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The Impact of Mining Waste and Biogas Digestate Addition on the Durability of Soil Aggregates

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Abstract: Waste management is one of the greatest contemporary challenges as the world strives for sustainable development. We set out to investigate the impact of mining waste (carboniferous rock) and organic waste (biogas digestate) on the physical properties of soils. The wastes were applied to Podzol, soil characterised by low chemical and physical quality with the particle size distribution (PSD) of loamy sand. The paper sets out to answer the question of whether a one-time application of mine and/or biogas digestate onto soil positively affects the durability of the soil structure and if the changes were permanent. For this purpose, we analysed soil texture, total organic carbon (TOC), water-stable aggregates and the mean weight diameter of water-stable aggregates (MWD). The combined addition of biogas digestate and the two types of waste improved the soil structure. The content of soil water-stable aggregates with dimensions 5–10 mm ($A_{5–10}$) and 1–5 mm ($A_{1–5}$) increased the MWD and the content of aggregates of diameters <1 mm ($A_{<1}$) decreased. The effects of the experiment were permanent, as differences resulting from the soil treatments were still visible four years after the application. This shows that wastes, especially biogas digestate, could be successfully used in agriculture.

Keywords: Podzols; waste application; water-stable aggregates; soil structure condition

Citation: Pranagal, J.; Ligęza, S.; Gmitrowicz-Iwan, J. The Impact of Mining Waste and Biogas Digestate Addition on the Durability of Soil Aggregates. *Agriculture* **2023**, *13*, 1815. https://doi.org/10.3390/agriculture13091815

Academic Editor: Pavel Krasilnikov

Received: 29 August 2023
Revised: 11 September 2023
Accepted: 11 September 2023
Published: 15 September 2023

1. Introduction

Soil is subjected to various degradation factors. It includes compaction, soil erosion, salinization, acidification, nutrient deficiency, and various types of contamination [1]. The global soil degradation is a constantly growing problem [2,3]. One of its forms is a physical degradation resulting in excessive soil compaction and deterioration of soil structure. Studies by Drewry et al. [4], Pranagal et al. [5] and Reynolds et al. [6] showed that high density and deterioration of the soil structure in the plant root zone has a negative effect on growth. Considerable soil compaction and deterioration of its structure cause problems with soil aeration and the plants' access to water and nutrients. Further implications include an increase in mechanical resistance to root movement, disturbed development of root systems, and difficulties in soil tillage. All these factors usually lead to lower yields.

Soil is a non-renewable, complex and dynamic natural resource [3,7,8]. The introduction of organic and mineral materials can modify the physical properties of soil [9–11]. An improvement in soil properties can be accomplished by many methods. Most of them involve the application of various materials and substances to the soil. The most popular substances are fertilisers. Other popular materials include wastes and products from their processing [12–16]. In Poland, these materials are usually digestate from sewage treatment plants, lignite, biochar, waste mineral wool, and municipal waste compost [17–20]. In recent years, the number of agricultural biogas plants in Poland has increased [21]. Simultaneously, studies on the influence of biogas digestate on the soil quality have also increased [22–24]. The agricultural utilisation of wastes has two positive aspects, getting rid of the wastes and improving soil quality [22,25].

An essential aspect of applying mining and/or organic waste to soil is the resulting change in its structure and physical qualities, as they strongly influence the soil–plant–atmosphere relationship [26–28] and define the conditions of the biochemical transformations, chemical reactions, and microbial processes which take place in the soil [17,29,30]. Numerous studies have concluded that the content of water-stable aggregates is a good and sensitive indicator of the soil structure quality [31,32].

This paper presents a study with two objectives, (1) reduce the environmental impact of wastes by reducing their amount, and (2) improve the soil structure. In our study we tested two types of wastes which are difficult to manage, carboniferous rock (mining waste), a side effect of coal extraction, and biogas digestate organic waste from an agricultural biogas plant. The materials were introduced to a soil of a loamy sand (LS) texture of poor agricultural quality. The soil was classified as Podzol (PZ) developed from fluvioglacial sand [33]. The research set out to analyse the changes in soil structure caused by the application of the wastes after a period of four years. We tried to answer the question of whether the one-time application of the tested waste caused permanent positive changes on the soil structure.

2. Materials and Methods

2.1. Study Area and Sampling

The experiment was set up in eastern Poland (51°12′ N; 23°17′ E; Figure 1) in the temperate climate zone. The growing season is 210–215 days long (on average), starting in March and lasting till the end of October. The experiment took place from 2014 to 2018. The first year of the experiment (2015) was very warm and dry, with an average air temperature of 9.7 °C and a total annual precipitation of 533 mm. In 2016, it was a bit colder (9.1 °C) with more precipitation (698 mm). In the third year, the total annual precipitation was 598.2 mm and the mean annual air temperature was 8.9 °C. The fourth year was notably warmer (9.6 °C), with a lower total annual precipitation (433.6 mm). In comparison, the average air temperature in Poland in 1951–2020 was 8.2 °C, and the average annual precipitation was 608 mm [34,35].

