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Rehabilitation of Disturbed Lands with Industrial Wastewater Sludge

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Abstract: Wastelands of the mining industry are among the largest of disturbed areas that demand revitalization. To reduce environmental impact and to better manage these geo-resources, the formation of sustainable plant and soil complexes and the restoration of self-recovery soil function are critical points. The successful return of vegetative cover at post-mining sites requires eliminating the deficiency of organic matter. For this, we assessed the usability of non-traditional ameliorants to provide a better understanding of benefits from mutual dependencies of environmental resources. To prevent losses and to close resource cycles, we studied the applicability of wastewater sludge from the pulp and paper (SPP) industry as an amendment to counteract soil degradation and rehabilitate human-disturbed lands. Waste rock limestone, beresite, and phosphogypsum substrates of post-mining sites were used in vitro for the application of sludge and peat mixture and consequent grass seeding. The formed vegetative cover was analyzed to compare the germination and biomass growth on reconstructed soils. We assessed the efficiency of ameliorant combinations by two approaches: (1) the traditional technique of cutting-off plant material to measure the obtained plant biomass, and (2) digital image analysis for RGB-processed photographs of the vegetative cover (r^2 = 0.75–0.95). The effect of SPP on plant cover biomass and grass height showed similar results: land rehabilitation with the formation of a 20 cm soil layer on mine waste dumps was environmentally suitable with an SPP:soil ratio of 1:3. However, excessive application (ratio 1:1 of SPP to the soil) negatively affected seed germination and plant vegetation.

Keywords: land revitalization; post-mining development; sustainable land-use management; resource nexus; waste recycling; soil restoration; biomass production

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1. Introduction

1.1. Rehabilitation of Post-Mining Areas

Post-mining sites are classified as technogenically disturbed lands due to the impossibility of using them in accordance with their economic and administrative purposes, a high degree of land degradation, and the adverse environmental effects of wind deflation and water erosion [1,2].

Major impacts arise from disturbed areas of mining waste dumps [3]. These sites are characterized by complex landscape damage [4,5], geochemical transformation, and physical disruption of soils. The local environmental situation can be improved by sustainable land-use management through actions of rehabilitation and (or) conservation [6,7]. A mix of engineering and biological work allows the formation of a sustainable soil–plant complex [8,9] and further phytostabilization [10].

According to the FAO World Reference Base for Soil Resources, the studied soils are classified as technosols, as such, their technical origin prevails over their properties and pedogenesis. The successful development of vegetative cover on these soils requires elimination of the organic matter deficiency [8,11,12]. A restored balance of the mineral and organic components improves the structure of technosols [13–16], optimizes soil conditions [17,18], and provides local biocenosis with nutrients [19–21].

1.2. Wastewater Sludge as a Potential Ameliorant

The proper selection of ameliorants is one of the decisive points in the rehabilitation of post-mining lands: inexpensive organic amendments with a prolonged effect are the priority. In this aspect, sewage sludge (SS) is being studied as a non-traditional ameliorant for the reclamation of human-disturbed lands [22].

Sewage sludge is derived as a residue product from the biological stage of wastewater treatment, and in this way, SS may be characterized by a varied range of products of microorganism vital activity. Sewage sludge contains high concentrations of organic matter and numerous nutrients, including nitrogen and phosphorus. This makes SS a potentially inexpensive organic ameliorant for land rehabilitation [23–25].

The high content of P makes it possible to classify SS as a phosphorus ameliorant. The shares of plant-available P [20,26,27] and N rises [28,29] in soils treated with SS. The high amount of organic matter in the sludge improves aggregate stability, which positively affects the physical characteristics of the soil in terms of its water-holding capacity [20], density, and erosion resistance [14,28,29]. On the other hand, higher levels of several other nutrients, K, Ca, Mg, and Na [20,29], and of metals, Cu, Zn, Pb, Mn, Cr, and Cd [30–33], are also noted in treated soil.

Due to the raised contents of metals and the ecological risk of their leaching, migration, and accumulation, it is necessary to consider the pH of treated soil [34,35]. The pH of SS is mainly determined to be in the range of 6.5–7.5 [20,36–38]. However, the introduction of sludge does not equally affect the acidity and electrical conductivity of the soil [29,39]. Research results indicate both an increase [30,40] and a decrease [24,41] in soil acidity after adding SS.

The application of optimal sludge doses (no more than 15–45%), improves vegetative cover [37,42,43], stimulates biomass production [20,43,44], and positively affects the rate of plant growth [20,30,37,43,45]. However, opposite results may also be achieved. In [27,46,47], excessive SS application has led to plant growth inhibition, which could be due to the phytotoxicity threshold of the sludge being reached.

Differences in the impact of SS on soil–plant complexes can be explained by the heterogeneity of the sludge compositions. The chemical composition and physicochemical properties of the sludge can vary depending on the wastewater itself, the treatment system, and the sludge processing [31,48].

Municipal sewage sludge (MSS) is actively used as a soil additive in agriculture and forestry, land restoration, and reclamation of infertile soil. Even though MSS contains waste products of microorganism activity, mainly attributed to low hazardous substances (e.g., classification of the Russian Federal Law No. 89-FZ, 'On Production and Consumption Waste'), the sludge can contain a significant amount of toxic inorganic and organic compounds, dangerous pathogens, and high concentrations of metals [20,31,42,49]. To prevent soil contamination, SS is processed by stabilization and disinfection, and assessed for compliance with the regulations. Currently, regulation is mainly carried out in terms of general characteristics: chemical composition, the content of metals, and quantity of pathogens (according to GOST R 54534-2011, GOST R 17.4.3.07-2001, and GOST R 54651-2011).

Due to differences in the chemical composition and physicochemical properties of wastewater sludge of industrial origin, their distinct assessment of applicability is required [50]. This study, as a solution, proposes to use wastewater sludge from pulp and paper mills (SPP) for the replenishment of organic matter and nutrients to reclaim dumps. Seven of the ten largest PPMs of the Russian Federation (Figure 1) are in the Northwestern Federal District of the Russian Federation. The production rate accounts for more than three thousand tons of dry SPP per year (without dehydration, the moisture content of

SPP is over 80–90%). In the same district, 123.3 thousand hectares of disturbed area needs remediation (according to the state report 'On the State and Protection of the Environment of the Russian Federation in 2017').

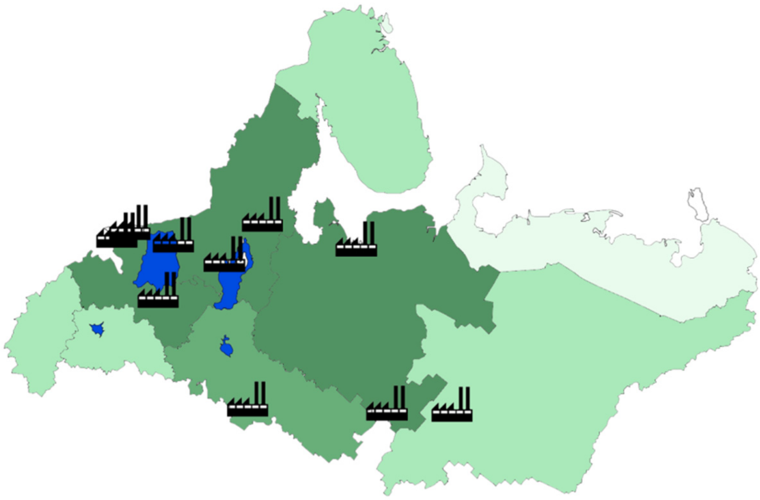


Figure 1. Map of the largest pulp and paper mills in the Northwestern Federal District of the Russian Federation; shades of green indicate production volume, blue is for water bodies.

The composition and physicochemical characteristics of SPP indicate their amelioration potential. There is a high content of organic matter, phosphorus, nitrogen, and nutritious macro and microcomponents (such as Ca, Fe, and Mn), as in MSS [51]. However, there are also results with low levels of nutrients [52], that confirm the need for each sludge to be assessed.

Wastewater sludge from pulp and paper mills (SPP) and MSS differ in the presence of impurities of lignin and cellulose fiber [53], and increased C: N ratio, which can be an obstacle for available nitrogen [54]. Concerning the cultivated soil, SPP improves the water-holding capacity [54], and the presence of fiber improves the structure of the soil and reduces the effect of water erosion [55]. That makes SPP a potentially inexpensive organic ameliorant.

Therefore, the main aim of this work is to evaluate the efficiency of SPP as a soil amendment for disturbed post-mining areas, with the following goals: (1) determination of SPP and optimal soil composition for wasteland reclamation, and, (2) evaluation of the growth efficiency and plant cover formation on reclaimed layers of soils and composition of mine waste.

1.3. Assessment of Suitability of Non-Traditional Ameliorant

The assessment of the applicability of non-traditional ameliorants considers two issues: (1) amelioration potential, and, (2) environmental safety of the substrate.

The evaluation of ameliorants is based on two method paths: direct and indirect assessment of the substrate. Direct assessment consists of analyzing the chemical composition and physicochemical characteristics of the ameliorant and their compliance with the regulated norms. Indirect methods imply an evaluation of an ameliorant through an assessment of the impact on: (1) plants—analysis of plant growth and vegetation [56–58], and, (2) soil organisms—the qualitative and quantitative composition of soil microorganisms.

The advantage of such indirect methods is in the assessment of the impact of the ameliorant on the two most influential factors in the ecologically effective restoration of technosols: (1) on plants, to reduce the negative environmental impact by the formation of a turf layer [59], and, (2) on soil organisms, to play an essential role in the main processes of soil formation. This method path reduces the time, labor, and material costs for determining the entire spectrum of possible components and physicochemical characteristics of the analyzed ameliorant (toxic organic compounds, pesticides, metals, various salts, etc.) [46,58].

