubs to separate them from overly expansive herbaceous plants.
- Meadow communities in the first years of vegetation should be mowed once a year, in autumn, before the sowing period of undesirable plants. After the first and the second mowing, the biomass can be left on the reclaimed area to reduce water erosion.
- Botanical studies have not shown a significant difference in the conditions of vegetation introduced on a polygon built using the 2-layer technology (cheaper technology) and the multi-layer technology (more expensive technology). Thus, the 2-layer method could successfully reclaim post-mining waste heaps as a more affordable and equally effective method.

Multi-layer technology is recommended on the part of the heap where an intensive process of rainwater infiltration occurs, and the risk of acid drainage appearance is high (e.g. flat top of the heap).

10 Glossary

GIG – Central Mining Institute

EC - Electrical conductivity

DM-dry matter (%)

OM-organic matter (%)

CFA–fly ash from coal combustion

BFA–fly ash from plant biomass combustion

DL–decarbonisation lime

AG–aggregate

SL–sealing material

ES–energetic slags

SWS–sewage sludge

CM–mushroom compost

MVC-meadow vegetation cover

Mes_Mea- mesic meadow species

Dry_Mea- dry meadow species

ML- Multi-layer cover

TW- two-layer cover

PCA-Principal Component Analysis

11 References

Asik, B.B., Turan, M.A., Celik, H., Katkat, A.V., 2009. Effects of Humic Substances on Plant Growth and Mineral Nutrients Uptake of Wheat (Triticum durum cv. Salihli) Under Conditions of Salinity. Asian J. Crop Sci. 1, 87–95. doi:10.3923/ajcs.2009.87.95

Bauerek, A., Bebek, M., Fraczek, R., Paw, K., Kasperkiewicz, W., 2017. Variability of chemical composition of acidic runoff waters from an active spoil heap of mining wastes representing sediments of the cracow sandstone series of the upper silesian coal basin. Prz. Geol. 65, 450–458.

Boroń, M., Ociepińska, M., Żeber-Dzikowska, I., Gworek, B., Kondzielski, I., Chmielewski, J., 2019. Xerothermic pavements – a meadow biodiversity richness. Jaworzno case study. Environ. Prot. Nat. Resour. 30, 29–34. doi:10.2478/oszn-2019-0014

Bruce, R.., Rayment, G.., 1982. Analytical methods and interpretations used by the Agricultural Chemistry Branch for Soil and Land Use Surveys. Bulletin QB82004. Queensland Department of Primary Industries., Brisbane.

Çelik, H., Katkat, A.V., Aşik, B.B., Turan, M.A., 2010. Effects of humus on growth and nutrient uptake of maize under saline and calcareous soil conditions. Žemdirbystė=Agriculture 97, 15–22.

George, E., Horst, W.J., Neumann, E., 2011. Adaptation of Plants to Adverse Chemical Soil Conditions, Marschner's Mineral Nutrition of Higher Plants: Third Edition. Chapter 17. Elsevier Ltd. doi:10.1016/B978-0-12-384905-2.00017-0

Gitari, W.M., Petrik, L.F., Etchebers, O., Key, D.L., Iwuoha, E., Okujeni, C., 2008. Passive neutralisation of acid mine drainage by fly ash and its derivatives: A column leaching study. Fuel 87, 1637–1650. doi:10.1016/j.fuel.2007.08.025

Grzebisz, W., Gransee, A., Szczepaniak, W., Diatta, J., 2013. The effects of potassium fertilization on water-use efficiency in crop plants. J. Plant Nutr. Soil Sci. 176, 355–374. doi:10.1002/jpln.201200287

Guo, W., Nazim, H., Liang, Z., Yang, D., 2016. Magnesium deficiency in plants: An urgent problem. Crop J. 4, 83–91. doi:10.1016/j.cj.2015.11.003

Hazelton, P., Murphy, B., 2016. Interpreting soil test results. What do all the numbers mean? 3 rd Edition. CSIRO Publishing. doi:10.1111/sum.12402

Heaton, E., Voigt, T., Long, S.P., 2004. A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass and Bioenergy 27, 21–30. doi:10.1016/j.biombioe.2003.10.005

Hermans, C., Verbruggen, N., 2005. Physiological characterization of Mg deficiency in Arabidopsis thaliana. J. Exp. Bot. 56, 2153–2161. doi:10.1093/jxb/eri215

John, H., Dullau, S., Baasch, A., Tischew, S., 2016. Re-introduction of target species into degraded lowland hay meadows: How to manage the crucial first year? Ecol. Eng. 86, 223–230. doi:10.1016/j.ecoleng.2015.11.001

Kabata-Pendias, A., Pendias, H., 1999. Biogeochemistry of Trace Elements. Wydawnictow Naukowe PWN, Warszawa.

