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Minimising Coal Mining's Impact on Biodiversity: Artificial Soils for Post-Mining Land Reclamation

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Abstract: Coal mining and the energy industry generate large amounts of solid waste, which must be disposed of in landfills and lead to numerous environmental problems. This paper presents a method for creating artificial soil mixtures based on an EU-funded international research project called RECOVERY. The main idea behind the proposed solution is the safe use of coal combustion by-products (energetic slag and decarbonation lime), mining waste (aggregate and sealing material) and spent mushroom compost as components for creating artificial soils. Laboratory tests of the soil substitutes showed low concentrations of heavy metals and high macronutrient content, adequate for proper plant growth. As a result of a two-year study on the application of soil cover on a 4000 m^2 testing ground, species characteristics for the mesotrophic, dry meadow, ruderal and segregated vegetation were found. In the second year of the in situ study, an apparent reduction in soil salinity was observed. The principal component analysis confirmed that decreasing soil salinity positively affected ruderal and dry meadow species. In contrast, high salinity levels showed no adverse effect on mesotrophic meadow vegetation. The results demonstrated that applying soil covers elaborated from industrial by-products is valuable for recovering high-acidity coal mine waste heaps.

Keywords: artificial soils; waste heap; land rehabilitation; biodiversity increase; circular economy approach

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1. Introduction

Mining waste from coal extraction and processing is one of the most significant waste streams in the European Union. In 2018, the total amount of waste in the EU27 from mining and quarrying was 26.3%, followed by other services, i.e., manufacturing (10.7%), waste and water (10.2%), households (8.2%) or energy (3.5%) [1]. In Poland, waste from mining and quarrying accounts for more than 55% of all industrial waste, while waste from energy production accounts for 10% [2]. According to Klojzy et al. [3], there is an average of 0.3 tonnes of waste material per 1 tonne of hard coal produced. Waste rock and power plant waste dumped on heaps represent a long-term environmental problem. Nevertheless, of the total amount of mining waste generated in 2020 in Poland, up to 42% was disposed of on spoil heaps [2].

Coal mining waste can be defined as the material left over from the exploration, extraction and processing of coal residues, including waste rock, slag or rock aggregates [4]. Most of these wastes are routinely used for land reclamation and landscaping. However, their properties can vary considerably depending on the origin of the waste and the geology of the coal seams. Coal combustion by-products and waste materials from mining activities may contain some macronutrients, i.e., nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) or magnesium (Mg) [5], which are necessary for plant growth and development [6]. They also include micronutrients, i.e., iron (Fe), copper (Cu), manganese (Mn), molybdenum

(Mo), zinc (Zn) and other heavy metals, high concentrations of which are not suitable for effective reclamation of post-mining sites [7,8]. One of the first problems associated with the composition of mining waste is the low capacity of organic matter that has an essential function for soil vegetation [9,10]. The second is the high content of heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb) or nickel (Ni), which are considered to be very harmful to plant metabolism [11,12].

Another crucial type of industrial waste material used in land reclamation is coal combustion by-products (CCBs) from coal-fired power plants, which consist of fly ash, bottom ash, boiler slag and flue gas desulfurization (FGD) residues [13,14]. The main contents of FGD are calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$) [15]. The addition of alkaline FGD increases soil pH and is therefore useful as an additive in the remediation of highly acidic soils, such as coal mine waste heaps.

A serious environmental problem in the coal mining industry is a process commonly referred to as acid mine drainage (AMD), which occurs in the formation of highly acidic water from waste rock and CCBs [16,17]. These contaminated waters are formed when sulfide-bearing minerals containing high concentrations of heavy metals, including Fe, Mn, Al, Cu, Ca, Pb, Mg, Na or Ni, are exposed to oxygen and water [18].

The acid formation reactions are best illustrated by studying the oxidation of pyrite (FeS_2), which reacts to the form of sulfuric acid (H_2SO_4) [19].

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (1)$$

Then, Fe^{2+} ions are oxidized to Fe^{3+} and the process releases more hydrogen ions, decreasing the pH of the environment.

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow +4Fe^{3+} + 2H_2O \quad (2)$$

$$4Fe^{3+} + 12H_2O \rightarrow +4Fe(OH)_3 + 12H^+ \quad (3)$$

The environmental consequence is a surface pH of 2 or 4 and high sulfate concentrations (1–20 g/L). This process destroys plant growth and blocks spontaneous vegetation succession for many decades.

Various neutralising agents such as lime (calcium oxide), slaked lime, calcium carbonate, sodium carbonate, sodium hydroxide or magnesium oxide and hydroxide have been used for the active treatment of acid mine drainage [16]. Based on the above, fly and bottom ashes from coal and lignite-fired power plants can be beneficially used for modification to neutralise the acid potential of mine waste and regulate trace element availability in the amended soils [20].

Another environmental problem associated with CCBs is their content of harmful trace metals and metalloids. Therefore, their application to soil must only occur after a thorough elemental analysis of both the CCBs and the soil and plant requirements [13].

The use of various organic and inorganic wastes is a common environmental practice undertaken to rehabilitate land and solve many economic problems. Municipal solid waste, sewage sludge, livestock manure or other organic wastes (for example, grape marc, rice hull or pine bark) may replace commonly used materials such as peat, sand or natural soils to form soil substitutes [21]. Organic additives improve the structure and physical soil properties by increasing organic matter, altering pH and nutrient availability [22]. However, our previous study [5] showed that the use of sewage sludge for soil remediation also has negative aspects due to the high content of biogens and heavy metals contamination. Furthermore, the direct application of waste from animal production, especially poultry manure, in the soil poses a risk of soil and groundwater contamination with pathogenic bacteria, heavy metals and pharmacology pollutants (antibiotics) [23]. For this reason, using stabilized organic waste, such as spent mushroom compost, seems preferable to sewage sludge or fresh livestock manure. Compared to other organic and mineral fertilizers, fresh compost mushroom contains about 1–2% nitrogen, 0.2–0.3% phosphorus and 1.3–2.4%

potassium [24]. However, the nutrients are released slowly over a long period of time, allowing plants to use them more efficiently.

