

Article

The Influence of Tree Species on Soil Development and Soil Classification in Reclaimed Post-Mining Areas

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Abstract

Soil formation in post-mining areas is strongly influenced not only by parent material but also by the vegetation introduced during reclamation. Tree species affect pedogenic processes through litter input, root activity and associated microbial communities. This study investigates soil development in reclaimed post-mining landscapes, focusing on the combined influence of tree species and substrate properties. Two forest sites in Poland were analysed: Szczakowa (former open-pit sand mine) and Bełchatów (lignite mine spoil heap), 30–40 years after reclamation and afforestation with four dominant species: silver birch, European larch, Scots pine and red oak. Differences in soil development were observed among tree species. Stands with deciduous trees (birch and oak) were generally associated with clearer horizon differentiation, higher soil organic carbon and nitrogen content, and more pronounced iron redistribution compared with coniferous stands. The mean thickness of the combined organic-rich surface horizons was 12.4 cm at Szczakowa and 10.8 cm at Bełchatów. Coniferous species were more often linked with soil acidification and early stages of podzolisation-like processes, particularly in sandy substrates, whereas soils under deciduous species showed features related to brunification and organic matter incorporation. The study also included a comparison of soil classification systems, indicating that the World Reference Base for Soil Resources (WRB) offers a flexible framework for describing young and anthropogenically transformed soils compared with traditional national classifications. From a sustainability perspective, the results highlight that strategic species selection during reclamation, specifically promoting birch on sandy substrates and oak on heterogeneous technogenic substrates, enhances soil organic carbon accumulation, nutrient retention and iron cycling, thus contributing to the long-term restoration of ecosystem services on degraded post-mining landscapes.



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Keywords: arenosols; technosols; sustainable reclamation; tree species; pedogenesis; soil classification

1. Introduction

The reclamation of post-mining areas is a complex and long-term process aimed at restoring ecological functions and soil productivity in severely degraded landscapes. A

central challenge is soil formation, driven by the interaction of abiotic and biotic factors, including initial substrate properties, vegetation type, and microbial activity [1,2]. The presence of vegetation plays a crucial role in modifying soil structure, organic matter accumulation, and nutrient cycling, ultimately determining the trajectory of pedogenic processes [3].

Tree species differ considerably in their growth characteristics, biomass production, litter quantity and quality, nutrient cycling, and decomposition rates, all of which influence soil development and ecosystem recovery. Consequently, the selection of tree species is considered one of the key factors determining the success of forest reclamation on post-mining sites. Scots pine (*Pinus sylvestris*), European larch (*Larix decidua*), silver birch (*Betula pendula*), and red oak (*Quercus rubra*) represent contrasting functional groups that differ in litter chemistry, nutrient return, and their influence on soil-forming processes. These species have been widely used in forest reclamation and afforestation programmes in Poland because of their high adaptability to nutrient-poor post-mining substrates [4,5]. Although *Quercus rubra* is a non-native species in Poland, it has frequently been introduced into reclaimed mining areas and poor forest habitats owing to its rapid growth, high biomass production, and tolerance of degraded environmental conditions [6].

In post-mining landscapes, both soil genesis and ecosystem recovery are significantly influenced by vegetation, particularly tree species. Silver birch (*Betula pendula*) and red oak (*Quercus rubra*) generally promote greater nutrient return through litter decomposition and enhanced biological activity, whereas Scots pine (*Pinus sylvestris*) and European larch (*Larix decidua*) are more frequently associated with soil acidification and slower organic matter turnover [7,8]. These functional differences may substantially influence the trajectory of soil development.

Arenosols are sandy, weakly developed soils occurring on coarse-textured parent materials under nutrient-poor conditions. Under coniferous vegetation and sufficient precipitation, Arenosols may undergo podzolisation, a process associated with the translocation of organic matter, iron (Fe), and aluminium (Al), accompanied by progressive soil acidification. Technosols are the dominant soil type in reclaimed post-industrial areas, especially in former mining regions, including spoil heaps and industrial waste deposits. These anthropogenic soils are formed from heterogeneous substrates, such as mine wastes, ash, or rubble, and frequently exhibit complex layering patterns reflecting deposition and reclamation practices. Over time, Technosols may develop diagnostic and transitional horizons, including ochric, humic, and spolic horizons [9–15].

The interpretation of soil development in reclaimed mining areas is additionally complicated by the occurrence of geogenic carbon derived from fossil lignite residues incorporated into mine spoils. Unlike recently accumulated biogenic carbon, geogenic carbon is chemically stable, biologically recalcitrant, and does not necessarily reflect contemporary biological activity or pedogenic processes. Distinguishing between geogenic and biogenic carbon remains a major methodological challenge in studies of reclaimed mine soils because conventional carbon analyses may not adequately separate these two pools. Consequently, measured carbon values may combine inherited carbon derived from coal-bearing materials with carbon recently incorporated through vegetation inputs and microbial activity, potentially obscuring the interpretation of soil development and carbon sequestration processes [16]. The role of geogenic carbon in pedogenesis therefore remains insufficiently understood and requires further investigation under contrasting reclamation conditions.

Understanding the interactions between tree species and contrasting post-mining substrates is important for developing substrate-matched tree-species selection schemes,

improving reclamation planning, and supporting long-term forest restoration in Central Europe [5,12,13,17,18].

The two study sites represent contrasting models of post-mining soil development. Szczakowa, a former sand mine, is characterised by homogeneous sandy parent material, providing relatively uniform conditions for pedogenesis. In contrast, the Bełchatów external spoil heap consists of heterogeneous anthropogenic substrates containing lignite-derived geogenic carbon and carbonates. Besides differences in parent material, the two sites also differ in substrate heterogeneity and reclamation history, which together create contrasting environmental conditions controlling soil development. Therefore, the influence of geogenic carbon should be interpreted together with other site-specific factors rather than as an isolated driver of pedogenic processes.

Because reclaimed soils commonly exhibit weakly developed or anthropogenic diagnostic horizons, their classification may differ considerably among national and international soil classification systems. Evaluating the applicability of different classification systems is therefore important for improving the interpretation of pedogenic processes, facilitating international comparisons, and assessing soil development in reclaimed landscapes [19].

The aim of this study was to assess the effects of four tree species on soil-forming processes developing on two contrasting post-mining substrates after 30–40 years of reclamation and to compare the applicability of the World Reference Base for Soil Resources (WRB) and the Polish Soil Classification system in terms of their ability to describe weakly developed and anthropogenic horizons, represent transported and technogenic parent materials, capture early pedogenic changes, and facilitate consistent comparison of reclaimed soils.

The specific objectives were to: (i) evaluate the influence of four tree species on soil morphology and physicochemical properties; (ii) compare soil development under homogeneous sandy and heterogeneous technogenic substrates; (iii) assess the role of geogenic carbon and other site-specific substrate characteristics in shaping pedogenic processes; and (iv) compare the applicability of four soil classification systems for reclaimed post-mining soils.

Based on the available literature on the effects of tree species, litter properties, and substrate conditions on soil development in reclaimed mine soils [5,12,13,15,18,20–22], the following hypotheses were formulated: (1) tree species are associated with differences in soil development and pedogenic processes in reclaimed post-mining soils; (2) the magnitude of tree-species effects differs between homogeneous sandy substrates and heterogeneous technogenic substrates because of differences in parent material and other site-specific environmental conditions; and (3) deciduous tree species are associated with more pronounced soil development than coniferous species, as indicated by greater organic matter accumulation and stronger horizon differentiation.

2. Materials and Methods

2.1. Study Sites

The study was conducted at two reclaimed post-mining sites in Poland: the Szczakowa sand quarry in southern Poland and the Bełchatów external spoil heap in central Poland. These sites differ substantially in their geological origin, parent material, and reclamation history, providing contrasting conditions for investigating soil development and ecosystem restoration processes.

The Szczakowa site (50°14' N, 19°25' E), located within the White Przemsza River basin in the Silesian Upland, originated from open-pit sand extraction. Mining activities disturbed approximately 3500 ha of land, creating excavations ranging from 5 to 25 m in depth. The parent material consists of fluvio-glacial Quaternary loamy sands and loams

(QIs) deposited in a pre-Quaternary morphological depression. The region is characterized by a moderately humid climate, with a mean annual air temperature of 8.8 °C and mean annual precipitation of 733 mm during the period 1990–2019 [23]. Initial reclamation treatments included a two-year fertilization cycle (140, 130, and 150 kg ha^{−1} of N, P, and K, respectively) and a two-year cultivation of yellow lupine (*Lupinus luteus* L.), which was subsequently incorporated into the substrate as green manure. These treatments were followed by afforestation [5]. Given that soil sampling was conducted in 30–40-year-old stands, initial technical and biological reclamation at the studied plots took place between the late 1970s, preceding tree planting.

The Bełchatów site (51°13' N, 19°25' E) is situated on the external spoil heap of the Bełchatów lignite open-pit mine. The substrate is composed of Neogene acidic sands with admixtures of loam and clay (Ns), representing a heterogeneous anthropogenic parent material. The region experiences a temperate climate with a mean annual temperature of 7.6 °C and annual precipitation ranging from 580 to 600 mm [23]. Prior to afforestation, the spoil material was ameliorated through neutralisation with bog lime, mineral fertilisation (60, 70, and 60 kg ha^{−1} of N, P, and K, respectively), and a one-year cultivation of grasses and legumes [5]. Similarly, this biological amelioration immediately preceded tree planting 30–40 years prior to the study.

At both sites, the study was conducted in pure stands of four tree species: Silver birch (*Betula pendula* Roth), European larch (*Larix decidua* Mill.), Scots pine (*Pinus sylvestris* L.), and Red oak (*Quercus rubra* L.). To streamline sampling point identification, abbreviations combining tree species and location were used (e.g., Pine-SM for pine in Szczakowa, Pine-LM for pine in Bełchatów). This consistent naming system, applied to all tree species at both sites, resulted in eight distinct combinations (Birch-SM, Birch-LM, Oak-SM, Oak-LM, Larch-SM, Larch-LM, Pine-SM, and Pine-LM), which were used throughout the study. The suffixes SM and LM refer to the two contrasting substrates: SM (sand mine, Szczakowa), representing soils developed on sandy parent material of a former sand pit, and LM (lignite mine, Bełchatów), representing soils formed on anthropogenically deposited overburden containing geogenic carbon.