2. Materials and Methods

We focused on assessing the rate of formation of the soil–vegetation complex during the amelioration and rehabilitation of disturbed lands. The soil–plant complex formation was evaluated by analyzing the growth and development of grass plants on the formed models of mine waste layers. We used two methods of measurement to analyze the growth and development of vegetative cover: a traditional approach for collecting and recalculating plant material, and alternative digital methods of data processing [60–63].

2.1. Materials

2.1.1. Wastewater Sludge

Wastewater sludge from the pulp and paper mill (SPP) was taken from a biological wastewater treatment facility of sulfite pulp production. The sludge was a grey mass waste, consisting mainly of excess activated sludge with various possible inclusions: lignin substances, alumina, and cellulose fiber [43,53,55]. The sludge was dried and left for an incubation period of up to 90 days to reduce the phytotoxicity of the sediment and stabilize the compounds, according to Hechmi et al. [64]. The main properties of SPP (pH, total C, N, and K, and metals—Mn, Zn, Cu, and Pb) were determined by standard methods: the content of carbon, hydrogen and nitrogen were found in the air-dry state of SPP samples using a LECO CHN628 analyzer (USA); the phosphorus content was determined using a Hach Lange DR 5000 spectrophotometer (Germany); qualitative chemical analysis of metals was carried out using a Shimadzu ICPE 9000 atomic emission spectrometer (Japan). The composition of the sludge is shown in Table 1.

Table 1. Results of physical and biochemical properties of used SPP compared with average compositions of municipal sewage sludge (MSS) and sludge from pulp and paper industry (SPP).

Characteristic	SPP	MSS	SPP
	This Work	Ref.	Ref.
pH	6.00 ± 0.50	6.6 [33], 6.86 [38] 6.96 [37], 6.98 [65] 7.05 [36] 7.03–7.12 [42]	6.11 [66] 6.56 ± 0.09 [67] 6.71 [68] 7.38 ± 0.09 [69]
Electrical conductivity, µS/cm	0.56	2.61 [36], 2.83 [26], 2.85 [33]	1.15 ±1.44 [67] 1.70 [68]
Organic matter, %	96.00 ± 0.1	26.6 [37], 27.57 [38] 52.7 [36], 65.0 [65] 83.2 [26], 83.5 [70]	10.82 [66] 63.7 [68]
C, %	47.21 ± 0.15	Organic 47.7 ± 13.7 [71] Total 41.6 ± 3.5 [72]	6.28 [66] 26.0 [52] 41.2 [73]
N, %	0.36 ± 0.05	4.83 [37], 5.22 [26] 19.4 [42] 78 [33]	1.68 [52] 3.90 [68] 4.18 [73]
P, %	0.16 ± 0.05	2.43 [37], 3.9 [70] 20.2 [42]	0.29 [52] 0.867 [73] 2 [55], 3.83 [68]
Mn, mg/kg	Below detection limit	210 [20] 560.70 [65]	109.7 ± 3.1 [69]

Table 1. *Cont.*

Characteristic	SPP	MSS	SPP
	This Work	Ref.	Ref.
Zn, mg/kg	430 ± 50	534 [36], 592.8 [70], 667.62 [65] 952.1 [37], 1062 [20]	165 [52] 258.0 ± 7.2 [69]
Cu, mg/kg	210 ± 10	90.0 [36], 96.00 [38] 162.56 [65] 843.8 [70], 975 [42]	69 [52] 133 ± 15 [69]
Pb, mg/kg	Below detection limit	13.53 [38], 15.9 [70] 48.2 [20] 186 [42]	33.5 ± 1.1 [69]

Depending on the reviewed literature source, the data accuracy may be not presented by the authors. For the parameters with significantly varying numbers (such as organic matter), the numbers were shown in a single row if the values were close enough.

2.1.2. Mining Rocks for the Rehabilitation Layer

The experiment was based on three types of mining waste: (1) waste rock from gold mining, (2) phosphogypsum from storage facilities of the phosphate fertilizer production, and (3) crushed limestone from mine stockpiles. In (1), beresite is a low-temperature metasomatic rock characterized by quartz, sericite, and carbonate, resulting from the replacement of both igneous and sedimentary protoliths. Mining operations in Russia provide large masses of these waste rocks; the composition of the studied samples is shown in Table 2.

Table 2. Average compositions of waste rock, minerals are listed in descending order.

Carbonaceous Beresites, C (Total) = 0.5–9.0%				Argillisites–Beresites, C (Total) ≤ 0.03–1.20%			
Unaltered	Low Alteration (5–15%)	Pervasive Alteration (15–50%)	High Alteration (>50%)	Low Alteration (5–15%)	Pervasive Alteration (15–50%)	High Alteration (>50%)	
						Sericitic	Quartzitic
quartz	quartz	quartz	quartz	hydrosericite	carbonate rock	sericite	quartz
plagioclase	biotite	hydrosericite	sulfide (pyrite, arsenical pyrite)	quartz	sericite	carbonate rock	sericite
K-feldspar	muscovite	carbonate rock (ankerite)	carbonate rock	sericite	quartz	quartz	carbonate rock
biotite	hydrosericite	sericite	+/− sericite	kaolinite	kaolinite	kaolinite	kaolinite
muscovite	sericite	carbonaceous matter	hydrosericite	+/− carbonate rock	+/− hydrosericite	pyrite	pyrite
carbonaceous matter	carbonaceous matter	pyrite		clinkstone	clinkstone	+/− clinkstone	+/− clinkstone
	+/− carbonate rock	+/− muscovite		muscovite	pyrite		
	tourmaline	tourmaline		pyrite			

In (2), phosphogypsum is the calcium sulfate hydrate formed as a by-product of phosphate fertilizer production, consisting mainly of $CaSO_4 \cdot 2H_2O$ (>80%). The volume of waste buried at gypsum disposal and storage facilities can reach tens of millions of tons [50].

In (3), crushed limestone is primarily composed of calcium carbonate mineral (>97%) from mine dumps. According to the analysis of particle size distribution, the diameter of crushed chips varied between 8 and 25 mm. Laboratory analysis of mine waste samples indicated their close geochemical proximity to the global abundances of the elements (Table 3).

Table 3. The average element composition of used mine waste, mg/kg.

Beresite Waste Rock		**Phosphogypsum**		**Limestone**	
Mg	8300	S	236,600	Ca	387,604
Na	8770	Ca	280,202	Mg	17,000
Ca	8050	Si	3597	Mn	23.00
Ti	6000	P	3226	V	2.10
Mn	840	Al	1799	Zn	1.20
Ba	720	Fe	1747	Ni	1.20
V	180	F	1600	Cd	0.74
Sr	130	Na	297	Cu	0.47
Zn	102	K	249	Pb	0.10
Cr	99	Cl	181	As	0.10
Ni	75	Mg	200	Sb	0.10
Cu	49	Mn	77		
As	31				
Co	23				
Pb	14				
Cd	2				
Mo	1				

2.1.3. Soil

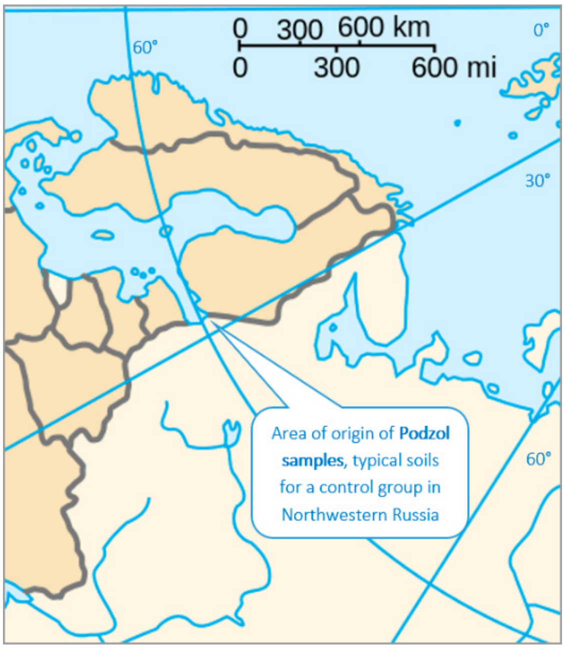
The soil of natural origin for the control group was sampled in the Leningrad Oblast at the field-protective territory, as human-altered soil (Figure 2, N60.2811, E30.2342). Soil samples represented the upper 30 cm fertile layer of deformed sandy Podzols (>80% of the 0.05–2.00-mm fraction). The soil density was 1.3 ± 0.05 g/cm^3, the pH$_{water}$ was of 5.00 ± 0.5, and the content organic matter 6.85 ± 0.7%. The soil was air-dried and passed through a 2-mm sieve.

2.1.4. Peat Mixture

Peat mixture is an alternative experimental ameliorant for comparing and assessing the SSP applicability degree as a soil amendment. Peat mixture was studied because of its highly widespread use as a soil additive in soil rehabilitation works. The peat mixture that was used was a commercial product, being a sifted and deoxidized peat of medium decomposition with the addition of lime (100–180 mg/L nitrogen (NO_3 + NH_4), 135–255 mg/L phosphorus (P_2O_5), 115–215 mg/L potassium (K_2O), and pH~5–6).

2.1.5. Plant Material

The effect of soil additives was assessed on the mix of two plant species of the cereals family: ryegrass *Lolium perenne* and meadow fescue *Festuca pratensis*. Ryegrass and fescue are locally widespread species of flora that adapt well to anthropogenic conditions and are recommended for land reclamation. The seeding rate of the grass mixture was set as 200 t/km^2 (20 centner /ha), according to GOST R 57446–2017 'Best available techniques. Disturbed lands reclamation. Restoration of biological diversity'.



(**a**)

(**b**)

Figure 2. Soil sampling area: (**a**) provenance of typical soils of coniferous woodlands in Leningrad Oblast (based on the free blank map, commons.wikimedia.org); (**b**) agricultural land and forest shelter belts with disturbed Podzols westwards and southwards of a cleared field of the rural settlement of Agalatovo (based on the Yandex satellite image).