The coal mining waste dumps of the Upper Silesian Coal Basin in Poland cover an area of over 4000 ha [25]. These landfills cause different environmental problems and have a negative influence on the landscape. The main objective of this study was to evaluate novel soil mixtures as a cover for the land rehabilitation of coal mining-affected areas. Several blends were tested as soil covers for two different semi-natural plant communities, which had a high ability to deliver ecosystem services to coal-affected areas [26]. The main purpose of these soil covers is to transform the high acidity of the residues deposited in the coal mining waste heap into an environmentally friendly mixture and to evaluate the suitability of the developed soil covers for the development of semi-natural meadow communities on land degraded by mining activities.

2. Materials and Methods

2.1. Coal By-Product and Waste Materials

Our previous study [5] confirmed that a mixture of CCBs (fly ashes from coal and biomass combustion and decarbonization lime from the water softening process) and mining wastes (aggregates and slags from coal processing) with the addition of organic materials such as spent mushroom compost may be very useful for producing artificial soils for difficult terrains.

Based on previous research, five components were selected for elaborating two soil substitute covers i.e.: decarbonization lime (DL) and energetic slag (ES) from Łaziska Power Plant, aggregate < 2.0 mm from clay shales (AG), sealing material (SL) delivered by Sobieski Coal Mine and spent compost mushrooms (CM) from the agriculture farm in Kryry. To enhance plant succession on the highly acidified spoil heap of the Janina Mine, the fly ashes from coal or biomass combustion were replaced by energetic slag. The characteristics of CCBs and waste materials are listed in Table 1.

Table 1. Physicochemical properties of CCBs and mining wastes used for soil substitutes covers.

Parameter	CCBs		Wastes [5]		
	ES	DL [5]	AG	SL	CM
pH	9.8	9.6	7.50	8.0	7.1
EC (mS·cm^{-1})	0.35	1.57	0.50	0.90	7.76
OM (%)	4.38	7.02	15.9	35.6	60.4
Ca (%)	2.74	32.0	0.43	0.34	8.22
N (%)	<0.15	0.32	0.18	0.40	2.36
K (%)	2.14	0.04	2.32	1.69	1.03
Mg (%)	1.69	5.44	0.24	0.57	0.42
P (%)	0.11	0.01	0.02	0.03	0.78
Na (%)	0.32	0.01	0.09	0.08	0.13
S (%)	0.32	0.24	3.95	0.63	1.97
Cd (mg·kg^{-1})	1	<1	4	<1	<1
Cr (mg·kg^{-1})	53	1	22	76	7
Cu (mg·kg^{-1})	46	3	85	31	29
Ni (mg·kg^{-1})	47	9	26	33	7
Pb (mg·kg^{-1})	3	4	213	53	2
Zn (mg·kg^{-1})	22	36	1281	141	183

ES—energetic slag; DL—decarbonisation lime; AG—aggregate; SL—sealing material; CM—spent mushroom compost.

The obtained results showed that a neutral pH value was measured only for the CM, whereas AG and SL components presented mildly and moderately alkaline pHs of 7.6 and 8.0, respectively. The strongly alkaline pH of DL was involved in high concentrations of calcium, up to 30%, and magnesium, up to 5%. In contrast, the pH of ES may have been involved with the higher content of calcium, magnesium and other soluble compounds in reactive forms, i.e., CaO, MgO, which in an aqueous solution form release hydroxide ions (OH^-). The highest content of organic matter (60.4%) was observed with CM as compared to the coal by-products (4.38–7.02%) and mining waste (15.9–35.6%). The nitrogen concentration revealed that all mining wastes recorded values less than 0.5%, while its concentration for CM was 2.36%. The organic additive was also characterized by a much higher content of phosphorus, 0.78%, compared to coal combustion by-products and mining waste (0.01–0.11%). Moreover, both CM and AG contained much more sulfur (1.97 and 3.95%, respectively) than other wastes, ranging between 0.24–0.63%. The concentration of heavy metals in CM and mining wastes was comparable, including the excessive zinc and lead content in AG, i.e., 1281 and 213 mg·kg^{-1}, respectively. The aggregates were also characterised by a higher concentration of Cu (76 mg·kg^{-1}) and Pb (213 mg·kg^{-1}), while SL and ES presented an excessive content of Cr (76 and 53 mg·kg^{-1}) in comparison to the rest of the components (1–22 mg·kg^{-1}).

2.2. Formulation of Soil Substitute Covers

Two types of soil substitute covers, so-called A and B, were prepared by an appropriate blending of CCBs, mining and organic wastes using the weight method (Figure 1).