2.2. Sampling and Measurements

For each tree species × site combination, one representative soil profile was excavated to a maximum depth of 150 cm or to the parent material, whichever occurred first. The representative profiles were used for morphological description, horizon identification and collection of soil samples for laboratory analyses and principal component analysis (PCA). In addition, three soil cores, each 0–90 cm deep, were collected from three independent sampling plots representing the same tree species × site combination. These soil cores were used to determine the thickness of the organic-rich surface horizons and to support soil classification. Accordingly, the laboratory analyses and PCA were based on samples collected from the representative soil profiles, whereas the thickness of the organic-rich surface horizons was assessed using four independent observations for each tree species × site combination, comprising one representative soil profile and three additional soil cores.

Soil classification was performed using information obtained from both the representative soil profiles and supporting soil cores according to the World Reference Base for Soil Resources (WRB) [14], the Polish Soil Classification (SgP) [24], the Forest Soil Classification (FSC) [11], and Soil Taxonomy [25].

In the field, soil horizons were distinguished on the basis of observable changes in colour, texture, structure, consistence, moisture status, root abundance, and the distinctness and topography of horizon boundaries. Horizon boundaries were recorded at the depth at which a consistent change in one or more of these properties was observed. The

field-determined horizon boundaries and the thicknesses of the individual soil horizons are shown in the profile photographs presented in Figures 1 and 2. The morphological descriptions and WRB horizon symbols are provided in Tables 1 and 2, whereas the corresponding soil classifications according to WRB, SgP, FSC, and Soil Taxonomy are presented in Section 3.3.

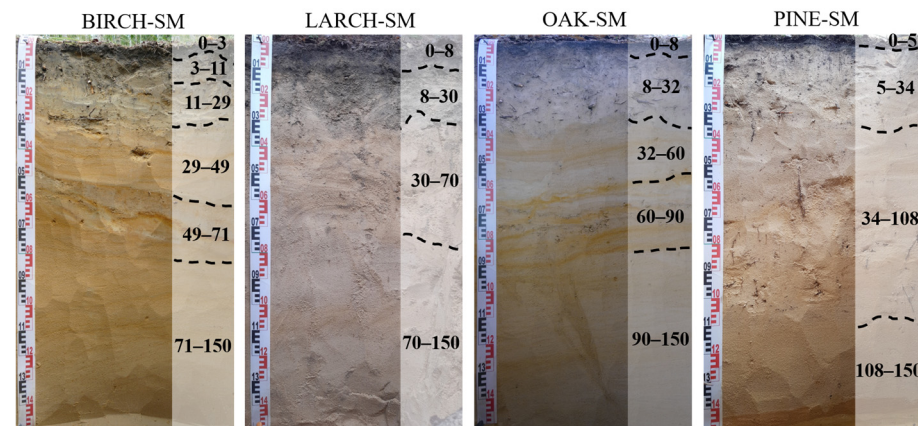


Figure 1. Photographs of representative soil profiles under the four investigated tree species at the Szczakowa site. Field-determined horizon boundaries and the thicknesses of the individual soil horizons are indicated on the photographs. The corresponding morphological descriptions and WRB horizon symbols are provided in Table 1, whereas the soil classifications according to WRB, SgP, FSC, and Soil Taxonomy are presented in Section 3.3.

Table 1. Soil description for Szczakowa under four tree species. LS, loamy sand; SL, sandy loam; L, loam; S, sand; BSW, subangular blocky weak; SS, single grains; MO, moist; WE, wet; SM, slightly moist; Cm, common; F, few; V, very few; N, none; A, abrupt; C, clear; CW, clear wavy; G, gradual; GS, gradual smooth; GW, gradual wavy.

Tree Species	Depth (cm)	Horizon (WRB)	Colour (Moist)	Texture	Structure	Moisture	Roots	Lower Boundary
BIRCH-SM	1–0	O	-	-	-	-	-	-
	0–3	A	10YR 3/2	LS	BSW	M	Cm	A
	3–11	AB	10YR 5/2	LS	BSW	M	Cm	C
	11–29	BC	10YR 5/4	SL	BSW	M	Cm	CW
	29–49	C1	10YR 6/8	LS	SS	M	F	CW
	49–71	C2	10YR 6/4 (90%), 7.5YR 6/8	L	SS	M	VF	C
	71–150	C3	10YR 6/8	S	SS	WE	N	-
LARCH-SM	1–0	O	-	-	-	-	-	-
	0–8	A	10YR 4/1	S	BSW	SM	Cm	C
	8–30	AC	10YR 5/4	S	BSW	SM	Cm	G
	30–70	C1	10YR 6/6	S	SS	M	VF	C
	70–150	C2	10YR 7/4	S	SS	M	N	-
OAK-SM	2–0	O	-	-	-	-	-	-
	0–8	A	10YR 4/3	LS	BSW	SM	F	GS
	8–32	CA	10 YR 6/3	S	BSW	SM	F	GS
	32–60	C1	2.5Y 7/4	S	BSW	M	VF	GW
	60–90	C2	10YR 7/4, 6/8; dust 2.5YR 7/2	LS	BSW/SS	M	N	GS
	90–150	C3	10YR 7/3	S	SS	M	N	-
PINE-SM	1–0	O	-	-	-	-	-	-
	0–5	A	10YR 4/2	S	BSW	SM	F	C
	5–34	C1	10YR 7/6	S	SS	SM	VF	C
	34–108	C2	10YR 7/6	S	SS	M	VF	C
	108–150	C3	10YR 7/6	S	SS	M	N	-

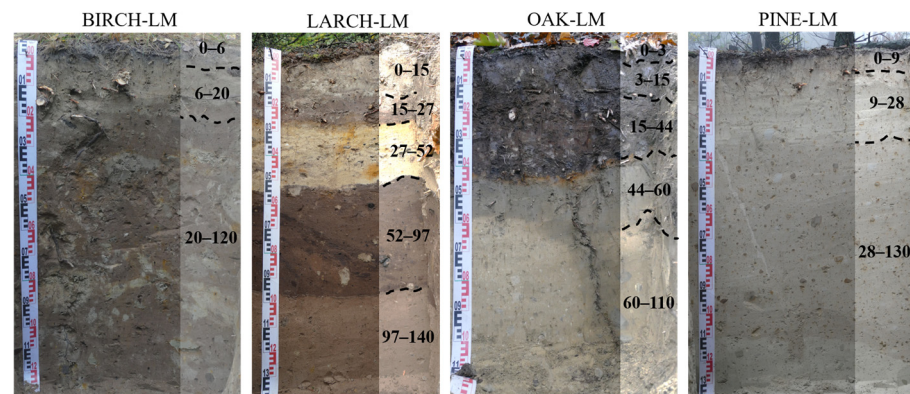


Figure 2. Photographs of representative soil profiles under the four investigated tree species at the Bełchatów site. Field-determined horizon boundaries and the thicknesses of the individual soil horizons are indicated on the photographs. The corresponding morphological descriptions and WRB horizon symbols are provided in Table 2, whereas the soil classifications according to WRB, SgP, FSC, and Soil Taxonomy are presented in Section 3.3.

Table 2. Soil description for Bełchatów under four tree species. LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; SiL, silt loam; BSW, subangular blocky weak; BS, subangular blocky; MS, massive; SS, single grains; SM, slightly moist; DR, dry; F, few; V, very few; N, none; A, abrupt; C, clear; CW, clear wavy; G, gradual.

Tree Species	Depth (cm)	Horizon (WRB)	Colour (Moist)	Texture	Structure	Moisture	Roots	Lower Boundary
BIRCH-LM	1–0	O	-	-	-	-	-	-
	0–6	AC	10YR 5/4, 10YR 4/1, 10YR 5/1	LS	BS	SM	F	C
	6–20	Cu1	10YR 5/3, 10YR 4/4	LS	SS	SM	VF	G
	20–120	Cu2	(dominant), 2.5Y 5/3, 7.5YR 4/6	SCL	SS	SM	N	-
LARCH-LM	1–0	O	-	-	-	-	-	-
	0–15	CuA	10YR 5/3	LS	SS	SM	F	CW
	15–27	Cu1	7.5YR 3/3	LS	SS	SM	F	C
	27–52	Cu2	10YR 6/8	LS	SS	SM	VF	A
	52–97	Cu3	10YR 3/3	LS + clay pieces	SS	SM	VF	A
	97–140	Cu4	10YR 4/4	LS	SS	SM	N	-
OAK-LM	1–0	O	-	-	-	-	-	-
	0–3	AC	10YR 2/1	SL	BSW	SM	F	C
	3–15	CuA	10YR 3/2	SiL	BSW	SM	F	G
	15–44	Cu1	10YR 3/4	SiL	BSW	SM	VF	CW
	44–60	Cu2	10YR 5/3	SiL	MS	SM	VF	CW
	60–110	Cu3	10YR 6/3	SiL	MS	D	N	-
PINE-LM	1–0	O	-	-	-	-	-	-
	0–9	AC	10YR 5/3, 10YR 5/2	LS	BS	SM	F	C
	9–28	C1	10YR 6/2, 10YR 7/1, 10YR 5/1	SL	SS	SM	VF	G
	28–130	Cu2	10YR 7/2	SL	SS	SM	N	-

Soil samples from each distinguished horizon in the representative were collected for detailed laboratory analysis. All samples were air-dried and sieved through a 2 mm mesh before analysis. Each soil horizon was described according to its morphological characteristics following the guidelines of the World Reference Base for Soil Resources (WRB) [14].

Soil texture was analysed using a Laser Particle Sizer ANALYSETTE 22 (Fritsch GmbH, Idar-Oberstein, Germany). For soil physicochemical properties, the pH was measured potentiometrically in both H₂O and 1 M KCl solutions at a 1:2.5 (m:v) soil-to-solution ratio to assess soil acidity under varying conditions [26] using a standard combination electrode and a pH meter (CPI-551, Elmetron, Zabrze, Polska). Total organic C (C%), total N (N%), and total sulphur (S%) content were determined using the dry combustion method with a TruMac[®]-CNS analyzer (LECO Corporation, St. Joseph, MI, USA). Prior to CNS analysis, carbonates were removed from the soil samples by fumigation with 10% HCl to eliminate interference from inorganic carbon. We acknowledge that the measured total organic carbon (TOC) pool includes both biogenic and geogenic fractions, and the precise quantification of the latter remains a recognised methodological limitation of this study. The soil's sorption properties were assessed through the measurement of hydrolytic acidity (Hh) and cation exchange capacity (CEC). Hh was determined in 1 M (CH₃COO)₂Ca. Exchangeable cations such as Ca²⁺, K⁺, Mg²⁺, and Na⁺ were extracted with 1 M CH₃COONH₄ and quantified using an ICP-OES spectrometer (iCAP 6000 Series, Thermo Fisher Scientific, Cambridge, UK).