2.2. Trial Set-Up

An experimental setup consisted of models of the mine waste layers (dump surface) and soils with plant cover. The models were formed at the working surface of 15 × 15 cm according to the following scheme: a 15–20 cm thick layer of the dumped waste and 20 cm of cultivated soil with soil additives, as a minimal required layer thickness for land rehabilitation.

The comparative evaluation was conducted in two types of ameliorants (soil additives): a wastewater sludge of pulp and paper industry, and a peat mixture as an alternative soil additive. The application of soil additives was carried out at three established ratios based on recommendations for introducing a peat mixture, recommendations for the optimal soil density for grass plants, a literature review of scientific works in this field, and preliminary analyses of substrates. To assess the effective ratio of soil additive to soil, all other models were formed with the addition of the ameliorants at ratios (by volume) of 1:1, 1:2, 1:3 (SPP/peat:soil).

After stabilization of the complexes (1 week), seeds of the grass plants were evenly sown in all models. The general scheme of the model complexes and their principle of formation is shown in Figure 3.

The complex of models was set-up in favorable microclimatic conditions (T > 20 °C; RH (atm) < 50%, W (soil) < 80%) with LED phyto-lighting providing the required lighting conditions (full spectrum of luminescence, 35 W/lamp).

The experiment was carried out for 70 days to complete all grass vegetative periods (60–70 days); the results of the study represent 40 days, to evaluate the exponential growth stage of the grasses (ryegrass *Lolium perenne* and meadow fescue *Festuca pratensis*). The following parameters were measured in the plants: seed germination, biomass growth, and growth rate.

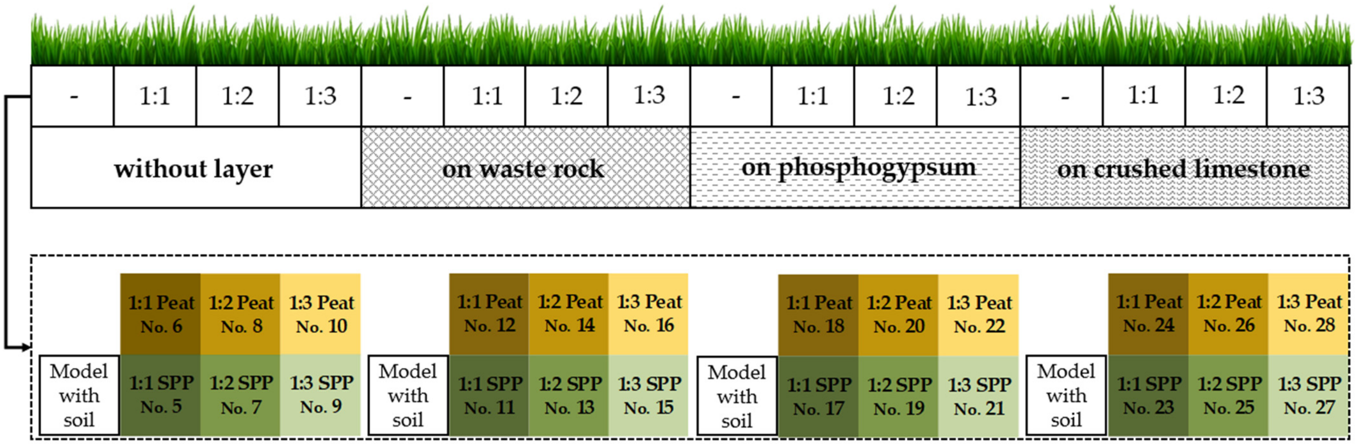


Figure 3. Scheme of the formation of 28 model types with side and top views. Models consist of: A group—control models with soil on different layers, B group—six types of models with different substrates (SPP, peat with soil) and their ratios (1:1, 1:2, 1:3) without a layer for rehabilitation, C group—six types of models on a rehabilitation layer of waste rock, D—six types of models on a rehabilitation layer of phosphogypsum, E—six types of models on a rehabilitation layer of crushed limestone.

2.3. Measurements Method by the DIA for Plant Cover Assessment Trial

The assessment of the applicability of non-traditional ameliorants for plant cover includes two measurement approaches: (1) the traditional method measuring physical quantities (seed germination, grass height) and the cutting of plant material, and, (2) a method using digital image analysis (DIA).

The method of DIA consisted of a systematic approach to photographing vegetative cover following the plant material analysis [60,62,74]. The advantage of this method (in comparison with the traditional approach) lies in the obtainment of data without high expenditure of materials and time (the method is carried out without destroying the analyzed plant material) [60,75,76].

The measuring method for DIA consisted of data collection (shooting plant material) and processing digital RGB (Red, Green, Blue) images. Digital processing of images was carried out using the Java-based open-source software ImageJ as follows: (1) removal of the background (soil, stones, various inclusions, etc.) [62,77,78], counting [78], classification [79], information processing based on color correction [62,75], and measurements of determined physical quantities (the number of units of pixels, roundness, lines—for recalculating biomass, seeds, and shoots) [62,80].

2.4. Analysis of Plant Growth and Vegetation

Vegetative cover and the accumulation of plant biomass are essential for restoring the technogenic ecosystem [8]. Plant vegetative cover prevents land degradation and air pollution by wind deflation and water erosion. Sustainable plant and soil cover have a beneficial impact on environmental security and quality.

Vegetative cover assessment was carried out on all growth stages of grass plants: germination and exponential growth stage by biomass and plant height. For plant biomass and growth rate, a *Gompertz sigmoid function* analysis was used [81].

2.4.1. Germination

The germination assay included a comparative assessment of seed germination percentages in the studied models, to the control groups of models. The germination assay was carried out on two species of grass plants—ryegrass *Lolium perenne* and meadow fescue *Festuca pratensis*. The calculation of germination was estimated based on the number of germinated seeds (%) for 5–7 days from the day of planting. The recalculation was carried out using digital image processing.

2.4.2. Plant Cover Biomass

The biomass of the vegetative cover was analyzed by two methods of measurement: the traditional method, with the destruction of plant material, and the digital data processing method. Both methods of measurement were conducted in the period of exponential grass cover growth:

1. Direct visual measurement (traditional method): three-time cuts of aboveground plant material (3 cm from the ground) were made bi-weekly to measure an increase in the biomass.

2. Digital image analysis (alternative method): This was based on a digital RGB-image analysis of vegetative cover. The method was carried out on a 2–3 day RGB image shooting basis to estimate the biomass growth through the LAI (leaf area index). The index characterizes vegetative cover as the area of vegetative cover per unit of surface (land) area. Dimensionless quantity reflects the plant unit's projected area (LAI = leaf area/land area, m^2/m^2) [62,75]. An example of the RGB image processing results is represented in Figure 4.

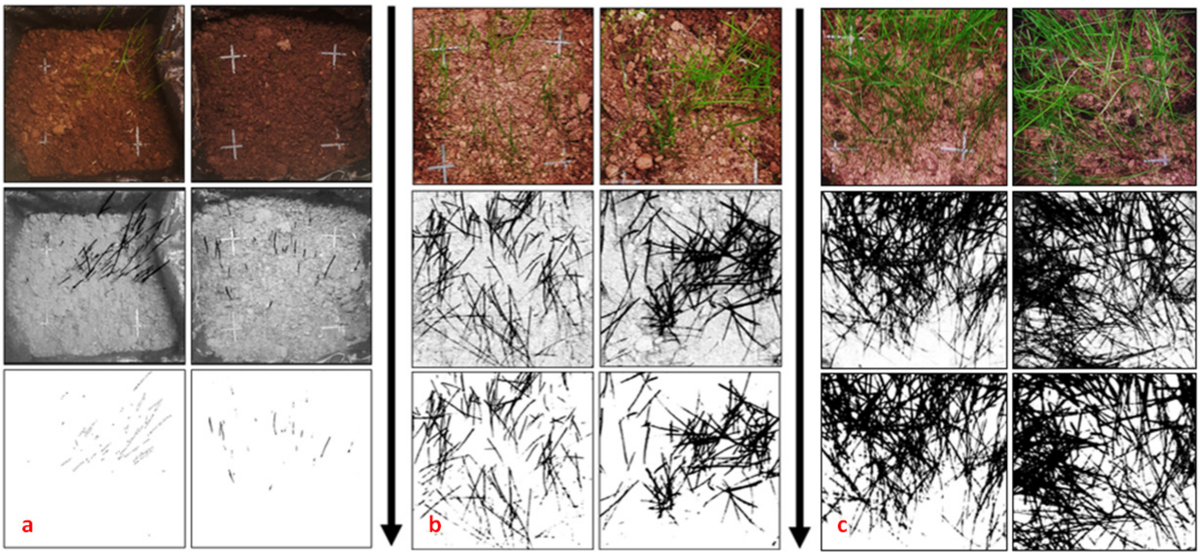


Figure 4. Example of images for digital RGB image processing (in steps) for grass cover in different vegetation stages (1,2,3 weeks): (**a**) RGB image before digital image processing; (**b**) color correction for background removal; (**c**) removal of the background (soil, stones, various inclusions, etc.).

2.4.3. Plant Cover Height Rate

The height rate of the vegetative cover was analyzed by DIA which was based on a digital RGB image analysis of vegetative cover [82]. The method consisted of 2–3 days of RGB image shooting of grass cover, in height, against a black background, with a measuring scale beside the plant cover. The scale was selected automatically on the image and the pixel/mm ratio was calculated by the scale. The background was separated from the plant semi-automatically. Digitization of grass cover for the estimation of the plant cover height was based on comparison of the obtained measured growth lines with the size marks.

2.4.4. Data Analysis

Origin 8.5 Pro software (OriginLab Corporation, Northampton, MA, USA) and Java-based open-source software ImageJ were used to analyze the experimental data. The normality of distribution and homogeneity of variance were tested; the differences among treatments were analyzed by ANOVA tests.