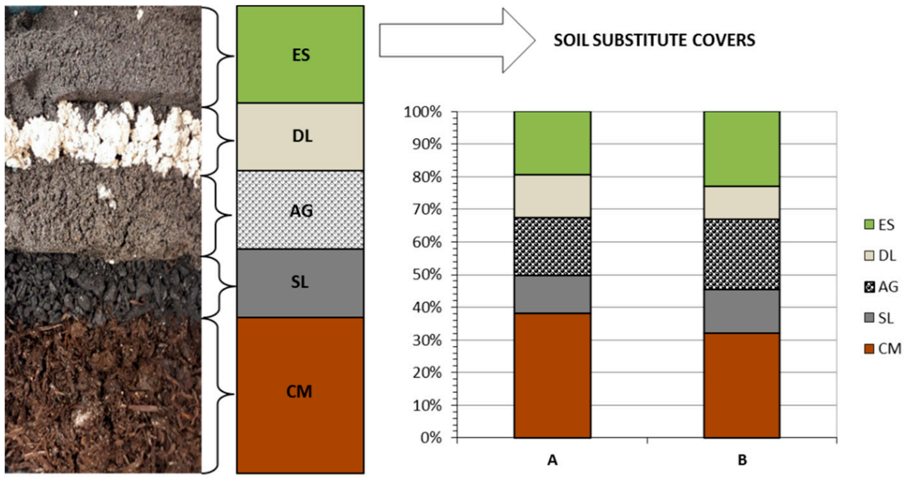


Figure 1. List of wastes and their percentage range (% m/m) for soil substitute covers: ES—energetic slag; DL—decarbonisation lime; AG—aggregate; SL—sealing material; CM—spent mushroom compost.

Soil covers differed from each other in terms of the type of components and their percentage share. The soil mixtures were elaborated for creating biodiversity in the area of post-mining activity, such as (A) low vegetation of dry and poor habitats and (B) low vegetation of mesic habitats. The reasons for such a blending process were to ensure some primary factors for ensuring a sustainable reclamation of the affected mining areas, i.e., the optimal structure of the soil blends (loose and lumpy), appropriate soil parameters (pH, hydrolytic conductivity) and adequate content of nutrients and organic matter.

2.3. Study Area

The testing ground (4000 m^2) was located on the Janina Mine spoil heap, property of Tauron Wydobycie S.A (Figure 2), which is the post-exploitation heap located in the town of Libiąż (50°05′03.5″ N, 19.18′18.7″ E). It covers an area of about 80 hectares (partly reclaimed) and reaches 35 m in height, and is one of the biggest mining spoil heaps of this kind located in the Silesia region in Poland. The annual coal production by the Janina Mine is in the range of 1000–1400 thousand tonnes. The waste heap contains waste rock, a mixture of clay shales, siltstones and sandstones with crubs of coal. Slope heaps are exposed to strong erosion caused by rainwater and snowmelt runoff. It is also a good "field laboratory" for assessing land rehabilitation techniques due to the highly acidic character of the wastes.

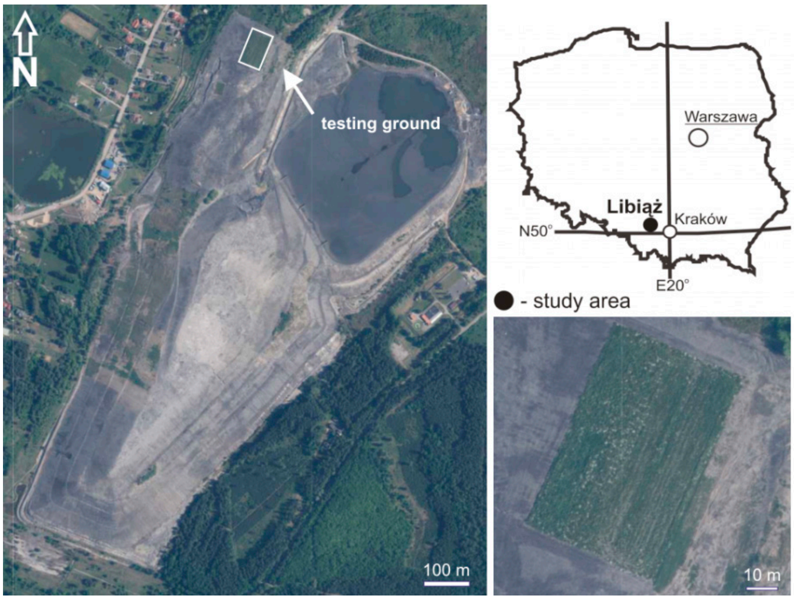


Figure 2. Geographical location of the Janina Mine spoil heap with testing ground.

Despite the passing of several years since the suspension of waste storage operations, there has been no spontaneous succession of vegetation on the surface of the Janina waste dumps (Figure 3).

(**a**) (**b**)

Figure 3. Janina mine spoil heap (**a**) acid rainwater from exposed pyritic spoil, (**b**) surface area of mining waste heap without vegetation cover.

The AMD process manifested in the occurrence of highly acidic runoff water (pH differs from 2.1 to 3.5) contaminated by metals: Al, As, Cd, Co, Cu, Fe, Mn, Ni and Zn, prevents vegetation development [27].

2.4. Analytical Procedures

The determination of the amount of organic matter (OM) was performed by measuring the loss-on-ignition of a sample at 550 °C in a laboratory furnance (HT 16/16 with a P310 controller, Nabertherm GmbH, Lilienthal, Germany). The content of the main chemical elements (Ca, K, Mg, Na, and P) and heavy metals (As, Cd, Cr, Cu, Fe, Ni, Mn, Pb, and Zn) was determined by the wave dispersive X-ray fluorescence spectrometry method (ZSX Primus II analyser, Rigaku Analytical Devices Inc., Wilmington, NC, USA), equipped with a 4 kW X-ray Rh tube. The content of total carbon (TC), and total sulfur (S_t) was determined with the infrared spectroscopy method (ELTRA CHS, Eltra GmbH, Haan, Germany), whereas the total nitrogen (N_t) content was determined by the Kjeldahl method. The pH was measured by a pH meter (CPC-411, Elmetron, Zabrze, Poland), whereas the electrical conductivity (EC) was measured using an electrode (IJ44AT, Elmetron, Poland).

The available water capacity (AWC) of the soil covers was calculated as the water required for complete hydration of the tested soil.