In the Bełchatów samples in which carbonates were detected, carbonate content was determined using the Scheibler volumetric method. The carbonate-derived carbon content was subsequently calculated and subtracted from the total carbon content measured by dry combustion.

Soil structure was described in the field using standardized morphological classes according to the WRB guidelines. The mean thickness of the organic-rich surface horizons was calculated from one soil pit measurement and three adjacent soil cores within each stand; the resulting standard deviation represents within-stand spatial variability.

Selective iron extraction was performed to characterise pedogenic iron transformations and to assess the degree of soil development under contrasting tree species and parent materials.

The Fe forms in the soil were analysed using various methods: Fet (total extractable Fe) was determined using a mixture of concentrated nitric acid (HNO₃) and perchloric acid (HClO₄) in a 1:3 ratio. The acid ammonium oxalate method was used to assess contents of Feox (oxalate-extractable Fe) and represents amorphous and poorly crystalline iron forms. Active iron(III) was measured using the sodium pyrophosphate method, which identifies organically bound Fe (Fep). The dithionite-citrate-bicarbonate (DCB) method was employed to determine Fed (dithionite-extractable Fe). Dithionite extraction reduces Fe(III) to Fe(II), but mainly extracts amorphous and crystalline iron oxides without assigning them a definite valence [27].

2.3. Data Processing and Statistical Analysis

Principal component analysis (PCA) was used as an unconstrained linear ordination method to summarise relationships among the investigated soil profiles and measured soil properties. PCA was performed separately for the Szczakowa and Bełchatów sites using CANOCO 5.15 [28]. The data matrix included the four tree species as observational units for each site and the following soil variables: horizon depth, pH measured in KCl, cation exchange capacity (CEC), base saturation (BS), total nitrogen (N%), total organic carbon (C%), sand, silt, clay, and acid-extractable iron (Fe%). Before PCA, the soil-property data were subjected to a logarithmic transformation and centred by soil properties. No centring or standardisation by samples was applied. The PCA summary statistics and response-variable scores for the measured soil properties are provided in Supplementary Table S1.

The thickness of the combined organic-rich surface horizons (O + A) was analysed using a two-way analysis of variance (ANOVA), with tree species and study site included as fixed factors and their interaction included in the model. Post hoc comparisons among tree species within each study site were performed using Tukey's honestly significant difference (HSD) test. Statistical significance was accepted at $p < 0.05$. The results are presented as means $\pm$ standard deviation (SD), with four observations per tree species $\times$ site combination ($n = 4$). The ANOVA was performed using Statistica 14 software [29].

3. Results

3.1. Soil Morphology

3.1.1. Soil Structure

At the Szczakowa site (SM), the upper soil horizons of all examined profiles generally exhibited a weak subangular structure, consistent with an early stage of soil development. With increasing depth, particularly below 30–50 cm, the structure changed to single grain, indicating progressively weaker aggregation in the deeper sandy material. Among the examined SM profiles, Birch-SM and Oak-SM showed the most clearly developed structure in the upper horizons, which may indicate a stronger contribution of vegetation-related organic inputs to aggregate formation in these particular profiles (Table 1).

In contrast, the soil profiles examined at Bełchatów (LM) showed a more complex pattern of structural development. The Oak-LM profile maintained a subangular structure across several horizons, whereas the Pine-LM and Birch-LM profiles exhibited a combination of structural types. The Larch-LM profile was predominantly characterized by a single-grain structure (Table 2).

3.1.2. Root Distribution

Root abundance was assessed semi-quantitatively in each soil horizon using the abundance classes provided in the WRB field guidelines [WRB]. The classes none, very few, few, and common correspond to defined ranges of root numbers per unit area and root-diameter class. Both sites showed a similar general vertical pattern of root distribution. The highest recorded root-abundance classes occurred in the upper soil horizons, followed by a gradual decrease with depth. Roots were absent in the deepest horizons, a common occurrence in many soil profiles where roots do not penetrate beyond a certain depth. Accordingly, the results presented in Tables 1 and 2 represent class-based field estimates of root abundance rather than direct measurements of root biomass, root length density, or exact root numbers.

3.1.3. Colour Variations

At Szczakowa, the surface horizons differed in colour among the examined profiles: Birch-SM was dark greyish brown (10YR 3/2), Larch-SM was dark grey (10YR 4/1), Oak-SM was brown (10YR 4/3), and Pine-SM was dark greyish brown (10YR 4/2). The colours generally became lighter with depth, while the 10YR hue remained dominant and value and chroma generally increased (Table 1). At Bełchatów, the surface horizons showed greater colour variability: Birch-LM displayed yellowish-brown and grey hues, Larch-LM was brown (10YR 5/3), Oak-LM was very dark (10YR 2/1), and Pine-LM showed various shades of brown to greyish brown. With depth, the hues became more variable, but the colours generally became lighter (Table 2). The interpretation of the colours indicates that darker colours in the A horizons, such as those in the oak profile, suggest a higher accumulation of organic matter. Lighter colours in the deeper horizons are more indicative of the parent material, which is homogeneous and sandy at Szczakowa, as shown by the consistent 10YR hue throughout the profile. The more complex colour patterns in Bełchatów

reflect the heterogeneous nature of the anthropogenic parent material at that site. These colour differences suggest that the soils at both sites are in the early stages of development, with Bełchatów showing more variation due to its diverse substrate (Figures 1 and 2).

3.1.4. The Thickness of Organic-Rich Surface Horizons (O + A)

The thickness of the organic-rich surface horizons (Ol/Olf/A) was measured at four sampling points within each tree species $\times$ site combination, comprising one soil profile and three soil cores. Each bar represents the mean of these four measurements. (Figure 3).

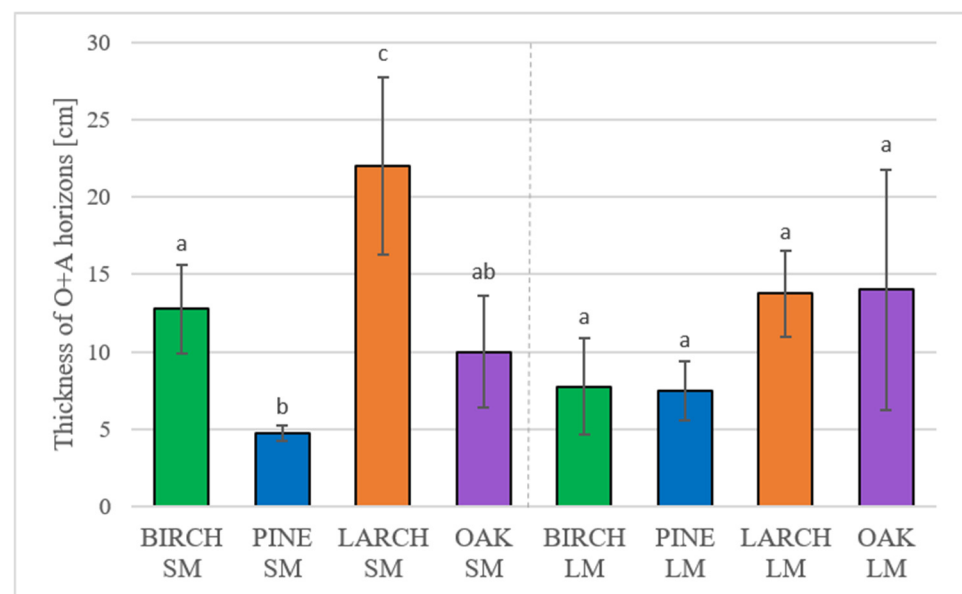


Figure 3. Mean thickness of the combined organic-rich surface horizons (O + A) under the four investigated tree species at the Szczakowa and Bełchatów sites. Error bars represent ± 1 SD ($n = 4$). Different lowercase letters indicate significant differences among tree species within the same site according to Tukey's HSD test following two-way ANOVA ($p < 0.05$).

The two-way ANOVA showed a significant main effect of tree species, $F(3, 24) = 11.24$, $p < 0.001$, and a significant tree species $\times$ site interaction, $F(3, 24) = 4.18$, $p = 0.016$, whereas the main effect of site was not significant, $F(1, 24) = 1.25$, $p = 0.275$. At the Szczakowa site (SM), the mean thickness of the organic-rich surface horizons across the four investigated stands was 12.4 cm. The greatest mean thickness was recorded for Larch-SM, followed by Birch-SM, Oak-SM, and Pine-SM. According to Tukey's HSD test, Larch-SM had a significantly greater mean thickness than Birch-SM, Pine-SM, and Oak-SM. At the Bełchatów site (LM), the corresponding mean thickness was 10.8 cm. The greatest mean thickness was recorded for Oak-LM, followed by Larch-LM, Birch-LM, and Pine-LM; however, no significant differences among tree species were detected at this site. Overall, larch stands had the greatest mean thickness of organic-rich surface horizons at both sites when the site-specific means were considered. The smallest mean thickness was recorded for Pine-SM at Szczakowa and Pine-LM at Bełchatów. Oak-LM showed the greatest variability among the four measurements, whereas birch stands showed contrasting patterns between sites, with a greater mean thickness at Szczakowa than at Bełchatów.

3.2. Soil Properties

At Szczakowa (SM), the soil predominantly consists of sandy textures, with occasional loamy sand horizons. At Bełchatów (LM), there is a greater variability in soil texture, ranging from loamy sand to silty loam (Figures 4 and 5).