3. Results and Discussion

3.1. Germination

The germination assay was carried out to estimate the amelioration efficiency on the substrates in comparison with the control soil, and to assess the phytotoxicity of the treated soil. Germination assay identifies unsuitable conditions, i.e., soil salinity, presence of toxic compounds, and plant nutrition deficiency [54,58,83].

The germination and biomass growth assays showed that the germination of seeds in the studied soil–plant complexes of the grass mix (ryegrass *Lolium perenne* and meadow fescue *Festuca pratensis*) depended on: (1) the ratio of the components and, (2) waste rock layers. The germination results are shown in Figure 5.

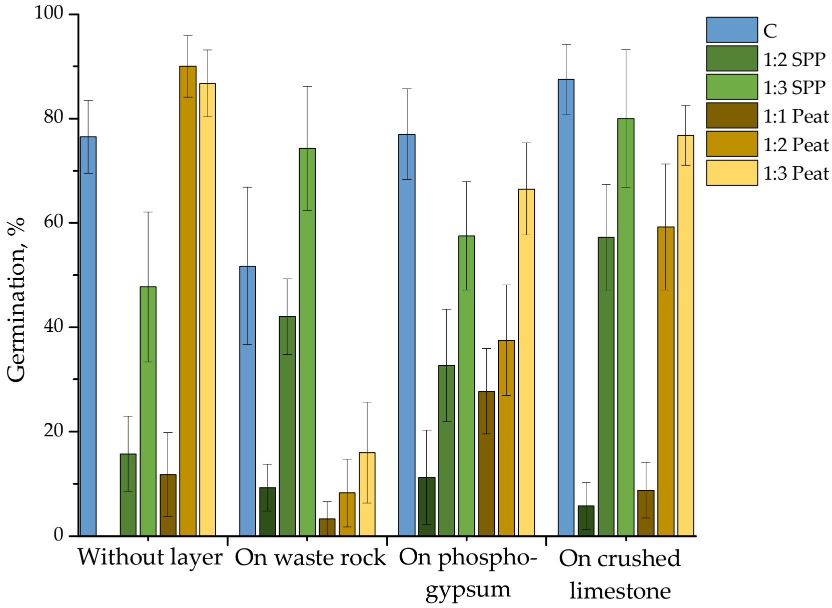


Figure 5. Diagrams of seed germination (%) by four groups of rehabilitation layers with seven types of models—control model (soil), wastewater sludge SPP and peat mixture: A—without layer, B—on waste rock, C—on phosphogypsum, D—on crushed limestone. The data represent the mean of 4 replicates; the vertical bars indicate standard deviations.

The results showed high germination levels on the control soils (~70–80%) relative to the treated soils, which is explained by the high fertility of the control soil. The optimum conditions for seed germination were obtained at: (1) a ratio of 1:2 (peat:soil)—50–60%, and, (2) a ratio of 1:3 (SPP/peat:soil)—65–75% and 60–70%. Results indicated a non-phytotoxic effect of SPP in optimal ratios for ryegrass and meadow fescue. However, soils treated with peat mixture showed healthier results of seed germination at most types of layers than soils treated with SPP.

Drastic inhibition of seed germination was observed at soils treated with an extensive amount of SPP, 1:1. Similar results were observed in earlier studies [16,69]. Hence, high dosages of SPP should be avoided to prevent a negative effect on plant cover formation.

Evaluation of seed germination of ryegrass and meadow fescue on reclaimed layers showed a difference in germination, which can be explained by: (i) neutralization of the soil layer due to waste forming dumps (layers), (ii) optimal regimes (air, water, and nutrient), and (iii) the degree of soil moisture. Optimal air regimes are determined by the density of the substrate and the ratio of the components; the water regime depends on the moisture capacity and water loss of the substrates; the nutrient ratio depends on the content of the applied components in the initial additive. Factors (ii) and (iii) can be formed by differences in substrate densities and the ratio of components, and the influence of factor (i) is further confirmed by the analysis of the biomass of a vegetative cover and the percentage of germination on waste rock models. The lowest results were observed in model groups formed on the waste rocks, and the highest was found on the crushed limestone layer.

Speaking of the result dissimilarity, we assume that several factors could affect the difference in the seed germination. Low seed germination on the waste rock can be explained by the particle size distribution: the rest of the model mixtures have a forming mineral layer of low water permeability, while the 1–4 cm beresite crushed specimens provide better water drainage and thus can contribute to moisture shortage under equal laboratory precipitation. Furthermore, SPP is characterized by a higher water-holding capacity as compared with peat mixture, so the seed germination on waste rock varies significantly. The control samples confirm this hypothesis: considering the variability of germination over the blank layer, crushed limestone, and phosphogypsum, we see levels close to 80%, while over the waste rock, the percentage is normally below 70%, close to 50%. Moreover, the capillary uptake of metals from the mineral substances may inhibit the grasses as reported in early studies by Aoyama and Kuroyanagi [83] and recent laboratory research by Wiewióra and Żurek, [84] and several other authors.

Overall, the results of the seed germination assay determined that with the application of a rational amount of SPP, there is no phytotoxic effect on seed germination from the treated soil. However, the results of the experiments could be influenced by many other factors: salinity [54,58,84] (and EC [85]), excessive ammonium nitrogen levels [16,54,58], high amount of metals [54], and poor physical structure [86].

3.2. Plant Cover Biomass

An analysis of biomass sections was carried out in three-time measurements by weighing plant material cuts. The results of the plant cover biomass assay (weight of plant material cuts) are shown in Figure 6.

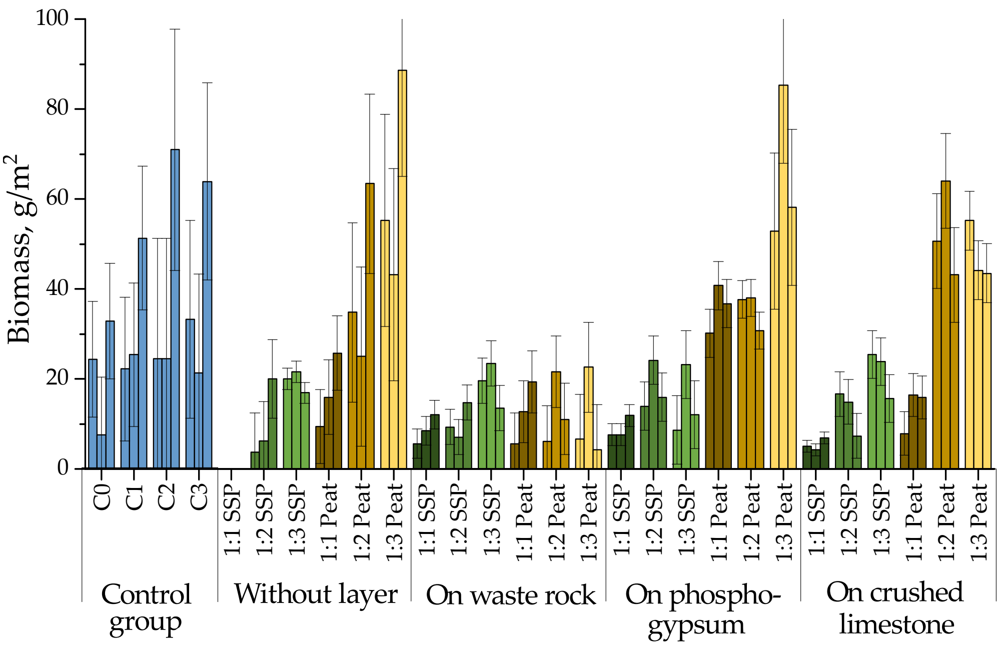


Figure 6. Diagram of the biomass by the weight of plant material cuts (g/m^2): A group of models: A—without layer, B—on waste rock, C—on phosphogypsum, D—on crushed limestone; with six types of wastewater sludge and peat mixture (SPP, peat) and ratios (1:1, 1:2, 1:3); with 3-time measurements. The data represent the mean of 4 replicates; the vertical bars indicate standard deviations.

The method of plant biomass analysis using DIA and LAI made it possible to analyze the rate of plant biomass growth over the entire growing season (exponential growth stage). The result of 36 days of measurement reflected the main trends and identified the main factors of the impact on the reclaimed layer and formed plant–soils complexes (Figure 7).