Kang, J., Hesterberg, D., Osmond, D.L., 2009. Soil Organic Matter Effects on Phosphorus Sorption: A Path Analysis. Soil Sci. Soc. Am. J. 73, 360–366. doi:10.2136/sssaj2008.0113

Klojzy-Karczmarczyk, B., Mazurek, J., Paw, K., 2016. Possibilities of Utilization of Aggregates and Extractive Waste from hard Coal Mining at Janina Mine in the Process of Reclamation of Open-pit Mines. Miner. Resour. Manag. 32, 111–134. doi:10.1515/gospo-2016-0030

Krull, E.S., Skjemstad, J.O., Baldock, J. a, 2009. Functions of Soil Organic Matter and the Effect on Soil Properties. GRDC Final Rep. CSO 00029 Residue Manag. Soil Org. Carbon Crop Perform. 1–128.

Lee, M.S., Wycislo, A., Guo, J., Lee, D.K., Voigt, T., 2017. Nitrogen fertilization effects on biomass production and yield components of miscanthus × giganteus. Front. Plant Sci. 8, 1–9. doi:10.3389/fpls.2017.00544

Lepš, J., Šmilauer, P., 2000. Multivariate analysis of ecological data [Mnohorozměrná analýza ekologických dat.]. – Biologická fakulta Jihočeské univerzity v Českých Budějovicích. České Budějovice.

Malhotra, H., Sharma, S., Pandey, R., 2018. Phosphorus Nutrition: Plant Growth in Response to Deficiency and Excess, in: Plant Nutrients and Abiotic Stress Tolerance. Chapter 7. pp. 1–590. doi:10.1007/978-981-10-9044-8

McCauley, A., Jones, C., Jacobsen, J., 2011. Plant Nutrient Functions and Deficiency and Toxicity Symptoms. Nutr. Manag. Modul. 9, 1–16.

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

Neitzke, M., 2002. Changes in energy fixation and efficiency of energy capture in above-ground biomass along an environmental gradient in calcareous grasslands. Flora 197, 103–117. doi:10.1078/0367-2530-00020

Shen, Q., Wen, Z., Dong, Y., Li, H., Miao, Y., Shen, J., 2018. The responses of root morphology and phosphorus-mobilizing exudations in wheat to increasing shoot phosphorus concentration. AoB Plants 10, 1–11. doi:10.1093/aobpla/ply054

Tokarczyk, N., 2017. Forest encroachment on temperate mountain meadows - Scale, drivers, and current research directions. Geogr. Pol. 90, 463–480. doi:10.7163/GPol.0112

US Environmental Protection Agency, 1994. Acid Mine Drainage Prediction. U.S Environ. Prot. Agency 52.

van Dobben, H.F., Wamelink, G.W.W., Slim, P.A., Kamiński, J., Piórkowski, H., 2017. Species-rich grassland can persist under nitrogen-rich but phosphorus-limited conditions. Plant Soil 411, 451–466. doi:10.1007/s11104-016-3021-z

Venterink, H.O., Güsewell, S., 2010. Competitive interactions between two meadow grasses under nitrogen and phosphorus limitation. Funct. Ecol. 24, 877–886. doi:10.1111/j.1365-2435.2010.01692.x

Weigelt, A., Bol, R., Bardgett, R.D., 2005. Preferential uptake of soil nitrogen forms by grassland plant species. Oecologia 142, 627–635. doi:10.1007/s00442-004-1765-2

Wissuwa, M., Gamat, G., Ismail, A.M., 2005. Is root growth under phosphorus deficiency affected by source or sink limitations? J. Exp. Bot. 56, 1943–1950. doi:10.1093/jxb/eri189