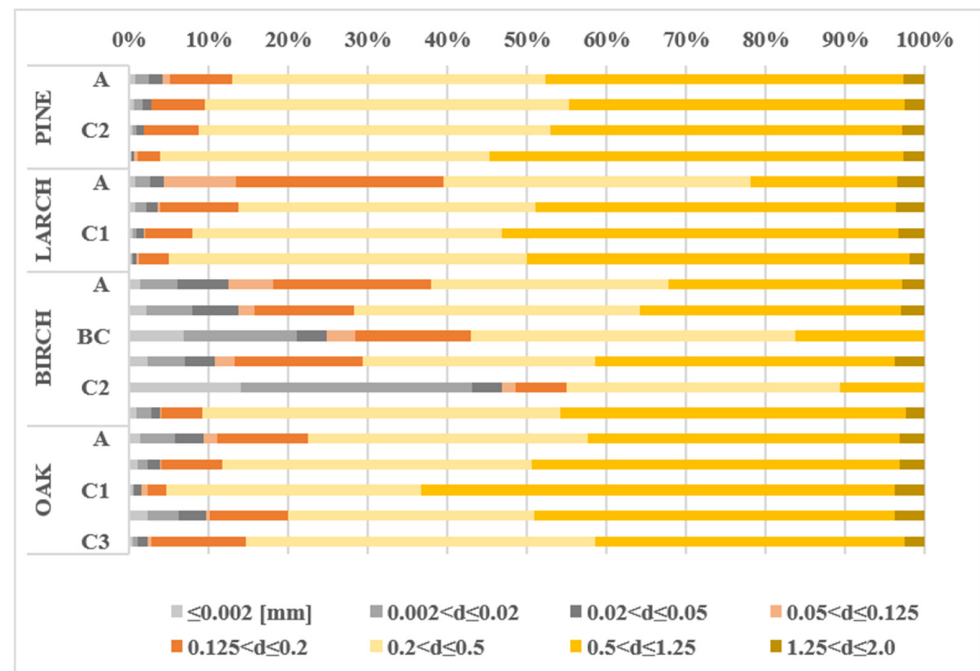


Figure 4. Soil particle size distributions in the investigated soil profiles in Szczakowa.

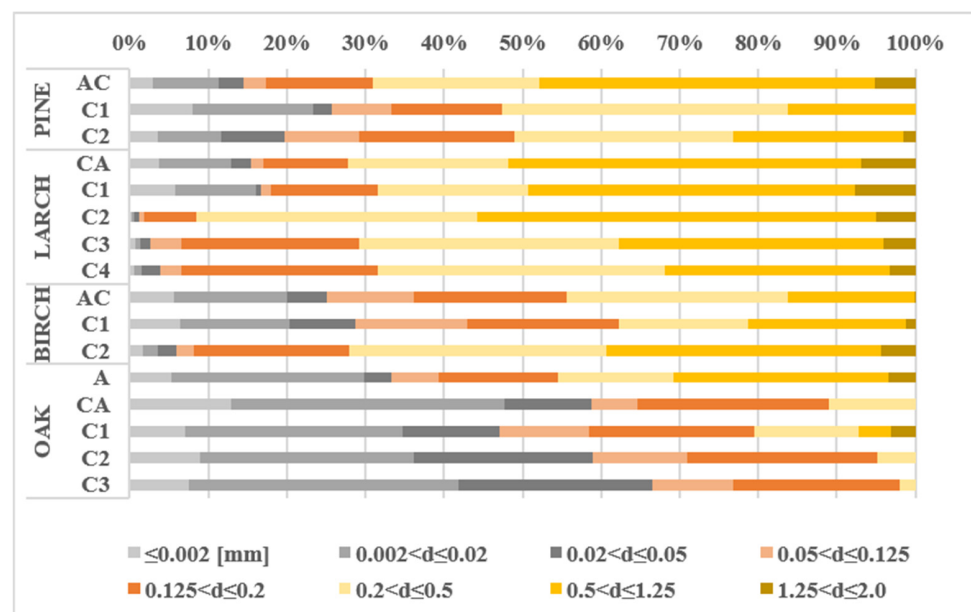


Figure 5. Soil particle size distributions in the investigated soil profiles in Bełchatów.

3.2.1. pH Values

At Szczakowa, the $\text{pH}(\text{H}_2\text{O})$ of the surface organic (O) horizon varied across species; the O horizon under Pine-SM was the most acidic, with a $\text{pH}(\text{H}_2\text{O})$ of 3.8. Larch-SM had a $\text{pH}(\text{H}_2\text{O})$ of 4.9, while Birch-SM and Oak-SM had slightly higher $\text{pH}(\text{H}_2\text{O})$ values of 5.3 and 4.7, respectively. These differences suggest that pine was associated with more acidic soil conditions compared with the other tree species at this site. With increasing depth, $\text{pH}(\text{H}_2\text{O})$ increased in all profiles at Szczakowa. For instance, $\text{pH}(\text{H}_2\text{O})$ in the Pine-SM profile increased from 4.7 in the A horizon to 6.1 in the C3 horizon. Similarly, Larch-SM, Birch-SM, and Oak-SM showed increases in pH from their respective surface horizons to deeper horizons, with $\text{pH}(\text{H}_2\text{O})$ ranges of 5.6–6.7, 4.7–6.3, and 4.7–6.4, respectively. This pattern indicates that pH generally increased with depth at this site.

At Bełchatów, the pH(H₂O) of the surface organic horizons was generally lower than at Szczakowa. Unlike at Szczakowa, Larch-LM had the most acidic surface horizon, with a pH(H₂O) of 3.5, followed by Pine-LM (3.7), Oak-LM (4.4), and Birch-LM (4.8). The vertical distribution of pH(H₂O) at Bełchatów was more variable than at Szczakowa. For example, Pine-LM showed a pH(H₂O) range of 4.1–4.6 from the AC to the C2 horizon, with a slight increase with depth. Larch-LM and Birch-LM displayed more stable pH(H₂O) ranges of 4.3–4.8 and 4.5–4.7, respectively. However, Oak-LM at this site exhibited the strongest vertical variation in pH(H₂O), which increased from 4.0 in the A horizon to 8.7 in deeper horizons, probably reflecting the heterogeneous parent material.

The comparison between the two coniferous species showed a site-specific pattern: Pine-SM had a more acidic surface horizon than Larch-SM at Szczakowa, whereas Larch-LM had a more acidic surface horizon than Pine-LM at Bełchatów. The difference between pH(H₂O) and pH(KCl) was generally larger in the surface horizons at both sites, reflecting a greater contribution of exchangeable acidity associated with organic matter. This difference tended to decrease with depth (Table 3).

3.2.2. C and N Content

The C and N contents, as well as the C:N ratio, varied between the two study sites—Szczakowa (SM) and Bełchatów (LM)—and among the examined profiles under the different tree species (Table 3). The observed values differed among species, sites, and soil horizons. In the organic surface horizon, the highest C content was recorded in soil under pine, with 43.5% at Szczakowa and 45.3% at Bełchatów. Birch stands showed slightly lower and similar values at the two sites, with 42.1% at Szczakowa and 42.3% at Bełchatów. Soil under larch showed a notably lower C content at Szczakowa (25.2%) than at Bełchatów (40.7%). Oak stands showed the most pronounced difference between sites, with 12.7% at Szczakowa and 43.9% at Bełchatów.

Soil under birch showed the highest N content at Szczakowa (1.29%) and Bełchatów (1.38%). Larch and pine stands showed comparable N contents, with 0.93% and 1.07% at Szczakowa and 1.37% and 1.02% at Bełchatów, respectively. Oak stands showed the lowest N content, with 0.48% at Szczakowa and 0.87% at Bełchatów. Thus, the N content of the organic surface horizons followed the order Birch-SM > Pine-SM > Larch-SM > Oak-SM at Szczakowa and Birch-LM > Larch-LM > Pine-LM > Oak-LM at Bełchatów. In the surface mineral horizons, soil under birch showed the highest C and N contents at Szczakowa, with 4.64% C and 0.23% N in the A horizon. Larch-SM had 0.85% C and 0.07% N, while Pine-SM and Oak-SM showed lower values, with C contents of 0.58% and 0.24%, respectively. At Bełchatów, Oak-LM showed the highest measured values in the A horizon, with 13.01% C and 0.74% N. The A horizons of the other LM profiles contained between 0.32% and 0.56% C. The TOC values reported for the Bełchatów profiles represent the measured carbon pool, which may include both biogenic and geogenic carbon fractions. C and N contents generally decreased with depth at both sites. However, the vertical patterns differed among the examined profiles. At Szczakowa, the Birch-SM profile maintained higher C and N values across several mineral horizons than the other SM profiles. At Bełchatów, soil under oak retained relatively high C content even in deeper horizons, with values ranging from 0.72% to 2.36%. In contrast, the profiles under the other species generally showed a more rapid decrease in both C and N contents with depth. In the organic surface horizon, pine stands showed the highest C:N ratio at both sites. The Oak-SM profile showed the lowest C:N ratio at Szczakowa, whereas a higher ratio was recorded in Oak-LM. In the mineral horizons, the C:N ratio generally decreased with depth. Soil under birch at Szczakowa showed a more gradual decline in the C:N ratio, whereas Oak-LM showed relatively similar C:N ratios across several soil horizons.

Table 3. Basic soil properties of reclaimed soils under four tree species at Szczakowa and Bełchatów, including pH, organic C, total N, S, C:N ratio, hydrolitic acidity (Hh), exchangeable cations (Ca, K, Mg, Na), base saturation (VH), and cation exchange capacity (CEC) by soil horizon.