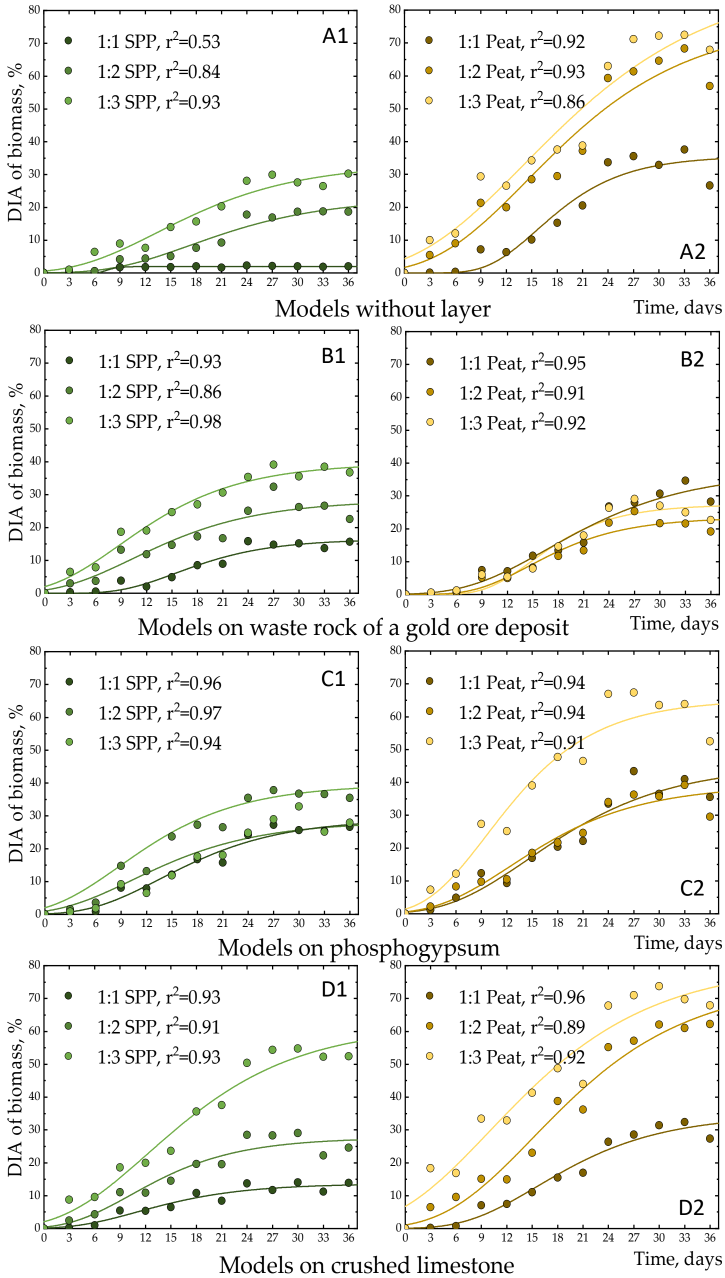


Figure 7. Rate of plant biomass growth by DIA and LAI (%): A—on the model without layer, B—on the waste rock of a gold ore deposit, C—on phosphogypsum, D—on crushed limestone, (**A1**,**B1**,**C1**,**D1**)—on mixture of soil and wastewater sludge SPP, and (**A2**,**B2**,**C2**,**D2**)—on mixture of soil and peat.

Comparison of the results of the two presented measurement methods on the plant material collecting days showed a correlation dependence of: $r_1^2 = 0.95$, $r_2^2 = 0.75$, and $r_3^2 = 0.75$.

The results of the biomass growth rate showed the dependence of the seed germination on the applied substrate. The effectiveness of the vegetative cover formation in the disturbed areas depended on the deposited layer, ameliorant, and its quantity.

The analysis of the weekly increase in the biomass of the vegetative cover showed that the peat mixture achieved better results of biomass increase (LAI > 50% on phosphogypsum, on crushed limestone, and models without layer) than soil with the addition of SPP (LAI < 40%).

Peat mixture applied into the soil in the ratios of 1:2 and 1:3 showed the highest results of vegetative cover formation and biomass growth rate, where LAI > 50% on control models, LAI > 30% on waste rock layer, LAI > 40% on phosphogypsum layer, and LAI > 60% on crushed limestone. Plant growth was accelerated and overall biomass growth was improved. The closest results of the biomass growth rate were in models where SPP was introduced into the soil in a ratio of 1:3, where LAI > 30% on all types of layers.

Speaking of the amount of application, the ratio 1:1 is not applicable to peat mixture nor SPP (LAI~10%), as an ameliorant. Inhibition of plant growth and lower overall productivity of the biomass of the vegetative cover were noted. These results can be explained by: (1) a high degree of soil lightness, i.e., a low density of the soil substrate unacceptable for the effective formation of grass vegetative cover, or an increase in the phytotoxicity of the soil layer, which in general results in an inhibitory effect on plant growth. Similar research results have already been noted with excessive addition of sewage sludges [8,39].

The analysis of the influence of the recultivated layer determined that the formation of a minimal 20 cm soil layer was the most ecologically effective vegetative cover form on models with a neutral medium (pH 6.5–7.0), due to the characteristics of the dump rocks. Rehabilitation of waste rock dumps (from gold mining) reflected the most negligible results in germination and biomass growth, which, in turn, was also explained by the acidity of the formed conditions.

The decrease in the acidity of the soil layer worsened the efficiency of biomass for reasons of: deterioration of the optimal acidity conditions, and an increase in the migration ability of metals, which led to an increase in the phytotoxic effect of soil layers [15,17].

No phytotoxic effect of the added ameliorants nor reclaimed layers was found in any of the studied models: there were no signs of chlorosis, necrosis, or other plant damage.

High results of biomass growth, normal growth, and vegetation of plants were observed when a peat mixture was added at ratios of 1:3 and 1:2 and SPP 1:3 to the soil, which confirmed the earlier obtained seed germination results.

Based on the obtained growth functions of the grass plant cover (Gompertz sigmoid function) and their correlation coefficients, it can be concluded that the development of the vegetative cover on the formed treated soil models proceeded without deviation and within the standard growth rate (r^2 = 0.84–0.98). Analysis of variance (ANOVA) was used to examine differences between types of formed soil–plant models. All statistical analyses were performed at the 95% confidence level ($p < 0.05$).

3.3. Plant Cover Height Rate

The results of plant cover height showed the dependence of the germination on the applied substrate and deposited layer.

The analysis of the weekly increase in plant cover height mainly confirmed results of biomass growth. The height grass cover formation on SPP mixture (obtaining a maximum of plant cover height ~10 cm) reached a higher maximum than grass cover on peat mixture (>10–15 cm). Results of plant cover height grown on a mixture of soil and SPP showed similar results on all types of rehabilitation layers. The obtained results of grass cover height are shown in Figure 8.

Based on the obtained growth functions of the grass plant cover (Gompertz sigmoid function) and their correlation coefficients, it can be concluded that the development of the vegetative cover on the formed treated soil models proceeded without deviation and within the standard growth rate (r^2 = 0.85–0.99). Analysis of variance (ANOVA) was used to examine differences between types of formed soil–plant models. All statistical analyses were performed at the 95% confidence level ($p < 0.05$). No visual or measurable signs of the impact of lower horizons on vegetation height were found. However, higher values of maximum vegetation height were noted in the following groups of models: (1) on the group without horizon 0, (2) on the rehabilitated layer of waste rock, and, (3) on phosphogypsum. Overall, no visual distortion was recorded, so the results of biomass measurements can be considered more indicative.

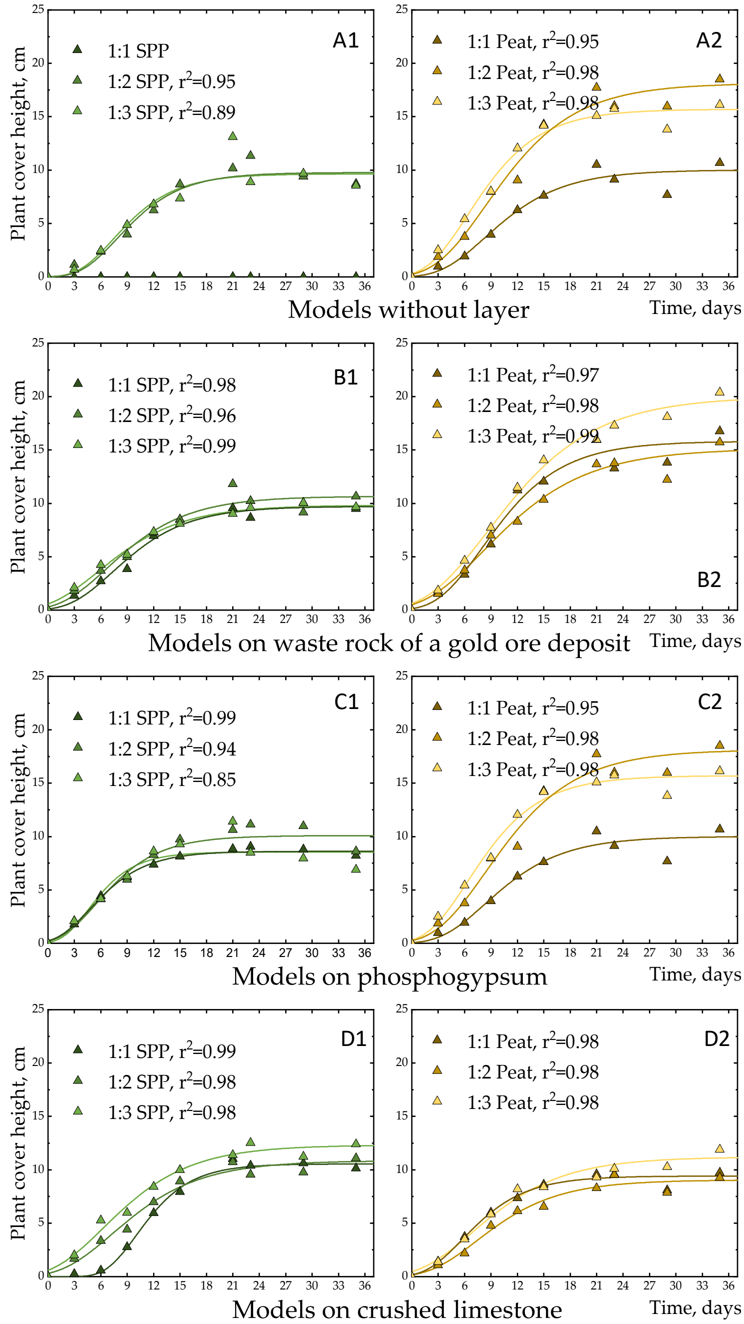


Figure 8. Rate of plant cover height (cm): A—on the model without layer, B—on the waste rock of a gold ore deposit, C—on phosphogypsum, D—on crushed limestone, (**A1**,**B1**,**C1**,**D1**)—on a mixture of soil and wastewater sludge SPP, and (**A2**,**B2**,**C2**,**D2**)—on a mixture of soil and peat.

3.4. Plant Growth and Vegetation

Measured characteristics were recounted in comparison with results from control models and maximum obtained values. Recounted characteristics were compiled in the total matrix of plant cover growth and vegetation indicators (Figure 9).