2.5. Seed Mixture of Meadow Habitats

Taking into account the habitat conditions on waste heap slopes, seeds of species with low and middle soil moisture requirements were used in the present study. Most of the meadow communities used belong to species typical of Central Europe, which may develop dynamic green biomass production, intensifying the rhizosphere activity and increasing the assimilation of carbon dioxide. For both types of soil substrate cover (A and B), the same mixture of seed consisting of species characteristic of dry meadow and mesic species was used (Table 2).

Table 2. Species composition of seed mixture for meadow habitats.

Type of Meadow Habitats	Producer	Species Composition
Dry meadow	Apitec, Niedzwiada, Poland	*Anthemis arvensis, Anthemis tinctoria, Betonica officinalis, Bromus erectus, Centaurea cyanus, Centaurea scabiosa, Cichorium intybus, Echium vulgare, Hypochoeris radicata, Knautia arnvensis, Lotus corniculatus, Salvia pratensis, Securigera varia, Verbascum nigrum, Vicia grandiflora, Dactylis glomerata*
Mesic meadow	Kado s.c., Pszczyna, Poland	*Achillea millefolium, Alopecurus pratensis, Chamomilla suaveolens, Crepis biennis, Daucus carota, Festuca arundinacea, Festuca rubra Leucanthemum vulgare, Lolium perenne, Lotus corniculatus, Melandrium album, Plantago lanceolate, Plantago media, Poa pratensis, Sanguisorba minor, Tragopogon pratensis, Trisetum flavescens*

2.6. Assessment of Developed Vegetation and Inventory of Plant Species

The testing ground was geodetically divided into four sections (10 $\times$ 80 m) to sow dry and mesic meadow habitats and other plants (shrubs and wetland habitats) for a further research study (Figure 4). The soil cover thickness on the ground surface was about 0.3 m. The experimental plots were set in the sections with meadow vegetation as follows: 6 plots in the dry meadow section (numbered from 1A to 6A), and 6 plots in the mesic meadow section (1B–6B). Detailed lists of the vascular plant species in the 1 m^2 experimental subplots were made in June 2021 and June 2022. The percentage cover of each plant species was evaluated using the following scale: 1%, 5%, 10%, 20% ... 100%. The observed plant species, due to their preference to occur in specific habitats, were classified into the following plant community types: dry meadow (Cl. *Agropyretea intermedio –repentis*, Cl. *Festuco-Brometea*, Cl. *Koelerio glaucae-Corynephoretea canescentis*), mesic meadow (Cl. *Molinio-Arrhenatheretea*), segatal vegetation (Cl. *Polygono-Chenopodietalia*, Cl. *Stellarietea mediae*) and ruderal vegetation (Cl. *Molinio-Arrhenatheretea*) [26]. The abundance of species classified to particular habitats defines the degree of similarity that the vegetation developed on the experimental plots to semi-natural and anthropogenic plant communities distinguished for the whole-country scale (Poland).

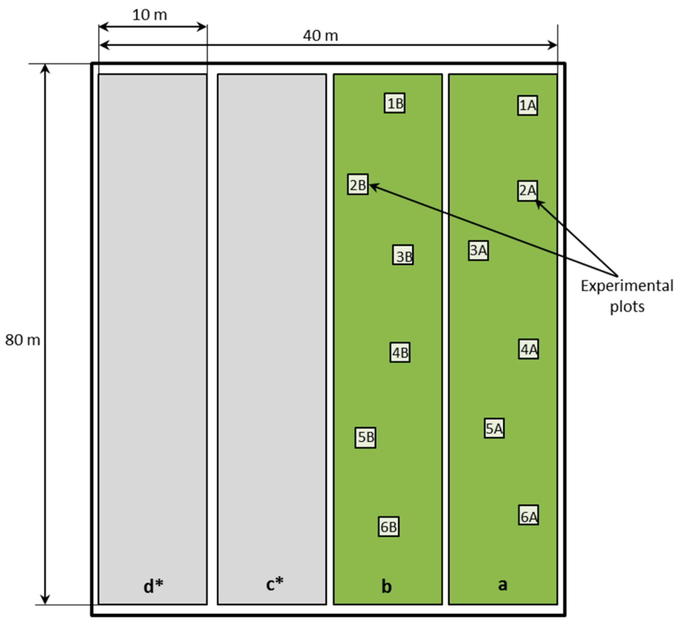


Figure 4. Design of the testing ground and experimental plots in the study area: a—dry meadow habitats, b—mesic meadow habitats, c—shrubs, d—wetland habitats, * further research.

2.7. Statistical Analysis

The normal distribution of data was confirmed using the Shapiro–Wilk test. The relationship between the vegetation variabilities and environmental factors was analysed using Pearson's linear correlation coefficient with Statistica 13.3 (StatsSoft, Cracow, Poland). Principal Component Analysis (PCA) was applied to determine conditions influencing the development of low vegetation on soil covers. The analysis was performed by using the CANOCO package. The variable's data were transformed using log(x+1) and standardised prior to the analysis [28].

3. Results

3.1. Physicochemical Properties of Soil Substitute Covers

The data gathered throughout the vegetation test with mesic and dry meadow showed a promising opportunity for implementing the tested soil covers as trials at the coal mine affected areas. The results of the nutrient concentrations in two selected soil covers are presented in Table 3.

Table 3. Physicochemical characteristic of soil substitute covers from 2021 to 2022 during meadow vegetation tests.