Tree Species	Horizon	pH H ₂ O	pH KCl	C%	N%	S%	C:N Ratio	Hh (cmol(+)-kg ⁻¹)	Ca (cmol(+)-kg ⁻¹)	K (cmol(+)-kg ⁻¹)	Mg (cmol(+)-kg ⁻¹)	Na (cmol(+)-kg ⁻¹)	SH/TEB (cmol(+)-kg ⁻¹)	VH (%)	CEC (cmol(+)-kg ⁻¹)
PINE-SM	O	3.8	2.9	43.50	1.07	0.18	40.54								
	A	4.7	3.8	0.58	0.04	0.02	15.86	6.30	0.20	0.02	0.04	0.01	0.27	4.07	6.57
	C1	5.1	4.0	0.07	0.01	0.01	5.94	1.46	0.17	0.01	0.06	0.01	0.25	14.69	1.71
	C2	5.1	4.6	0.03	0.01	0.01	2.37	0.95	0.17	0.01	0.11	0.01	0.30	23.73	1.25
	C3	6.1	5.5	0.03	0.01	0.01	2.16	0.62	0.22	0.01	0.12	0.01	0.35	36.22	0.98
LARCH-SM	O	4.9	4.2	25.20	0.93	0.12	27.03								
	A	5.6	4.1	0.85	0.07	0.02	12.95	5.07	1.26	0.06	0.23	0.01	1.56	23.51	6.63
	AC	5.2	4.4	0.20	0.02	0.01	11.25	2.54	0.13	0.02	0.06	0.01	0.21	7.56	2.74
	C1	6.0	4.7	0.02	0.01	0.01	2.20	1.44	0.19	0.01	0.10	0.01	0.31	17.63	1.75
	C2	6.7	5.7	0.01	0.01	0.01	1.42	0.62	0.22	0.01	0.10	0.01	0.34	35.58	0.97
BIRCH-SM	O	5.3	4.7	42.05	1.29	0.14	32.55								
	A	4.7	4.9	4.64	0.23	0.04	19.99	14.89	6.46	0.39	1.52	0.01	8.38	36.02	23.27
	AB	5.2	4.1	0.39	0.03	0.01	13.28	3.89	0.44	0.05	0.19	0.00	0.68	14.97	4.57
	BC	5.5	4.0	0.14	0.02	0.01	7.53	2.84	1.52	0.07	0.63	0.01	2.23	43.95	5.06
	C1	5.6	4.1	0.06	0.01	0.01	4.55	2.00	1.43	0.05	0.48	0.01	1.98	49.71	3.98
	C2	6.0	4.2	0.09	0.02	0.01	4.24	2.60	3.82	0.11	1.49	0.01	5.43	67.65	8.03
	C3	6.3	4.7	0.03	0.01	0.01	2.93	1.13	0.80	0.04	0.30	0.01	1.14	50.27	2.27
OAK-SM	O	4.7	4.0	12.74	0.48	0.08	26.57								
	A	4.7	3.8	0.24	0.01	0.01	16.46	3.75	0.09	0.03	0.07	0.01	0.20	5.13	3.95
	CA	5.1	4.1	0.06	0.01	0.01	6.70	1.50	0.25	0.03	0.16	0.01	0.44	22.77	1.94
	C1	5.5	4.4	0.02	-	0.01	3.59	1.08	0.45	0.03	0.20	0.01	0.68	38.54	1.76
	C2	5.9	4.8	0.02	-	0.01	3.64	1.08	0.84	0.04	0.36	0.01	1.24	53.63	2.32
	C3	6.4	5.0	0.02	-	0.01	3.46	0.62	0.25	0.02	0.12	0.01	0.39	38.67	1.02
BIRCH-LM	O	4.8	4.8	42.33	1.38	0.13	30.69								
	AC	4.7	3.4	0.56	0.06	0.01	9.06	2.92	1.28	0.06	0.29	0.01	1.63	35.84	4.55
	C1	4.6	3.9	0.20	0.06	0.02	3.19	3.06	0.64	0.04	0.13	0.01	0.82	21.02	3.88
	C2	4.5	3.7	0.15	0.04	0.03	3.56	2.38	1.44	0.02	0.04	0.01	1.51	38.74	3.89
PINE-LM	O	3.7	3.2	45.25	1.02	0.12	44.22								
	AC	4.1	3.4	0.39	0.07	0.01	5.27	3.13	1.09	0.05	0.10	0.01	1.25	28.57	4.38
	C1	4.1	3.6	0.10	0.06	0.01	1.83	2.21	0.37	0.02	0.03	0.01	0.44	16.50	2.64
	C2	4.6	3.7	0.05	0.05	0.01	1.02	1.46	0.56	0.03	0.07	0.01	0.66	31.05	2.12

Table 3. Cont.

Tree Species	Horizon	pH H ₂ O	pH KCl	C%	N%	S%	C:N Ratio	Hh (cmol(+).kg ⁻¹)	Ca (cmol(+).kg ⁻¹)	K (cmol(+).kg ⁻¹)	Mg (cmol(+).kg ⁻¹)	Na (cmol(+).kg ⁻¹)	SH/TEB (cmol(+).kg ⁻¹)	VH (%)	CEC (cmol(+).kg ⁻¹)
LARCH-LM	O	3.5	2.8	40.67	1.37	0.17	29.61								
	CA	4.5	3.5	0.32	0.07	0.02	4.45	2.41	1.46	0.07	0.20	0.01	1.75	42.04	4.16
	C1	4.3	3.1	0.40	0.06	0.02	6.35	3.61	2.15	0.10	0.11	0.01	2.38	39.72	5.99
	C2	4.7	3.8	0.04	0.05	0.01	0.95	0.94	0.25	0.01	0.01	0.01	0.28	22.95	1.22
	C3	4.8	3.5	0.44	0.07	0.02	6.25	2.97	1.78	0.03	0.08	0.01	1.90	39.04	4.88
	C4	4.2	3.1	0.10	0.06	0.02	1.80	1.22	0.91	0.03	0.04	0.01	0.99	44.77	2.21
OAK-LM	O	4.4	3.9	43.89	0.87	0.09	50.68								
	A	5.3	4.4	13.01	0.74	0.17	17.66	19.47	16.05	0.64	1.50	0.03	18.23	48.35	37.70
	CA	4.6	3.6	2.36	0.15	0.10	15.35	12.22	6.50	0.13	0.59	0.01	7.24	37.20	19.46
	C1	4.0	3.1	17.84	0.11	0.10	18.73	14.66	3.01	0.09	0.07	0.01	3.18	17.85	17.84
	C2	8.7	7.8	17.92	0.06	0.01	11.09	0.65	16.49	0.12	0.65	0.02	17.28	96.40	17.92
	C3	8.2	7.9	20.90	0.05	0.01	15.04	0.48	19.41	0.13	0.85	0.02	20.42	97.71	20.90

In samples containing carbonates, their content was determined quantitatively and converted to carbonate-derived carbon. This fraction was subtracted from the total carbon content; therefore, the C values presented in Table 3 are corrected for inorganic carbonate carbon.

3.2.3. Sorption Properties

Table 3 shows that the sorption properties of the studied soils vary across the Szczakowa (SM) and Bełchatów (LM) sites, with differences influenced by tree species and soil depth. At the Szczakowa site, Birch-SM exhibited the highest CEC values, ranging from 23.27 $\text{cmol}(+)\cdot\text{kg}^{-1}$ in the surface horizons to 2.27 $\text{cmol}(+)\cdot\text{kg}^{-1}$ in deeper horizons, indicating strong sorption capacity near the soil surface. Pine-SM and Larch-SM showed moderate CEC values, with Pine-SM ranging from 6.57 to 0.98 $\text{cmol}(+)\cdot\text{kg}^{-1}$ and Larch-SM from 6.63 to 0.97 $\text{cmol}(+)\cdot\text{kg}^{-1}$. Regardless of species, all soil profiles at this site showed a consistent decrease in CEC with depth, reflecting lower organic matter content and a reduced ability to retain cations in deeper horizons. At the Bełchatów site, Oak-LM exhibited the highest CEC values, ranging from 37.70 to 20.90 $\text{cmol}(+)\cdot\text{kg}^{-1}$, indicating a notably greater capacity for cation retention compared to soils under other species. The remaining tree species displayed moderate CEC values, generally ranging from 4 to 2 $\text{cmol}(+)\cdot\text{kg}^{-1}$. These values highlight the higher cation retention capacity associated with the Oak-LM profile at this site, likely due to variations in litter composition, decomposition rates, and interactions with the soil mineral fraction.

3.2.4. Total Fe and Fe Forms Content

Distinct patterns in total Fe content and its fractions, namely amorphous Fe (oxalate-extractable), oxide-bound Fe (dithionite-extractable), and organically bound Fe (pyrophosphate-extractable), were observed among tree species and between study sites (Table 4).

At the Szczakowa site (SM), Birch-SM had the highest total Fe (TFe) content, reaching 0.96% in the C2 horizon, with relatively high values throughout the profile (0.20–0.39%). Birch-SM also showed the highest contents of Fe_{ox}, reaching 0.10%, and Fe_d, reaching 0.19%, whereas Fe_p reached 0.04% in the deeper horizons. Larch-SM showed a gradual decrease in TFe with depth, from 0.14% in the A horizon to 0.07% in the C2 horizon, with consistently low concentrations of Fe_{ox}, Fe_d, and Fe_p. Pine-SM had a slightly higher TFe concentration in the surface A horizon (0.19%), followed by lower values in the deeper horizons. Oak-SM exhibited moderate TFe concentrations, with a local increase in deeper horizons, suggesting some accumulation of Fe oxides during profile development.

At the Bełchatów site (LM), Oak-LM showed the highest Fe accumulation, with TFe reaching 1.12% in the C3 horizon. Fe_{ox} reached 0.44%, Fe_d 0.24%, and Fe_p 0.25%, indicating a greater accumulation of both poorly crystalline and organically associated Fe forms. Larch-LM showed greater vertical variability, with TFe ranging from 0.13% to 0.34%, whereas Pine-LM showed more uniform TFe concentrations, ranging from 0.24% to 0.25%. Birch-LM and Pine-LM had comparable TFe concentrations overall, although their vertical distributions of Fe fractions differed. These results indicate that larch and pine, despite belonging to the same functional group, showed distinct patterns of Fe distribution with depth.

The Fe_{ox}/Fe_d ratio was used as an indicative measure of the relative contribution of poorly crystalline Fe to the pool of dithionite-extractable Fe oxides. Higher values indicate a greater relative contribution of poorly ordered Fe phases, whereas lower values indicate a greater contribution of more crystalline Fe oxides. This ratio was interpreted

cautiously because it can also be affected by organic matter, parent material, and site-specific redox conditions.

Table 4. Iron forms in the studied soils by tree species and soil horizon. Fet, total extractable Fe; Feox, oxalate-extractable Fe (amorphous and poorly crystalline forms); Fed, dithionite-extractable Fe (amorphous and crystalline iron oxides); Fep, pyrophosphate-extractable Fe (organically bound Fe).