The combined matrix of indicators proved the results of the germination assay and the biomass cover assessment (though LAI), replicating a particularly relevant amount of SPP soil application for disturbed land reclamation. In comparison with peat mixture additives, the recommended ratio of SPP to soil was 1:3, which was based on achieved results of grass cover growth and vegetation development.

Measured characteristics by comparison, %		WITHOUT LAYER						ON WASTE ROCK						ON PHOSHOGYPSUM						ON CRUSHED LIMESTONE					
		SPP			Peat			SPP			Peat			SPP			Peat			SPP			Peat		
		1:1	1:2	1:3	1:1	1:2	1:3	1:1	1:2	1:3	1:1	1:2	1:3	1:1	1:2	1:3	1:1	1:2	1:3	1:1	1:2	1:3	1:1	1:2	1:3
with control models	Germination	0	18	24	15	34	46	58	**124**	**116**	75	44	89	15	4	53	9	16	71	**105**	9	24	**116**	79	**104**
	Plant tissue cuts 1	0	14	77	29	54	33	36	**133**	**211**	**116**	**144**	**203**	22	36	75	19	64	98	21	23	25	30	**194**	**211**
	Plant tissue cuts 2	0	32	**109**	38	**123**	**118**	81	**127**	**219**	**207**	**193**	**432**	43	36	**119**	21	75	**121**	65	**110**	**115**	83	**325**	**224**
	Plant tissue cuts 3	0	37	31	22	29	22	47	**116**	**162**	67	56	**106**	22	27	25	13	13	29	35	20	8	29	79	80
with maximum	LAI (biomass), average	3	21	37	39	79	91	18	36	55	35	26	31	33	50	35	47	46	89	17	37	71	35	75	**100**
	LAI (biomass), max	3	25	41	51	93	98	21	44	53	47	34	39	37	51	45	59	53	91	19	39	74	44	84	**100**
	Plant height, average	0	54	54	70	65	89	53	59	69	56	49	61	54	60	57	84	77	**100**	54	61	55	53	94	90
	Plant height, max	0	56	64	74	69	90	54	54	61	48	47	58	49	58	49	82	77	**100**	44	55	56	52	91	79

Figure 9. Measured characteristics in comparison with control models/maximum.

The average rate of measured plant indicators showed the optimal SPP ratios for application to soils (soil treating) in disturbed land of the mining industry. Treated soils formed without the mining waste layer showed average values for plant growth and vegetation. The optimal ratios in the absence of a mine waste layer were 1:3 for SPP, and 1:2 and 1:3 for peat mixture, as the obtained values of the average rate of measured plant indicators were > 50%:

1. For the waste rock layer, the optimal ratios were obtained with soil at a 1:3 addition of SPP and peat mixture to the soil (average rate > 50%);
2. For the phosphogypsum layer, the optimal ratios for waste rock dump rehabilitation for SPP were 1:2 and 1:3, and for peat mixture, all types of ratios (1:1, 1:2, and 1:3) resulted in the average rate of measured plant indicators > 50%. The highest value of the average rate of measured plant indicators was obtained with a ratio of 1:3 peat mixture to soil (average rate >100%);
3. For the crushed limestone layer, the obtained results showed a more suitable addition of peat mixture than the addition of peat for crushed limestone; the average rate of measured plant indicators: (1) for SPP 1:2 (>60%) and 1:3 (>90%) to soil; (2) for peat mixture 1:2 (>100%) and 1:3 (>100%).

4. Conclusions

The assessment of the applicability of SPP as a soil additive for the rehabilitation of disturbed lands in the mining industry was carried out based on an evaluation of the plant cover growth, considering the climatic, environmental, and anthropogenic factors of the technogenic substance. The growth efficiency of a plant cover was evaluated by the following parameters: (1) seed germination, (2) plant cover biomass, and (3) plant cover height rate.

The SPP influence on seed germination was measured by the digital image analysis method. In general, a rational application of SPP to the soil does not hurt seed germination (seed germination > 50%). However, excessive application (in ratio 1:1 of SPP to the soil) negatively affected the germination parameter, showing phytotoxic effect and growth inhibition.

The influence on plant cover biomass was analyzed by the digital image analysis method and leaf area index (LAI). The SPP (in ratio 1:3) influence on biomass growth rate reflected similarly on all soil–plant complexes (LAI > 30% on all types of layers). However, it resulted in a lower biomass quantity in comparison with soils with peat mixture application (LAI > 50% on control models, LAI > 30% on waste rock layer, LAI > 40% on phosphogypsum layer, and LAI > 60% on crushed limestone).

The effect of SPP on the plant cover height rate replicated previous results of germination and plant cover biomass. However, it showed no significant difference in SPP ratios or mine waste layer type.

Overall, results of the evaluation of plant cover formation showed that peat mixture application resulted in healthier and higher levels of plant cover growth than SPP amendment. Nonetheless, SPP results were close to the result of peat mixture of plant growth influence in a ratio 1:3 to soil: (1) germination: 1:2 peat—50–60%, 1:3 peat—60–70%, and 1:3—SPP 65–75%; (2) biomass: 1:3 SPP LAI = 30–40% (in limestone >60%) compared with peat mixture LAI = 30–80%; (3) height: in SPP ratio 1:3 to soil—10 cm, and peat mixture—10–20 cm.

Land rehabilitation with the formation of a 20 cm soil layer on mine waste dumps is environmentally suitable with an SPP application ratio of 1:3 to the soil. The amount of SPP in ratio 1:1 was found not applicable as an ameliorant.

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References

1. Gendler, S.G.; Rudakov, M.L.; Kuznetsov, V.S. Evaluation principles of the dust influence of mining enterprises on the environment. *Latv. J. Phys. Tech. Sci.* **2019**, *56*, 62–69. [CrossRef]
2. Nevskaya, M.A.; Seleznev, S.G.; Masloboev, V.A.; Klyuchnikova, E.M.; Makarov, D.V. Environmental and business challenges presented by mining and mineral processing waste in the Russian federation. *Minerals* **2019**, *9*, 445. [CrossRef]
3. Kutepov, Y.I.; Kutepova, N.A.; Vasileva, A.D.; Mukhina, A.S. Engineering-geological and ecological concerns in operation and reclamation of high slope dumps at open-pit mines in Kuzbass. *Min. Inf. Anal. Bull.* **2021**, 164–178. [CrossRef]
4. Zuev, B.Y.; Zubov, V.P.; Fedorov, A.S. Application prospects for models of equivalent materials in studies of geomechanical processes in underground mining of solid minerals. *Eurasian Min.* **2019**, *2019*, 8–12. [CrossRef]
5. Marinin, M.A.; Alexandrovichisheysky, V. State-of-art of mine engineering reclamation while developing of steep-dipping ore fields. *Asian J. Microbiol. Biotechnol. Environ. Sci.* **2017**, *19*, 240–246.
6. Alekseenko, V.A.; Pashkevich, M.A.; Alekseenko, A.V. Metallisation and environmental management of mining site soils. *J. Geochem. Explor.* **2017**, *174*, 121–127.
7. Strizhenok, A.; Tcvetkov, P. Ecology-economical assessment of new reclamation method for currently working technogenic massifs. *J. Ecol. Eng.* **2017**, *18*, 58–64. [CrossRef]
8. Corrêa, R.S.; do Carmo Balduíno, A.P.; Teza, C.T.V.; de Mello Baptista, G.M. Vegetation cover development resulting from different restoration approaches of exploited mines. *Floresta E Ambiente* **2018**, *25*, e20171116. [CrossRef]
9. Alekseenko, A.V.; Drebenstedt, C.; Bech, J. Assessment and abatement of the eco-risk caused by mine spoils in the dry subtropical climate. *Environ. Geochem. Health* **2021**, *3*, 1–23. [CrossRef]
10. Radziemska, M.; Gusiatin, Z.M.; Bęś, A.; Czajkowska, J.; Mazur, Z.; Hammerschmiedt, T.; Sikorski, Ł.; Kobzova, E.; Klik, B.K.; Sas, W.; et al. Can the Application of Municipal Sewage Sludge Compost in the Aided Phytostabilization Technique Provide an Effective Waste Management Method? *Energies* **2021**, *14*, 1984. [CrossRef]
11. Das Gupta, S.; Kirby, W.; Pinno, B.D. Effects of Stockpiling and Organic Matter Addition on Nutrient Bioavailability in Reclamation Soils. *Soil Sci. Soc. Am. J.* **2019**, *83*, S27–S41.
12. Angst, G.; Mueller, C.W.; Angst, Š.; Pivokonský, M.; Franklin, J.; Stahl, P.D.; Frouz, J. Fast accrual of C and N in soil organic matter fractions following post-mining reclamation across the USA. *J. Environ. Manag.* **2018**, *209*, 216–226. [CrossRef] [PubMed]
13. Jeżowski, S.; Mos, M.; Buckby, S.; Cerazy-Waliszewska, J.; Owczarzak, W.; Mocek, A.; Kaczmarek, Z.; McCalmont, J.P. Establishment, growth, and yield potential of the perennial grass Miscanthus × Giganteus on degraded coal mine soils. *Front. Plant Sci.* **2017**, *8*, 726. [CrossRef] [PubMed]
14. Jordán, M.M.; Bech, J.; García-Sánchez, E.; García-Orenes, F. Bulk density and aggregate stability assays in percolation columns. *J. Min. Inst.* **2016**, *222*, 877–881.