Parameter	Unit	Soil Substitutes Cover A			Soil Substitutes Cover B		
		2020	2021	2022	2020	2021	2022
pH		8.1	7.67	7.50	8.0	7.70	7.40
EC	$mS \cdot cm^{-1}$	6.94	2.92	0.70	6.6	2.60	1.03
OM	%	23.05	23.54	20.14	22.95	25.34	20.48
Ca	%	6.33	3.73	3.50	5.88	3.77	4.17
K	%	1.86	1.82	1.72	1.86	1.73	1.72
Mg	%	1.11	0.65	0.75	1.08	0.61	0.61
Na	%	0.22	0.16	0.09	0.19	0.13	0.08
N_t	%	0.60	0.54	0.42	0.46	0.46	0.37
P_t	%	0.21	0.16	0.16	0.18	0.14	0.14
S_t	%	3.46	2.41	2.00	3.41	2.00	1.92
AWC	%	88.88			78.22		

EC—electrical conductivity, OM—organic matter, AWC—available water capacity (the average value measured in laboratory condition).

The concentration of OM was within the range of 20.14–23.54% for soil A and 20.48–25.34% for soil B, whereas in the first year of experiment, the AWC amounted to 88.88% and 95.30%, respectively. As may be observed, after two years of growing seasons, the contents of calcium decreased from 6.33% to 3.50% for soil A and from 5.88 to 4.17% for soil B. A slightly lower decrease was also observed for magnesium content, which varied from 1.11 to 0.75% for soil A and from 1.08 to 0.61% for soil B. The results showed that the content of total nitrogen in soils A and B dropped slightly after the second year of vegetation, whereas the values of potassium and phosphorus determined in the year 2022, were comparable to the first year. Although the concentrations of the main macronutrients (N_t, P_t, K, Ca, Mg) decreased, these amounts may be sufficient for supporting plant growth and further green biomass production.

The study revealed an almost twofold reduction in S_t concentration, from 3.46 to 2.00% for the mesic meadow cover and from 3.41 to 1.92% for the dry meadow cover, with a simultaneous decrease in Fe content. Furthermore, two years after the start of the growing test, the Na concentration was below 0.10% and the soils had relatively low EC values, which corresponds to the salinity class of non-saline soils [29]. In the second year of the experiment, the heavy metals content of the soil covers was also investigated. The results are presented in Figure 5.

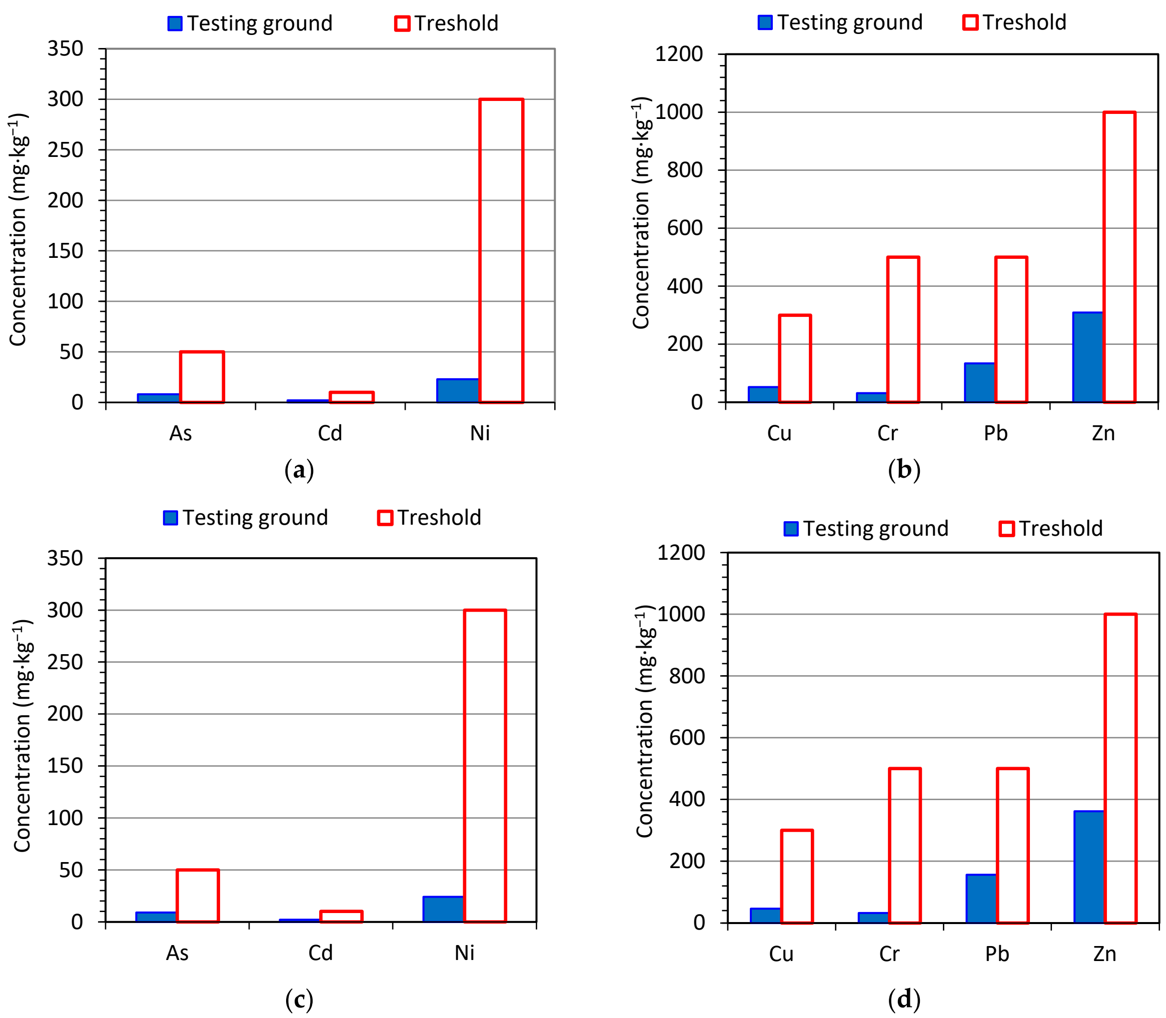


Figure 5. The concentration of trace elements in soil covers and their limited thresholds areas according to Polish Regulation [30]: (**a**) As, Cd, Cr, Ni in soil cover A; (**b**) Cu, Mn, Pb, Zn in soil cover A; (**c**) As, Cd, Cr, Ni in soil cover B; (**d**) Cu, Mn, Pb, Zn in soil cover B.