Tree Species	Horizon (WRB)	Fet [%]	Feox [%]	Fed [%]	Fep [%]	Feox/Fed
BIRCH-SM	A	0.30	0.03	0.06	0.02	0.50
	AB	0.27	0.03	0.05	0.03	0.60
	BC	0.39	0.04	0.05	0.04	0.80
	C1	0.34	0.03	0.06	0.04	0.50
	C2	0.96	0.10	0.19	0.04	0.53
	C3	0.21	0.02	0.04	0.03	0.50
LARCH-SM	A	0.14	0.01	0.03	0.01	0.33
	AC	0.12	0.02	0.03	0.02	0.67
	C1	0.08	0.01	0.02	0.01	0.50
	C2	0.07	0.01	0.01	0.01	1.00
OAK-SM	A	0.12	0.01	0.03	0.02	0.33
	CA	0.10	0.01	0.01	0.01	1.00
	C1	0.13	0.01	0.02	0.02	0.50
	C2	0.23	0.01	0.04	0.02	0.25
	C3	0.12	0.00	0.02	0.02	0
PINE-SM	A	0.19	0.02	0.04	0.03	0.50
	C1	0.09	0.01	0.02	0.01	0.50
	C2	0.11	0.00	0.02	0.01	0
	C3	0.09	0.01	0.03	0.01	0.33
BIRCH-LM	AC	0.31	0.10	0.06	0.04	1.67
	Cu1	0.35	0.11	0.06	0.06	1.83
	Cu2	0.24	0.13	0.07	0.06	1.86
LARCH-LM	CAu	0.23	0.09	0.05	0.04	1.80
	Cu1	0.34	0.15	0.08	0.09	1.88
	Cu2	0.13	0.06	0.05	0.02	1.20
	Cu3	0.21	0.12	0.06	0.06	2.00
	Cu4	0.13	0.04	0.02	0.03	2.00
OAK-LM	AC	0.74	0.42	0.19	0.15	2.21
	CAu	0.79	0.44	0.20	0.24	2.20
	Cu1	0.68	0.41	0.16	0.25	2.56
	Cu2	1.08	0.40	0.21	0.16	1.90
	Cu3	1.12	0.39	0.24	0.13	1.63
PINE-LM	AC	0.25	0.08	0.04	0.05	2.00
	C1	0.24	0.07	0.04	0.03	1.75
	Cu2	0.25	0.07	0.03	0.04	2.33

The Feox/Fed ratio differed between the two sites. At Szczakowa, it ranged from 0 to 1.00. Birch-SM showed ratios of 0.50–0.80, whereas the ranges for Larch-SM, Oak-SM, and Pine-SM were 0–1.00, 0–1.00, and 0–0.50, respectively. At Bełchatów, the ratios were higher, ranging from 1.20 to 2.56. The highest value was recorded in the Cu1 horizon of Oak-LM (2.56), followed by the Cu2 horizon of Pine-LM (2.33). Birch-LM and Larch-LM showed ranges of 1.67–1.86 and 1.20–2.00, respectively.

3.3. Soil Classification

The classification of the investigated soils utilised four main systems: the Forest Soil Classification (FSC) [9,11], the WRB [14], Systematyka Gleb Polski 6 (SgP) [24] and Soil Taxonomy [25].

For the sandy soils at the Szczakowa site (SM), the classifications across all systems are highly similar, reflecting the weak profile development (Table 5). Soils under Pine-SM and Larch-SM are both classified as Industrial and urbanzoic soils with an undeveloped profile in the FSC, reflecting the shallow humus horizon (A horizon) and the dominant sandy texture. This initial stage of development aligns with the WRB classification of these soils as Arenosol, which reflects weak profile development resulting from the sandy parent material.

Table 5. Comparative classification of the soil profiles studied under four tree species at the Szczakowa and Belchatów sites according to the World Reference Base for Soil Resources (WRB), Polish Soil Classification (SgP), Forest Soil Classification (FSC), and Soil Taxonomy.

Tree Species	Depth (cm)	(WRB)	Horizon (SgP)	(FSC)	(WRB)	(SgP)	Classification (FSC)	Soil Taxonomy
BIRCH-SM	1–0	O τ	Ol	Ol	Brunic Transportic Arenosol (Ochric, Protospodic)	type: arenosoles subtype: typical arenosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udipsamment
	0–3	A τ	A	Ain				
	3–11	AB τ	AB	AB				
	11–29	BC τ	BC	BC				
	29–49	C τ 1	C1	C1				
	49–71	C τ 2	C2	C2				
LARCH-SM	71–150	C τ 3	C3	C3				
	1–0	O τ	Ol	Ol	Transportic Arenosol (Ochric, Protospodic)	type: arenosoles subtype: typical arenosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udipsamment
	0–8	A τ	A	Ain				
	8–30	AC τ	AC	AC				
	30–70	C τ 1	C1	C1				
	70–150	C τ 2	C2	C2				
OAK-SM	2–0	O τ	Ol	Ol	Brunic Transportic Arenosol (Ochric)	type: arenosoles subtype: typical arenosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udipsamment
	0–8	A τ	A	Ain				
	8–32	CA τ	CA	CA				
	32–60	C τ 1	C1	C1				
	60–90	C τ 2	C2	C2				
	90–150	C τ 3	C3	C3				
PINE-SM	1–0	O τ	Ol	Ol	Transportic Arenosol	type: arenosoles subtype: typical arenosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udipsamment
	0–5	A τ	A	Ain				
	5–34	C τ 1	C1	C1				
	34–108	C τ 2	C2	C2				
	108–150	C τ 3	C3	C3				
BIRCH-LM	1–0	O _i	Ol	Ol	Spolic Technosol (Arenic, Ochric, Protospodic)	type: technogenic soils subtype: aggerosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udorthent
	0–6	AC	AC	ACan				
	6–20	Cu1	Ca1	Can1				
	20–120	Cu2	Ca2	Can2				
PINE-LM	1–0	O _i	Ol	Ol	Spolic Technosol (Arenic, Ochric)	type: technogenic soils subtype: aggerosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udorthent
	0–9	AC	AC	ACan				
	9–28	C1	C1	C1an				
	28–130	Cu2	Ca2	Can2				
LARCH-LM	1–0	O _i	Ol	Ol	Spolic Technosol (Arenic, Ochric, Protospodic)	type: technogenic soils subtype: aggerosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udorthent
	0–15	CAu	CAa	CAan				
	15–27	Cu1	Ca1	Can1				
	27–52	Cu2	Ca2	Can2				
	52–97	Cu3	Ca3	Can3				
	97–140	Cu4	Ca4	Can4				
OAK-LM	1–0	O _i	Ol	Ol	Spolic Technosol (Calcaric, Humic, Protospodic)	type: technogenic soils subtype: aggerosols	Subtype 25.1 Industrial and urbanzoic soils with an undeveloped profile (AU _i)	Anthroportic Udorthent
	0–3	AC	Aa	Aan				
	3–15	CAu	CAa	CAan				
	15–44	Cu1	Ca1	Can1				
	44–60	Cku2	Caca2	Canca2				
	60–110	Cku3	Caca3	Canca3				

Similarly, the SgP system classifies both soils as typical Arenosols, underscoring their weak profile development, sandy texture, and shallow A horizons. Although the soils under larch had slightly deeper A horizons (0–8 cm) than those under pine, both profiles were assigned to the same soil unit.

In contrast, Birch-SM demonstrated more advanced development. The FSC assigns these soils to the same subtype as Pine-SM and Larch-SM but the WRB classifies these soils as Brunic Arenosol, indicating a better-developed surface horizon and a more advanced differentiation in the profile than seen under pine and larch. The SgP system also recognises this progression, classifying birch soils as typical Arenosol, indicative of more mature pedogenesis. Oak-SM soils are classified similarly to the coniferous stands in the FSC as Industrial and urbanzoic soils with an undeveloped profile, based on the Ain horizon having less than 1% organic C and a thickness up to 10 cm. The WRB classifies oak soils as Brunic, Transportic Arenosol, reflecting initial profile development. The SgP system also classifies them as typical Arenosol, but notes the presence of signs of brunification in the subsurface horizons, which suggests the onset of early-stage profile development. According to soil taxonomy, all these soils have been classified as Anthroportic Udipsamment.

At the Bełchatów Mine (LM) site, the soil classification strongly reflects the anthropogenic influence derived from reclamation activities and the technogenic parent material. All soils at the LM site are classified as Industrial and urbanzoic soils with an undeveloped profile in the FSC, recognising the technogenic origin and the sandy texture of the parent material. The WRB system reinforces this, placing these soils under the Spolic Technosol category. The SgP classification follows suit, assigning them to the technogenic soils—aggersols, acknowledging the varying degrees of soil development shaped by the reclamation processes and the specific tree species used to classify the investigated soils (Table 5). According to soil taxonomy, all these soils have been classified as Anthroportic Udorthent.

3.4. Principal Component Analysis (PCA)

The PCA of surface soil properties at Szczakowa (SM) explained 91.0% of the total variance (PC1: 51.5%, PC2: 39.5%) (Figure 6; Supplementary Table S1). PC1 was positively associated with organic matter indicators (C%, N%, CEC) and finer particle fractions (silt, clay), while PC2 primarily separated soils by texture, with sand content loading positively and silt-clay fractions loading negatively.

Larch-SM was positioned on the positive side of PC2, reflecting its markedly sandy texture with the lowest silt and clay content, indicating minimal pedogenic modification of the parent material. Birch-SM occupied the opposite end of PC2 and scored high on PC1, reflecting the most advanced accumulation of organic matter and finer particles among the SM variants (C: 4.64% in the A horizon; CEC: 23.27 cmol(+) kg^{−1}). Pine-SM and Oak-SM clustered together on the negative side of PC1, indicating lower pH and base saturation compared with Birch-SM, but little textural differentiation. This pattern suggests that after 30–40 years, birch was associated with the most pronounced pedogenic change on sandy substrates, while pine and oak occupy intermediate positions with limited soil development.

The PCA for Bełchatów (LM) explained 97.7% of the total variance, with PC1 alone accounting for 89.1% (Figure 7; Supplementary Table S1). This overwhelming dominance of PC1 reflects a single major gradient driven by substrate heterogeneity rather than species effects.