15. Halecki, W.; Klatka, S. Aplication of Soil Productivity Index after Eight Years of Soil Reclamation with Sewage Sludge Amendments. *Environ. Manag.* **2021**, *67*, 822–832. [CrossRef]
16. Carabassa, V.; Domene, X.; Alcañiz, J.M. Soil restoration using compost-like-outputs and digestates from non-source-separated urban waste as organic amendments: Limitations and opportunities. *J. Environ. Manag.* **2020**, *255*, 109909. [CrossRef]
17. Soria, R.; Ortega, R.; Bastida, F.; Miralles, I. Role of organic amendment application on soil quality, functionality and greenhouse emission in a limestone quarry from semiarid ecosystems. *Appl. Soil Ecol.* **2021**, *164*, 103925. [CrossRef]
18. Strizhenok, A.V.; Korelskiy, D.S.; Choi, Y. Assessment of the Efficiency of Using Organic Waste from the Brewing Industry for Bioremediation of Oil-Contaminated Soils. *J. Ecol. Eng.* **2021**, *22*, 66–77. [CrossRef]
19. Larney, F.J.; Angers, D.A. The role of organic amendments in soil reclamation: A review. *Can. J. Soil Sci.* **2012**, *92*, 19–38. [CrossRef]
20. Zuo, W.; Gu, C.; Zhang, W.; Xu, K.; Wang, Y.; Bai, Y.; Shan, Y.; Dai, Q. Sewage sludge amendment improved soil properties and sweet sorghum yield and quality in a newly reclaimed mudflat land. *Sci. Total Environ.* **2019**, *654*, 541–549. [CrossRef]
21. Antonelli, P.M.; Fraser, L.H.; Gardner, W.C.; Broersma, K.; Karakatsoulis, J.; Phillips, M.E. Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation. *Ecol. Eng.* **2018**, *117*, 38–49. [CrossRef]
22. Smirnov, Y.D.; Suchkova, M.V. Development of the beneficial utilisation of urban sewage sludge using modern analysis methods. *J. Phys. Conf. Ser.* **2019**, *1384*, 012049. [CrossRef]
23. Halecki, W.; Klatka, S. Long term growth of crop plants on experimental plots created among slag heaps. *Ecotoxicol. Environ. Saf.* **2018**, *147*, 86–92. [CrossRef] [PubMed]
24. Žaltauskaitė, J.; Judeikytė, S.; Sujetovienė, G.; Dagiliūtė, R. Sewage Sludge Application Effects to First Year Willows (*Salix Viminalis* L.) Growth and Heavy Metal Bioaccumulation. *Waste Biomass Valorization* **2017**, *8*, 1813–1818. [CrossRef]
25. Al Ghouti, M.A.; Ali, M.; Ahmed, T. Potential benefits and risk assessments of using sewage sludge on soil and plants: A review. *Int. J. Environ. Waste Manag.* **2019**, *23*, 352. [CrossRef]
26. Mohamed, B.; Mounia, K.; Aziz, A.; Ahmed, H.; Rachid, B.; Lotfi, A. Sewage sludge used as organic manure in Moroccan sunflower culture: Effects on certain soil properties, growth and yield components. *Sci. Total Environ.* **2018**, *627*, 681–688. [CrossRef]
27. Urbaniak, M.; Wyrwicka, A.; Tołoczko, W.; Serwecińska, L.; Zieliński, M. The effect of sewage sludge application on soil properties and willow (Salix sp.) cultivation. *Sci. Total Environ.* **2017**, *586*, 66–75. [CrossRef]
28. Carabassa, V.; Ortiz, O.; Alcañiz, J.M. Sewage sludge as an organic amendment for quarry restoration: Effects on soil and vegetation. *Land Degrad. Dev.* **2018**, *29*, 2568–2574. [CrossRef]
29. Delibacak, S.; Voronina, L.; Morachevskaya, E.; Ongun, A.R. Use of sewage sludge in agricultural soils: Useful or harmful. *Eurasian J. Soil Sci.* **2020**, *9*, 126–139. [CrossRef]
30. Delgado, M.; Maeso, F.J.; Martín, J.V.; Gonzalez, M.I.; Martinez, S. Valorization of sludge from the quartz industry as soil amendment and crop production. *Soil Tillage Res.* **2019**, *194*, 104320. [CrossRef]
31. Alayu, E.; Leta, S. Brewery sludge quality, agronomic importance and its short-term residual effect on soil properties. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 2337–2348. [CrossRef]
32. Chu, L.; He, W. Toxic metals in soil due to the land application of sewage sludge in China: Spatiotemporal variations and influencing factors. *Sci. Total Environ.* **2020**, *757*, 143813. [CrossRef] [PubMed]
33. Nicolás, C.; Kennedy, J.N.; Hernández, T.; García, C.; Six, J. Soil aggregation in a semiarid soil amended with composted and non-composted sewage sludge-A field experiment. *Geoderma* **2014**, *219*, 24–31. [CrossRef]
34. Sarapulova, G.I. Environmental geochemical assessment of technogenic soils. *J. Min. Inst.* **2018**, *234*, 658–662. [CrossRef]
35. Lobacheva, O.; Dzhevaga, N. Method for removing valuable components from technogenic solutions by the example of rare earth elements. *J. Phys. Conf. Ser.* **2020**, *1679*, 042016. [CrossRef]
36. Koutroubas, S.D.; Antoniadis, V.; Damalas, C.A.; Fotiadis, S. Sunflower growth and yield response to sewage sludge application under contrasting water availability conditions. *Ind. Crops Prod.* **2020**, *154*, 112670. [CrossRef]
37. Burducea, M.; Lobiuc, A.; Asandulesa, M.; Zaltariov, M.F.; Burducea, I.; Popescu, S.M.; Zheljazkov, V.D. Effects of sewage sludge amendments on the growth and physiology of sweet basil. *Agronomy* **2019**, *9*, 548. [CrossRef]
38. Abbas, A.M.; Abd-Elmabod, S.K.; El-Ashry, S.M.; Soliman, W.S.; El-Tayeh, N.; Castillo, J.M. Capability of the invasive tree prosopis glandulosa Torr. To remediate soil treated with Sewage Sludge. *Sustainability* **2019**, *11*, 2711. [CrossRef]
39. Curci, M.; Lavecchia, A.; Cucci, G.; Lacolla, G.; De Corato, U.; Crecchio, C. Short-term effects of sewage sludge compost amendment on semiarid soil. *Soil Syst.* **2020**, *4*, 48. [CrossRef]
40. Siebielec, G.; Siebielec, S.; Lipski, D. Long-term impact of sewage sludge, digestate and mineral fertilizers on plant yield and soil biological activity. *J. Clean. Prod.* **2018**, *187*, 372–379. [CrossRef]
41. Bıyıklı, M.; Dorak, S.; Bülent Aşık, B. Effects of food industry wastewater treatment sludge on corn plant development and soil properties. *Pol. J. Environ. Stud.* **2020**, *29*, 2565–2578. [CrossRef]
42. Xue, D.; Huang, X. The impact of sewage sludge compost on tree peony growth and soil microbiological, and biochemical properties. *Chemosphere* **2013**, *93*, 583–589. [CrossRef] [PubMed]
43. Pashkevich, M.A.; Petrova, T.A.; Rudzisha, E. Lignin sludge application for forest land reclamation: Feasibility assessment. *J. Min. Inst.* **2019**, *235*, 106–112. [CrossRef]