The concentrations of toxic heavy metals in soil substitute covers A and B in the year 2022 varied in the following order: Zn > Pb > Cu > Cr > Ni > As > Cd, and did not exceed the permissible thresholds for soils classified in Group III, i.e., wooded and shrub lands as well as green areas [30]. The results of our study showed that concentrations of toxic metals in soil covers A and B, which may exert a harmful effect on plant growth and development, ranged between 8–9 mg·kg^{-1} for As, 2 mg·kg^{-1} for Cd, 31–32 mg·kg^{-1} for Cr, 23–24 mg·kg^{-1} for Ni, 46–52 mg·kg^{-1} for Cu, 134–156 mg·kg^{-1} for Pb, 309–362 mg·kg^{-1} for Zn.

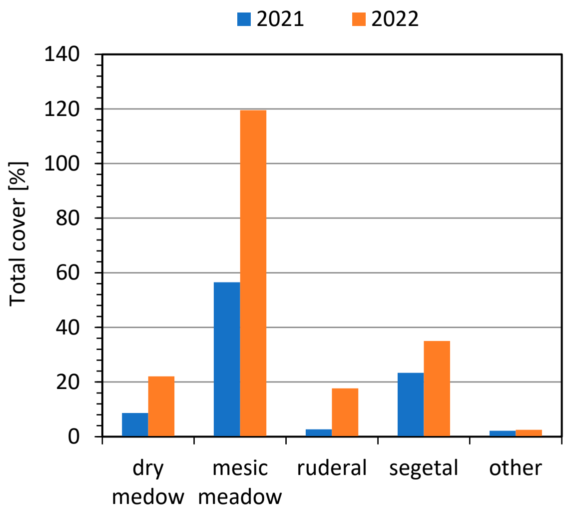
3.2. Assessment of Developed Method for Reclamation of the Study Area

In the first year of the growing season, more species were observed on soil B (26) than on A (22). The following year, the same number of plant species were observed on both soil covers (29). The comparison of the presence of species characteristic of dry and mesic meadow between the tested soil substrates are provided in Table 4. The results show that on soil substrate A, a higher occurrence frequency was observed for dry meadow species. In the case of soil substrate B, occurrences of mesic meadow species were more frequent.

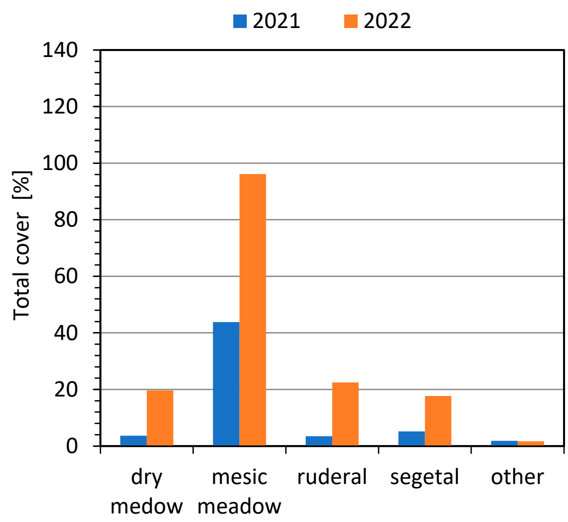
Table 4. Identification of dry and mesic habitats, from June 2021 to September 2022, on experimental plots.

Type of Meadow Habitats	Species	Experimental Plots											
		1A	2A	3A	4A	5A	6A	1B	2B	3B	4B	5B	6B
Dry meadow	*Anthemis arvensis*		v	v	v	v	v	v		v			
	Anthemis tinctoria	v	v	v	v	v	v	v	v	v	v		
	Betonica officinalis												
	Bromus erectus		v	v	v	v	v	v	v				
	Centaurea cyanus	v	v						v				
	Centaurea scabiosa	v			v			v	v	v	v	v	v
	Cichorium intybus	v		v		v		v	v		v	v	v
	Echium vulgare		v		v								
	Hypochoeris radicata												
	Knautia arnvensis				v								
	Lotus corniculatus	v	v				v	v	v	v	v		
	Salvia pratensis	v		v	v			v	v	v	v		
	Securigera varia												
	Verbascum nigrum		v										
	Vicia grandiflora												
	Dactylis glomerata			v	v			v			v		
Mesic meadow	*Achillea millefolium*	v	v	v	v	v	v	v	v	v	v	v	v
	Alopecurus pratensis												
	Chamomilla suaveolens		v	v	v	v		v					
	Crepis biennis	v							v	v	v	v	v
	Daucus carota								v	v			v
	Festuca arundinacea								v	v	v	v	
	Festuca rubra	v	v	v	v				v	v	v	v	
	Leucanthemum vulgare			v	v	v	v	v	v	v	v		v
	Lolium perenne	v		v	v	v	v	v	v	v	v	v	v
	Melandrium album		v					v	v	v			
	Plantago lanceolata	v		v	v	v		v					
	Plantago media												
	Poa pratensis	v	v	v	v		v	v				v	
	Sanguisorba minor												
	Tragopogon pratensis												
	Trisetum flavescens												