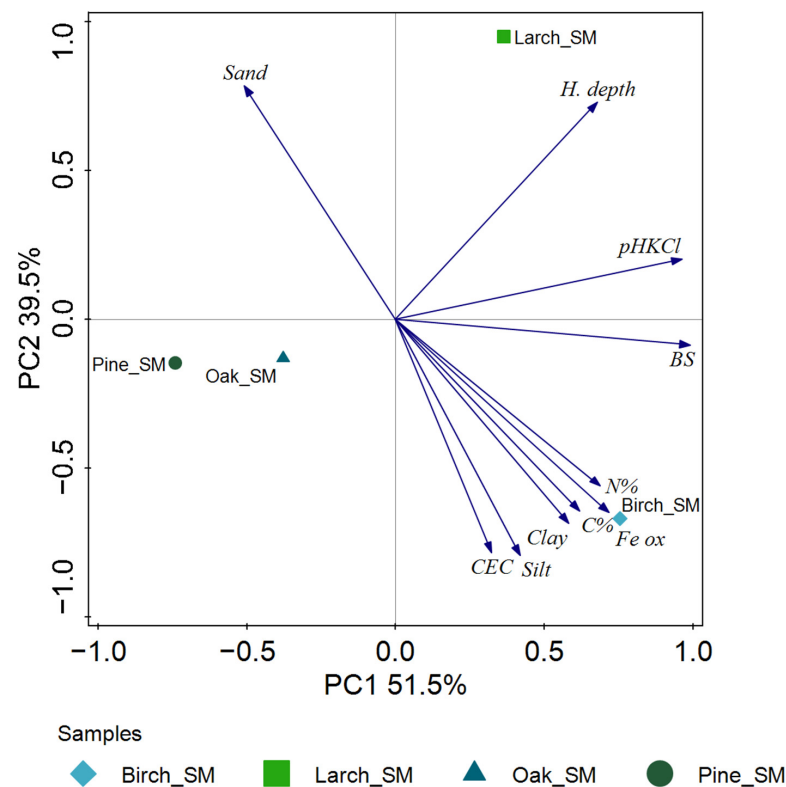


Figure 6. Principal Component Analysis (PCA) biplot of surface soil properties for the Szczakowa (SM) sand mine site. PC1 (51.5%) and PC2 (39.5%) together explained 91.0% of the total variance. SM, Sand Mine (Szczakowa); C%, total organic carbon; N%, total nitrogen; CEC, cation exchange capacity; Fe ox, oxalate-extractable Fe (amorphous and poorly crystalline forms); H. depth, humus horizon depth; BS, base saturation.

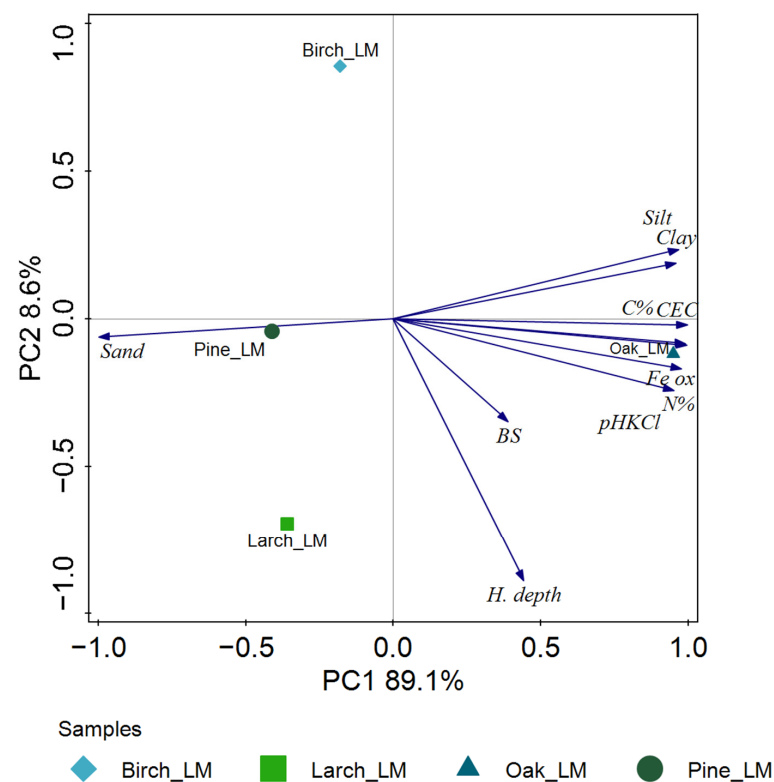


Figure 7. Principal Component Analysis (PCA) biplot of surface soil properties for the Bełchatów (LM) lignite mine site. PC1 (89.1%) and PC2 (8.6%) together explained 97.7% of the total variance.

LM, Lignite Mine (Bełchatów); C%, total organic carbon; N%, total nitrogen; CEC, cation exchange capacity; Fe ox, oxalate-extractable Fe (amorphous and poorly crystalline forms); H. depth, humus horizon depth; BS, base saturation.

Oak-LM was strongly separated from all other variants along PC1, driven by its exceptionally high C content (13.01% in the A horizon), elevated silt and clay fractions, high CEC (37.70 cmol(+) kg⁻¹), and notably elevated Fe across the profile (up to 1.12% in deeper horizons). This extreme position is attributable to the heterogeneous, carbon-rich technogenic substrate at this particular sampling point rather than to species-driven pedogenesis alone. Pine-LM, Larch-LM and Birch-LM formed a compact cluster on the negative side of PC1, sharing relatively high sand proportions and lower values of C, CEC, silt, clay and Fe. The close grouping of these three species indicates that substrate variability overrides species effects at this site during the early stages of soil development.

4. Discussion

4.1. The Role of Tree Species in Shaping Pedogenesis

Our research indicates that the two functional groups, deciduous (birch and oak) and coniferous (pine and larch), drive pedogenic processes along different trajectories, but also highlights that the underlying substrate modulates the effect of a specific tree species. Deciduous species generally promoted more advanced soil development compared to conifers. Numerous studies have consistently demonstrated that deciduous tree species exert a more substantial and faster influence on soil development compared to coniferous species [15,18,21,22].

The generally larger difference between pH measured in H₂O and KCl in the surface horizons indicates a greater contribution of exchangeable acidity associated with organic matter. This pattern should be interpreted together with litter quality and substrate buffering: acidic coniferous litter was associated with lower surface pH at Szczakowa, particularly under Pine-SM, whereas the carbonate-containing heterogeneous substrate at Bełchatów likely moderated the effect of litter-derived acidity, although Larch-LM had the most acidic surface horizon at that site. These pH patterns may influence Fe mobilisation and the direction of early pedogenic processes.

This accelerated pedogenesis is particularly clear through Fe dynamics, where deciduous species generally promote higher total Fe accumulation and a greater variety of Fe forms than conifers such as pine (*P. sylvestris*) and larch (*L. decidua*) [15,30]. In soils at the Szczakowa site (SM), birch exhibited the highest TFe content, reaching up to 0.96% in deeper horizons, along with the highest amorphous (oxalate-extracted) and oxide-bound (dithionite-extracted) Fe fractions. This strong influence of birch on Fe mobilisation in sandy soils is a key feature of its role as a driver of advanced pedogenesis in Arenosols. Conversely, at Bełchatów (LM), oak soils accumulated the highest Fe content, including high concentrations in the amorphous (up to 0.4%) and organically bound (up to 0.25%) fractions. This reflects strong interactions between Fe and organic matter promoted by the oak litter and root processes within the heterogeneous Technosol. The notably higher Fe fractions in deeper LM horizons (C3) under oak are highly indicative of pre-existing geogenic Fe reservoirs.

Although larch and pine generally showed lower Fe concentrations than birch and oak, their profiles were not identical. At Szczakowa, Larch-SM had a thicker organic-rich surface horizon and a less acidic surface horizon than Pine-SM, whereas Pine-SM showed a slightly higher total Fe concentration in the surface horizon. At Bełchatów, Larch-LM also had a thicker organic-rich surface horizon than Pine-LM and a more acidic surface horizon. The vertical distribution of Fe forms differed between the two species: Larch-LM showed

greater variation in Fe concentrations with depth, whereas Pine-LM exhibited relatively uniform Fe concentrations throughout the profile. These differences indicate that larch and pine may follow distinct trajectories of early soil development despite belonging to the same coniferous functional group.

The generally slower decomposition of coniferous litter and the resulting acidic conditions may limit Fe mobilisation, although the magnitude and vertical pattern of this effect differed between larch and pine. Higher organic inputs from deciduous species may increase the production of organic ligands involved in Fe chelation, regulate redox cycling and promote Fe translocation, which are features associated with early-stage brunification or podzolisation-like processes [31,32]. Despite these differences, the pyrophosphate-extractable Fe content remains minimal across all soils, suggesting that Fe cycling in these developing environments is primarily controlled by mineral processes rather than strong organic complexation [33].

The expression of these processes was strongly substrate-dependent, as also reported for reclaimed post-mining soils developed under different tree species and substrate conditions [5]. At Szczakowa, the homogeneous sandy substrate provided little buffering against litter-derived acidity, while its low clay content limited the retention of organic compounds and Fe. Consequently, acidity and ligand supply could act relatively directly on Fe mobilisation, with the stronger Fe response under birch suggesting that litter turnover and ligand production, rather than acidity alone, were important. At Bełchatów, carbonates likely buffered litter-induced acidity, whereas the heterogeneous spoil containing fine-textured, Fe- and carbon-bearing components promoted sorption and retention processes. Thus, the effect of oak was expressed mainly through organic matter accumulation and Fe retention rather than through strong acidification. Because litter chemistry and Fe-chelating capacity were not measured directly, this interpretation is based on the observed pH, CEC, carbon and Fe-fraction patterns.

The Fe_{ox}/Fe_d ratios were markedly higher at Bełchatów than at Szczakowa. At Szczakowa, ratios below or close to 1 indicated that dithionite-extractable Fe was generally equal to or greater than oxalate-extractable Fe. In contrast, Fe_{ox} exceeded Fe_d in all Bełchatów horizons, producing ratios of 1.20–2.56. These values indicate a strong contribution of Fe forms readily soluble in acid ammonium oxalate; however, ratios exceeding 1 cannot be interpreted directly as the proportional contribution of poorly crystalline Fe to the total pool of free Fe oxides. The pattern may reflect the operational selectivity of the extractants, the heterogeneous technogenic substrate, dissolution of additional Fe-bearing phases by oxalate, or incomplete recovery of Fe by the DCB procedure. Therefore, the Fe_{ox}/Fe_d values for Bełchatów were interpreted primarily as evidence of contrasting extractability of Fe rather than as a direct quantitative index of oxide crystallinity [34–36].