44. Artico, M.; Firpo, B.A.; Artico, L.L.; Tubino, R.M.C. Integrated use of sewage sludge and basalt mine environmental restoration. *Rev. Esc. Minas* **2020**, *73*, 225–232.
45. Kodešová, R.; Klement, A.; Golovko, O.; Fér, M.; Kočárek, M.; Nikodem, A.; Grabic, R. Soil influences on uptake and transfer of pharmaceuticals from sewage sludge amended soils to spinach. *J. Environ. Manag.* **2019**, *250*, 109407. [CrossRef]
46. Eid, E.M.; Alrumman, S.A.; El-Bebany, A.F.; Hesham, A.E.L.; Taher, M.A.; Fawy, K.F. The effects of different sewage sludge amendment rates on the heavy metal bioaccumulation, growth and biomass of cucumbers (*Cucumis sativus* L.). *Environ. Sci. Pollut. Res.* **2017**, *24*, 16371–16382. [CrossRef]
47. Eid, E.M.; Alrumman, S.A.; El-Bebany, A.F.; Fawy, K.F.; Taher, M.A.; Hesham, A.E.L.; El-Shaboury, G.A.; Ahmed, M.T. The evaluation of sewage sludge application as a fertilizer for broad bean (*Faba sativa* Bernh.) crops. *Food Energy Secur.* **2018**, *7*, e00142. [CrossRef]
48. Pöykiö, R.; Watkins, G.; Dahl, O. Characterisation of Municipal Sewage Sludge as a Soil Improver and a Fertilizer Product. *Ecol. Chem. Eng. S* **2019**, *26*, 547–557. [CrossRef]
49. Raheem, A.; Sikarwar, V.S.; He, J.; Dastyar, W.; Dionysiou, D.D.; Wang, W.; Zhao, M. Opportunities and challenges in sustainable treatment and resource reuse of sewage sludge: A review. *Chem. Eng. J.* **2018**, *337*, 616–641. [CrossRef]
50. Matveeva, V.A.; Smirnov, Y.D.; Suchkov, D.V. Industrial processing of phosphogypsum into organomineral fertilizer. *Environ. Geochem. Health* **2021**, 1–14. [CrossRef]
51. Asemaninejad, A.; Arteaga, J.; Spiers, G.; Beckett, P.; McGarry, S.; Mykytczuk, N.; Basiliko, N. Blended pulp mill, forest humus and mine residual material Technosols for mine reclamation: A growth-chamber study to explore the role of physiochemical properties of substrates and microbial inoculation on plant growth. *J. Environ. Manag.* **2018**, *228*, 93–102. [CrossRef] [PubMed]
52. Undurraga, P.; Hirzel, J.; Celis, J.E.; Perez, C.; Sandoval, M.A. Pelletized paper mill waste promotes nutrient input and N mineralization in a degraded Alfisol. *Chil. J. Agric. Res.* **2017**, *77*, 390–399. [CrossRef]
53. Hagelqvist, A. Batchwise mesophilic anaerobic co-digestion of secondary sludge from pulp and paper industry and municipal sewage sludge. *Waste Manag.* **2013**, *33*, 820–824. [CrossRef]
54. Pérez, R.A.; Sánchez-Brunete, C.; Albero, B.; Miguel, E.; Tadeo, J.L.; Alonso, J.; Lobo, M.C. Quality assessment of three industry-derived organic amendments for agricultural use. *Compost Sci. Util.* **2016**, *24*, 190–202. [CrossRef]
55. Rasa, K.; Pennanen, T.; Peltoniemi, K.; Velmala, S.; Fritze, H.; Kaseva, J.; Joona, J.; Uusitalo, R. Pulp and paper mill sludges decrease soil erodibility. *J. Environ. Qual.* **2021**, *50*, 172–184. [CrossRef] [PubMed]
56. Vasilyeva, M.; Kovshov, S.; Zambrano, J.; Zhemchuzhnikov, M. Effect of magnetic fields and fertilizers on grass and onion growth on technogenic soils. *J. Water Land Dev.* **2021**, *49*, 55–62.
57. Ivanov, A.V.; Smirnov, Y.D.; Petrov, G.I. Investigation of waste properties of subway construction as a potential component of soil layer. *J. Ecol. Eng.* **2018**, *19*, 59–69. [CrossRef]
58. Luo, Y.; Liang, J.; Zeng, G.; Chen, M.; Mo, D.; Li, G.; Zhang, D. Seed germination test for toxicity evaluation of compost: Its roles, problems and prospects. *Waste Manag.* **2018**, *71*, 109–114. [CrossRef]
59. Pashkevich, M.A.; Bech, J.; Matveeva, V.A.; Alekseenko, A.V. Biogeochemical assessment of soils and plants in industrial, residential and recreational areas of Saint Petersburg. *J. Min. Inst.* **2020**, *241*, 125–130. [CrossRef]
60. Sunoj, S.; McRoberts, K.C.; Benson, M.; Ketterings, Q.M. Digital image analysis estimates of biomass, carbon, and nitrogen uptake of winter cereal cover crops. *Comput. Electron. Agric.* **2021**, *184*, 106093. [CrossRef]
61. Huang, W.; Su, X.; Ratkowsky, D.A.; Niklas, K.J.; Gielis, J.; Shi, P. The scaling relationships of leaf biomass vs. leaf surface area of 12 bamboo species. *Glob. Ecol. Conserv.* **2019**, *20*, e00793. [CrossRef]
62. Xiong, Y.; West, C.P.; Brown, C.P.; Green, P.E. Digital Image Analysis of Old World Bluestem Cover to Estimate Canopy Development. *Agron. J.* **2019**, *111*, 1–7. [CrossRef]
63. Zhang, L.; Verma, B.; Stockwell, D.; Chowdhury, S. Density Weighted Connectivity of Grass Pixels in image frames for biomass estimation. *Expert Syst. Appl.* **2018**, *101*, 213–227. [CrossRef]
64. Hechmi, S.; Hamdi, H.; Mokni-Tlili, S.; Zoghlami, I.R.; Khelil, M.N.; Benzarti, S.; Hassen, A.; Jedidi, N. Carbon mineralization, biological indicators, and phytotoxicity to assess the impact of urban sewage sludge on two light-textured soils in a microcosm. *J. Environ. Qual.* **2020**, *49*, 460–471. [CrossRef] [PubMed]
65. Eid, E.M.; Hussain, A.A.; Taher, M.A.; Galal, T.M.; Shaltout, K.H.; Sewelam, N. Sewage Sludge Application Enhances the Growth of Corchorus olitorius Plants and Provides a Sustainable Practice for Nutrient Recirculation in Agricultural Soils. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 149–159. [CrossRef]
66. Gallardo, F.; Cea, M.; Tortella, G.R.; Diez, M.C. Effect of pulp mill sludge on soil characteristics, microbial community and vegetal production of Lolium Perenne. *J. Environ. Manag.* **2012**, *95*, S193–S198. [CrossRef]
67. Kaur, A.; Singh, J.; Vig, A.P.; Dhaliwal, S.S.; Rup, P.J. Cocomposting with and without Eisenia fetida for conversion of toxic paper mill sludge to a soil conditioner. *Bioresour. Technol.* **2010**, *101*, 8192–8198. [CrossRef]
68. Gomes, L.A.; Santos, A.F.; Góis, J.C.; Quina, M.J. Thermal dehydration of urban biosolids with green liquor dregs from pulp and paper mill. *J. Environ. Manag.* **2020**, *261*, 109944. [CrossRef]
69. Antonkiewicz, J.; Baran, A.; Pełka, R.; Wisła-Świder, A.; Nowak, E.; Konieczka, P. A mixture of cellulose production waste with municipal sewage as new material for an ecological management of wastes. *Ecotoxicol. Environ. Saf.* **2019**, *169*, 607–614. [CrossRef]
70. Bourioug, M.; Alaoui-Sehmer, L.; Laffray, X.; Benbrahim, M.; Aleya, L.; Alaoui-Sossé, B. Sewage sludge fertilization in larch seedlings: Effects on trace metal accumulation and growth performance. *Ecol. Eng.* **2015**, *77*, 216–224. [CrossRef]

71. Černe, M.; Palčić, I.; Pasković, I.; Major, N.; Romić, M.; Filipović, V.; Igrc, M.D.; Perčin, A.; Goreta Ban, S.; Zorko, B.; et al. The effect of stabilization on the utilization of municipal sewage sludge as a soil amendment. *Waste Manag.* **2019**, *94*, 27–38. [CrossRef] [PubMed]
72. Mohamed, B.; Olivier, G.; François, G.; Laurence, A.S.; Bourgeade, P.; Badr, A.S.; Lotfi, A. Sewage sludge as a soil amendment in a Larix decidua plantation: Effects on tree growth and floristic diversity. *Sci. Total Environ.* **2018**, *621*, 291–301. [CrossRef] [PubMed]
73. Zhang, L.; Xu, C.C.; Champagne, P. Energy recovery from secondary pulp/paper-mill sludge and sewage sludge with supercritical water treatment. *Bioresour. Technol.* **2010**, *101*, 2713–2721. [CrossRef] [PubMed]
74. Korotaeva, A.E.; Pashkevich, M.A. Spectrum survey data application in ecological monitoring of aquatic vegetation. *Min. Inf. Anal. Bull.* **2021**, *5*, 231–244. [CrossRef]
75. Elsayed, S.; Barmeier, G.; Schmidhalter, U. Passive Reflectance Sensing and Digital Image Analysis Allows for Assessing the Biomass and Nitrogen Status of Wheat in Early and Late Tillering Stages. *Front. Plant Sci.* **2018**, *9*, 1478. [CrossRef]
76. Jin, X.; Zarco-Tejada, P.J.; Schmidhalter, U.; Reynolds, M.P.; Hawkesford, M.J.; Varshney, R.K.; Yang, T.; Nie, C.; Li, Z.; Ming, B.; et al. High-Throughput Estimation of Crop Traits: A Review of Ground and Aerial Phenotyping Platforms. *IEEE Geosci. Remote Sens. Mag.* **2021**, *9*, 200–231. [CrossRef]
77. Xu, D.; Pu, Y.; Guo, X. Non-Photosynthetic Vegetation Cover from RGB Images in Mixed Grasslands. *Sensors* **2020**, *20*, 6870. [CrossRef]
78. Dinalankara, S.; Chandrasiri, T.S.; Dias, D.; Hettiarachchi, K.; Rodrigo, R.; Premaratne, U. Vision Based Automated Biomass Estimation of Fronds of Salvinia molesta. In Proceedings of the 2018 IEEE International Conference on Information and Automation for Sustainability (ICIAfS), Colombo, Sri Lanka, 21–22 December 2018; pp. 1–6.
79. Chianucci, F.; Lucibelli, A.; Dell'Abate, M.T. Estimation of ground canopy cover in agricultural crops using downward-looking photography. *Biosyst. Eng.* **2018**, *169*, 209–216. [CrossRef]
80. Hu, B.; Bennett, M.A.; Kleinhenz, M.D. A new method to estimate vegetable seedling Vigor, piloted with tomato, for use in grafting and other contexts. *Horttechnology* **2016**, *26*, 767–775. [CrossRef]
81. Archontoulis, S.V.; Miguez, F.E. Nonlinear regression models and applications in agricultural research. *Agron. J.* **2015**, *107*, 786–798. [CrossRef]
82. Tackenberg, O. A new method for non-destructive measurement of biomass, growth rates, vertical biomass distribution and dry matter content based on digital image analysis. *Ann. Bot.* **2007**, *99*, 777–783. [CrossRef] [PubMed]
83. Aoyama, M.; Kuroyanagi, S. Effects of heavy metal accumulation associated with pesticide application on the decomposition of cellulose and orchard grass in soils. *Soil Sci. Plant Nutr.* **1996**, *42*, 121–131. [CrossRef]
84. Wiewióra, B.; Żurek, G. The Response of the Associations of Grass and *Epichloë* Endophytes to the Increased Content of Heavy Metals in the Soil. *Plants* **2021**, *10*, 429. [CrossRef] [PubMed]
85. Gallardo, F.; Bravo, C.; Briceño, G.; Diez, M.C. Use of sludge from kraft mill wastewater treatment as improver of volcanic soils: Effect on soil biological parameters. *Revista de la Ciencia del Suelo y Nutrición Vegetal* **2010**, *10*, 48–61. [CrossRef]
86. Ye, Z.H.; Shu, W.S.; Zhang, Z.Q.; Lan, C.Y.; Wong, M.H. Evaluation of major constraints to revegetation of lead/zinc mine tailings using bioassay techniques. *Chemosphere* **2002**, *47*, 1103–1111. [CrossRef]