The highest average cover of the species in 2022 was observed for mesic habitat vegetation, i.e., 120% for soil A and 96% for soil B. This vegetation had the highest average coverage increase between 2021 and 2022. The average coverage of species typical of dry habitat vegetation was comparable on soil A (9% in 2021 and 22% in 2022) in comparison to soil B (4% in 2021 and 20% in 2022). The cover of species characteristic of ruderal vegetation changed from 2 to 23% (soil A) and from 3 to 12% (soil B), whereas for segetal vegetation, the coverage changed from 27 to 35% (soil A) and from 5 to 18% (soil B). These species can spread mainly by wind over long distances and fast-cover open areas. The other species of vegetation on soils A and B were below 3%, respectively. The proportion of each of the vegetation communities identified in the first and second year on dry and mesic habitats is shown in Figure 6.



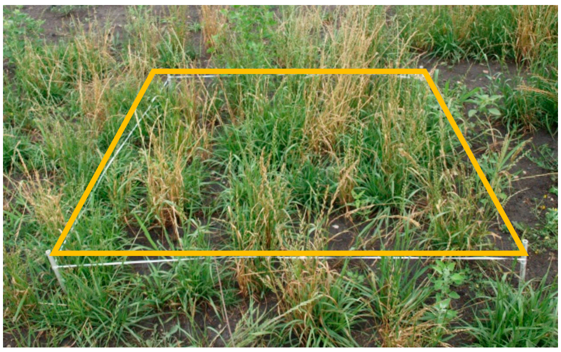
(**a**)



(**b**)

Figure 6. Cover of species characteristics for each habitat in 2021 and 2022: (**a**) soil cover A; (**b**) soil cover B.

The cover results in the experimental plots after the first and the second year are presented in Figure 7.



(**a**)

(**b**)

Figure 7. Examples of the experimental plots in the testing ground: (**a**) in 2021; (**b**) in 2022.

As illustrated in Figure 8c–f, the developed vegetation of various flower species has a high aesthetic value.

Figure 8. Development of meadow vegetation using soil covers at Janina Mine waste heap: (**a**) land area before the experiment; (**b**) testing ground after 7 months of reclamation; (**c**) testing ground after 18 months of reclamation; (**d**) testing ground in 2022 after planting and seeding; (**e**) mesic meadow vegetation; (**f**) dry meadow vegetation.

4. Discussion

Based on field results, PCA analysis was used to assess the influence of environmental factors on vegetation development (Table 5). The first ordinal axis of the PCA model (axis 1) accounts for 54.39% of the total variability of the vegetation developed in the field. This axis shows a negative correlation between vegetation development time (TIME, −0.69) and Ca soil content (−0.34), and a positive correlation with organic matter soil content (OM, 0.7) and soil salinity (EC, 0.67). The cover of ruderal vegetation and dry meadow species shows a strong negative correlation with that axis. The second axis (axis 2) explains 25.85% of the response variables' variation and shows the gradient in soil phosphorus content (P_t) and the amount of soil water available for plants. Segetal species cover shows a strong correlation with that axis (−0.95). Mesic meadow species cover has the strongest correlation (0.32) with the first ordination axis.

Table 5. Values of the correlation coefficient between environmental factors: axes 1 and 2 of the PCA model.

Parameter	EC	TIME	OM	AWC	P_t	Ca
Axis 1	0.67	−0.69	0.70	0.08	0.16	−0.34
Axis 2	0.01	−0.05	0.18	−0.38	−0.36	0.22

A graphical illustration of the first and second axes of the PCA analysis is shown in Figure 9.

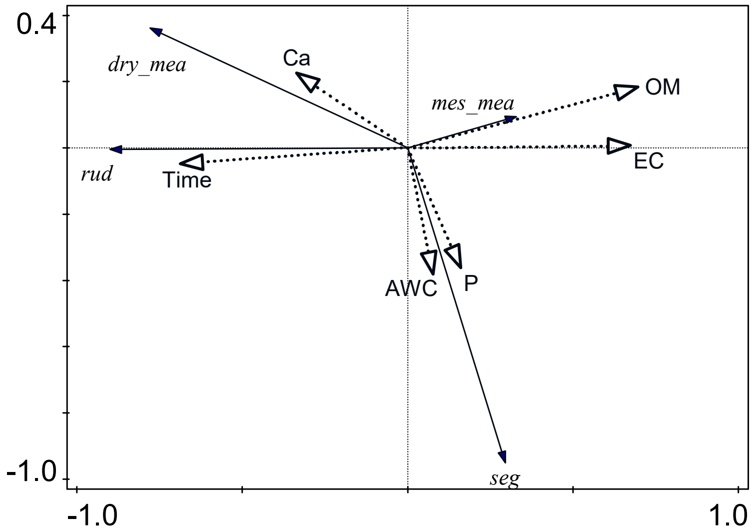


Figure 9. Principal Component Analysis (PCA) for meadow vegetation cover (MCA, %) with relation to physicochemical parameters of soils: *dry_mea*—dry meadow vegetation; *mes_mea*—mesic meadow vegetation; *seg*—segetal species, *rud*—ruderal vegetation species.