4.2. Substrate Influence and the Classification Dilemma at Szczakowa (SM)

The dichotomy between the sandy Arenosols of SM and the spoil heap Technosols of LM highlights the important role of parent material in modulating total Fe storage and its distribution among fractions. Sandy soils generally show lower Fe retention in stable oxide fractions compared to reclaimed Technosols, where the heterogeneous parent material, including clay-, Fe-, and carbon-bearing components, exerts stronger control over soil physicochemical properties. Our hypothesis that soil-forming processes might proceed more rapidly in the more ‘natural’ sandy soils of SM cannot be entirely confirmed. On the one hand, even the most advanced profile, the birch stand examined 40 years after reclamation, showed only an initial stage of B horizon development. This limited pedogenetic progression after 30–40 years confirms that these reclaimed soils remain in the early stages of development. On the other hand, the Technosol under oak in LM exhibited greater

variation in Fe forms and unexpected profile complexity, which is consistent with reports that Technosols, under favourable conditions and effective site engineering, including the way spoil heaps are constructed and layered, can undergo relatively rapid and substantial profile differentiation, reaching a complexity comparable to that of natural soils [37,38].

The PCA results provide quantitative support for the dominant role of the technogenic substrate at Bełchatów. The response-variable scores presented in Supplementary Table S1 show that the main LM ordination axis was strongly associated with clay, acid-extractable Fe, C, CEC, and pH, and negatively associated with sand. Because this axis explained most of the total variation, the main differentiation among the LM profiles was related to inherited textural and geochemical heterogeneity rather than to tree species alone. The clay fraction may increase water and nutrient retention, while inherited Fe-bearing minerals and carbon-rich material may strongly influence sorption properties, pH, and the distribution of Fe forms. These substrate-related gradients may therefore offset or mask the physicochemical differentiation induced by tree species, resulting in the close grouping of Birch-LM, Pine-LM, and Larch-LM and the distinct position of Oak-LM.

The high contribution of C to the LM ordination should be interpreted cautiously because the measured carbon pool includes both biogenic and geogenic fractions. Similarly, the acid-extractable Fe data do not allow inherited Fe from the parent material to be separated from Fe redistributed during pedogenesis. Thus, the PCA supports the interpretation of a dominant substrate-related gradient, but it does not provide direct proof that geogenic carbon or inherited Fe alone caused the observed differentiation.

4.3. Classification of Human-Transported Sandy Materials

The classification of soils at the Szczakowa site (SM) as Arenosols is primarily based on their morphology: sandy texture and weak horizonation. However, the documented history of the site, involving intensive technical and biological reclamation, underscores their anthropogenic origin. The reclamation process included reshaping the terrain and adding organic amendments, mineral fertilization, and green manure, which led to the formation of a continuous anthropogenic layer (≥ 50 cm). While these practices do not meet the specific diagnostic criteria for Anthrosols (which require long-term agricultural transformations such as plaggic or terric horizons), their anthropogenic nature is precisely captured in the WRB system by the Transportic qualifier. This highlights a significant advantage of the WRB over traditional Polish classification systems (FSC and SgP), which often assign such soils to broad, less descriptive categories like ‘industrial and urbanozoic soils with an undeveloped profile’ (AUi). The WRB’s ability to combine the Reference Soil Group (Arenosol) with the Transportic qualifier allows for a more nuanced description that reflects both the current soil properties and the site’s reclamation history.

4.4. Comparative Analysis of Soil Classification Systems

The ambiguous nature of SM soils highlights a significant difference in approach between the classification systems. The Polish FSC [9,11] and SgP [24] are primarily focused on mature, naturally developed forest soils and provide limited typological capacity to describe the complexity of early pedogenic stages typical of reclaimed environments, often grouping young or technically altered soils into broad units. In contrast, the WRB [14] has been extensively developed to accommodate a broad spectrum of both natural and anthropogenic soils. Its flexible, two-level structure, combining Reference Soil Groups with a comprehensive set of principal and supplementary qualifiers, including Spolic, Arenic, and Ochric, allows for the classification of both Technosols and Arenosols while retaining information on anthropogenic soil properties. This flexibility allows WRB to distinguish between the constructed Bełchatów Technosols and the human-transported materials

at Szczakowa, while integrating information on current soil properties and reclamation history. This comparative analysis highlights that accurate classification of reclaimed soils often requires historical documentation and context, which can be integrated into the WRB framework.

The practical value of the WRB framework was evident in its ability to distinguish the contrasting reclamation conditions at the two study sites. At Szczakowa, the classification as an Arenosol with the Transportic qualifier reflects both the sandy properties and the anthropogenic influence of human-transported material. At Bełchatów, the classification as a Technosol reflects the anthropogenic origin and heterogeneity of the spoil material, including carbonate-bearing and lignite-bearing layers.

These distinctions are relevant to reclamation planning at the studied sites because they help identify site-specific constraints related to water and nutrient retention, buffering capacity, rooting conditions, and the interpretation of soil carbon. In this context, the classification information may support decisions concerning substrate management, tree-species selection, and the monitoring of reclamation effects. Repeated WRB descriptions, combined with measurements of horizon thickness, pH, organic carbon, nitrogen, cation exchange capacity, and Fe forms, may also support long-term monitoring by helping to distinguish newly developed pedogenic features from properties inherited from the original substrate [14,39].

The national Polish classification systems also provided useful information, but represented some features of the reclaimed profiles less explicitly than WRB. Both FSC and SgP are primarily oriented towards soils with more clearly developed natural horizons and offer fewer possibilities for describing weakly developed profiles, transported sandy materials, and heterogeneous technogenic layers. Consequently, at the studied sites, the Szczakowa soils were assigned to broader categories that did not fully express the combination of sandy properties and reclamation history, whereas the complex layering and anthropogenic substrate features at Bełchatów were represented less explicitly.

4.5. Substrate Heterogeneity Versus Species Effects: Evidence from Multivariate Analysis

The contrasting PCA results between sites reveal that the relative importance of tree species versus substrate properties shifts with the degree of substrate heterogeneity. At Szczakowa, where the parent material is uniform (homogeneous Quaternary sands), the PCA separated species along meaningful ecological gradients (texture and fertility), indicating that tree species effects are the dominant driver of soil variability. In contrast, at Bełchatów, the PCA was dominated by a single axis (PC1: 89.1%) driven by substrate heterogeneity, with Oak-LM forming an extreme outlier. This suggests that in the early decades of pedogenesis on technogenic substrates, spatial variability in parent material composition can mask species-specific effects, a finding consistent with reports that Technosol properties are strongly controlled by initial deposition conditions [37,38].

4.6. Study Limitations

Several limitations should be considered when interpreting the results of this study. First, the detailed morphological and physicochemical characterization was based on one representative soil profile for each tree species $\times$ site combination. Three additional soil cores were collected from independent sampling plots representing the same tree species $\times$ site combination and were used to determine the thickness of the organic-rich surface horizons and to support soil classification. Consequently, the detailed laboratory results describe the investigated soil profiles and should not be interpreted as stand-level averages.

Second, the two study sites differed simultaneously in parent material, substrate heterogeneity, reclamation history, carbonate occurrence and climatic conditions. Therefore,

the differences observed between Szczakowa and Bełchatów reflect the combined influence of these site characteristics and cannot be attributed exclusively to a single substrate property. The observed tree species $\times$ substrate relationships should consequently be interpreted as site-specific patterns.

Third, the conventional TOC determination did not distinguish recently accumulated biogenic carbon from lignite-derived geogenic carbon. Therefore, the high carbon contents recorded in some Bełchatów horizons, particularly in the Oak-LM profile, cannot be attributed exclusively to vegetation-driven carbon accumulation or sequestration.

Fourth, while root distribution was assessed semi-quantitatively during soil profile descriptions following standard soil science protocols rather than by destructive fine-root coring, previous studies on comparable afforested post-mining sites have demonstrated that tree species strongly differentiate fine-root biomass, organic matter input, and biological activity in the upper soil horizons [40,41]. Consequently, although exact root biomass or density data were not quantified in the studied profiles, the observed qualitative trends in root abundance align with established species-specific belowground impacts on organic carbon accumulation and pedogenesis.

These limitations define the scope of the study but do not affect its value as a comparative assessment of soil development, Fe fractions and soil classification in two contrasting reclaimed post-mining environments.

5. Conclusions

This study, spanning 30–40 years since reclamation, demonstrates that post-mining soils remain in the initial stages of pedogenetic development. At the Szczakowa site, the soils are primarily classified as Arenosols, and at the Bełchatów site, as Technosols. The overall limited progression confirms that centuries are required for the full development of soil profiles in these anthropogenically disturbed landscapes. Tree species act as an important driver of pedogenesis during this early period, although their influence is strongly modulated and often subordinate to substrate properties. Deciduous species—particularly birch and oak—tend to promote more pronounced horizon differentiation and enhance the accumulation of organic C and N, leading to increased CEC and more active mobilisation and transformation of Fe in the profile compared to coniferous species (pine and larch). Reclamation strategies should account for substrate properties. At Szczakowa, the soil profile under birch showed more pronounced initial pedogenic differentiation, whereas at Bełchatów, the profile under oak exhibited the greatest morphological complexity among the investigated Technosols. The anomalously high C and CEC values under Oak-LM suggest that this complexity is strongly driven by the presence of geogenic carbon, necessitating further research to decouple biogenic and geogenic influences on sequestration.

From a sustainability perspective, the findings underscore that informed tree species selection is a cost-effective and nature-based strategy for accelerating the restoration of soil functions on degraded post-mining landscapes. Deciduous species, by enhancing soil organic carbon accumulation, cation exchange capacity and nutrient cycling, contribute to the long-term provision of ecosystem services, including carbon sequestration, water regulation and biodiversity support. Integrating substrate-specific species recommendations into reclamation planning can therefore improve the ecological and economic outcomes of mine land restoration, supporting broader land degradation neutrality objectives.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157889/s1>, Table S1. Response-variable scores for the first three principal component axes for the measured soil properties at the Bełchatów (LM) and Szczakowa (SM) post-mining sites.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
SM	Sand Mine (Szczakowa)
LM	Lignite Mine (Bełchatów)
CEC	Cation exchange capacity
TFe	Total extractable Fe
Fe _{ox}	Oxalate-extractable Fe (amorphous and poorly crystalline forms)
Fed	Dithionite-extractable Fe (amorphous and crystalline iron oxides)
Fep	Pyrophosphate-extractable Fe (organically bound Fe)
Hh	Hydrolitic acidity
VH	Base saturation
HD	Humus horizon depth
BS	Base saturation
PCA	Principal Component Analysis
WRB	World Reference Base for Soil Resources
SgP	Polish Soil Classification (Systematyka gleb Polski)
FSC	Forest Soil Classification

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