The study showed that time is a factor in both soil substrate parameters and vegetation development. A decrease in soil salinity and organic matter content was observed during the experiment. It can be assumed that the reduction of soil salinity is mainly due to ions leaching by rainwater. Part of the reduction in soil salinity was possible due to the uptake of ions from the soil by the developed vegetation. In the first growing season, soil salinity (EC > 2 mS cm^{-1}) classified the soil as very slightly saline, where sensitive plants may be restricted [31]. In the second growing season, the partial salinity of the soil decreased to a level that had a negligible impact on plants. The decreasing soil salinity could have had a positive influence on vegetation development, but mainly ruderal and dry meadow species. The increasing participation of ruderal species over the course of the experiment may also be a result of the time needed for the type of vegetation to spread. The ruderal species' seeds were not used in the seed mixture and had to reach the study field from the surrounding area. The positive correlation between time and the number of undesirable ruderal species confirms this assumption. On the other hand, the initial level of substrate salinity did not show adverse effects on mesic meadow vegetation species. This means that the increased salinity of the soil substrate shown in the first growing season allows meadow vegetation to thrive and could decrease the sprouting of undesired ruderal species.

Meadow vegetation is considered to use the land in a way that promotes soil organic carbon sequestration. Carbon accumulation in the form of organic matter takes place in the surface layer of the soil horizon [32]. Total soil organic carbon stocks in Polish upland meadows range from 1.27% to 17.9% in an optimally moist habitat [33]. Considering that organic matter contains 58% organic carbon [34], the percentage of OM in the accumulation layer of the soil cover of a mesic meadow ranges from 2.18% to 30.86%. There was a decrease in OM content from 23.54 to 20.01% in soil S3 and 25.34% to 20.48% in S5. This indicates that the decomposition of soil organic matter is faster than in carbon accumulation processes. This could be explained by the lower vegetation cover in the first growing season. Observations in subsequent years are necessary to assess the capacity of the developed ecosystems to store carbon.

It is well known that OM maintains the soil structure, improves water infiltration, increases the water holding capacity and minimises the risk of soil erosion. Furthermore, its decomposition provides plant with nutrients [9]. Research results from refs. [35,36] have shown positive effects of humic substances on seed germination, seedling growth, root initiation, root growth, shoot development and macro- and microelements uptake. Humic substances in soil may also mitigate abiotic stress conditions caused by unfavourable pH and high salinity. The initial concentration of organic matter in the developed soil substrate had a positive effect on the development of species characteristic of a mesic meadow. In the case of a dry meadow, an initial higher OM content is not required.

Organic matter content also increases the sorption capacity of P in the soil [37], which may result in decreased phosphorus availability to plants in soil covers with higher OM content. Phosphorus is an essential element for seed germination, seedling establishment and plant growth [38–41]; at the same time affecting meadow species diversity [40,42,43].

An increase in phosphorous values supported developing species related to arable land (sagittal species). The results of the study by Kamiński and Chrzanowski [44] confirm that meadows developed on soils with higher phosphorus content are more susceptible to synanthropization. This process is indicated by a greater number of species characteristic of segetial and ruderal plant communities. An increase in the proportion of species undesirable for meadow communities may also be determined by an increase in soil AWC. This soil parameter determines the capacity to reduce the risk of drought stress for plants [45].

The pH of soil covers does not significantly influence vegetation development; however, it is a significant factor affecting habitat conditions for many meadow species [39]. After the second year of semi-natural meadow vegetation, soil covers were characterised by an alkaline state (pH 7.4–7.5) and a Ca content of 3.50 to 4.17%. Such calcareous conditions often exhibit high bicarbonate concentrations in the soil solution and induce low Fe and Zn availability [46]. Soil Ca concentration showed a weak but positive effect on the development of dry meadow communities. High Ca content in habitats is characteristic of meadow community types, considered the richest and the most endangered ecosystems of Europe's natural environment [47].

There has been a significant decline in semi-natural grasslands worldwide over the past few decades [48]. Semi-natural meadow vegetation is a characteristic of ecosystems that can provide ecosystem services such as pollination, herbs for traditional medicinal use, nutrient cycling, nutrient and water retention, biomass production, recreation and climate regulation [49,50]. Data from the preliminary study showed that using CCBs and industrial wastes to develop soil covers for land rehabilitation of post-mining areas is possible, suitable for semi-natural meadow communities and environmentally friendly. However, further research is needed to assess the long-term development of semi-natural meadow communities on soil substrates from waste and coal by-products.

5. Conclusions

The results of this study demonstrated that the application of soil covers made from industrial by-products such as aggregate, energetic slag and sealing material is a valuable method for recovery of the waste heap. The addition of compost mushroom to mineral by-products improved the content of organic matter and macronutrients (N, P, K, Mg, Ca) of the artificial soils.

The laboratory phytotest with mesic and dry meadow species allowed for the selection of two of the twelve soil covers that had the highest values for the parameters, i.e., vegetation cover (90%) and a high number of meadow species. The obtained data on the physicochemical parameters of the soil substitutes showed a promising opportunity for implementing them for the reclamation of high-acidity coal mine waste heaps. The results of applying the soil covers on the testing ground showed spontaneous successions of mesic and dry meadow species after the second year of vegetation. After two years of exposition, the physicochemical analysis of soil covers confirmed the decline in electrical conductivity from 2.6 and 2.9 mS·cm^{-1} in 2021 to 0.7 and 1.0 mS·cm^{-1} in 2022. The heavy metals content in the second year of vegetation showed that concentrations of toxic elements such as As, Cd, Cr, Ni, Cu, Pb and Zn did not exceed the permissible level according to Polish regulations and may be applied in areas classified as green areas, including wooded or shrub lands. Moreover, vegetation with various flower species provides a high esthetic value to reclamation waste heap areas developed, and has the potential for delivering ecosystem services. The environmentally oriented recovery of industrial wastes, as proceeding in the current study, met circular economy goals as well as satisfied the "ecosystem-services" concept. It could be said that both the plants related to mesic and dry habitats belong to the dicotyledonous organisms, which may develop a dynamic green biomass production, intensifying the rhizosphere activity and increasing carbon dioxide assimilation.

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