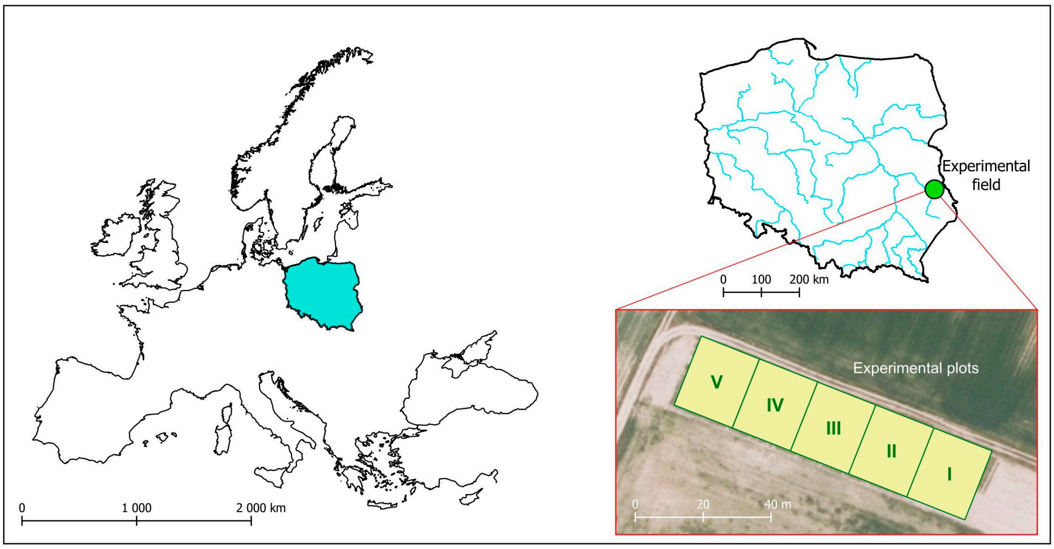

Figure 1. Study area; I–V: treatments.

The experiment was located on a flat area in the highest part of the upland. The region is characterised by a diverse soil cover [36]. The tested soil was Podzol (PZ) developed from fluvioglacial sand [33]. Before the application of the wastes, the PSD of the arable horizon Ap (0–20 cm) was identified as loamy sand (LS). The TOC content was establish as 8.46 g kg^{-1}.

The method of random blocks in three replicates was applied. Four crops in rotation were used as follows: the first year, winter wheat; the second year, winter rape; the third year, oat; and the fourth year, winter rye. Each experimental block consisted of five plots of 37.5 m^2. The plots were subjected to different treatments as follows: I—control (no additions); II—mineral fertilisation; III—mining waste; IV—organic waste; and V—both mineral and organic waste. The adopted scheme is described in Table 1. The wastes, carboniferous rock and biogas digestate, were added to the soil in treatments III, IV and V in the first year of the experiment (June 2014). The biogas digestate was added to the soil as a liquid. A more detailed description of the treatment and wastes can be found in the paper by Pranagal et al. [34].

Table 1. Description of the experiment's design [34].

<table>
<tr><th></th><th>No.</th><th>Treatment</th><th colspan="7">Dose</th></tr>
<tr><td rowspan="6">Treatment</td><td>I</td><td>Control soil</td><td colspan="7">None</td></tr>
<tr><td rowspan="2">II</td><td rowspan="2">Mineral fertilisation * (kg ha^{-1})</td><td>N autumn</td><td>N spring</td><td>P</td><td>K</td><td>Mg</td><td>Ca</td><td>S</td></tr>
<tr><td>40</td><td>80</td><td>100</td><td>120</td><td>40</td><td>60</td><td>20</td></tr>
<tr><td>III</td><td>Mining waste (Mg ha^{-1})</td><td colspan="7">Carboniferous rock
200</td></tr>
<tr><td>IV</td><td>Organic waste (m^3 ha^{-1})</td><td colspan="7">Biogas digestate
60</td></tr>
<tr><td>V</td><td>Mining (Mg ha^{-1}) and organic (m^3 ha^{-1}) waste</td><td colspan="5">Carboniferous rock
200</td><td colspan="2">Biogas digestate
60</td></tr>
</table>

* applied each year.

The sediments were acquired from the Wikana Bioenergia Sp. z o.o. agricultural biogas plant. The materials used in the production of biogas were maize silage (70%), sugar beet silage (15%), farm yard manure (5%), dairy waste (5%), and fruit pomace (5%). The biogas plant used mesophilic fermentation conducted at a temperature of 32–42 °C. The biogas digestate material was hydrated; the dry matter content was 8%. The TOC content was 633.8 g kg^{-1}, TN 28.8 g kg^{-1}, P 5580.6 mg kg^{-1}, K 26,609.9 mg k^{-1}, Mg mg kg^{-1}, pH (in KCl) was 8.7, C:N was 22.1, and electrical conductivity was 3.7 mS cm^{-1} [23]. The carboniferous rock mining waste came from the Lubelski Węgiel "Bogdanka" S.A coal mine. It was a mix of mudstones, claystones, and loams (PD = 2.72–2.84 Mg m^{-3}). It consisted of SiO_2 470 g kg^{-1} and Al_2O_3 220 g kg^{-1} [5,22]. The TOC content was 281.2 g kg^{-1}, TN 3.6 g mg^{-1}, P 14.8 mg kg^{-1}, K 33.8 mg kg^{-1}, Mg 139.8 mg kg^{-1}, pH (in KCl) was 7.6, C:N was 78.1, and electrical conductivity was 0.4 mS cm^{-1} [23]. The carboniferous rock used in our experiment had a solid, non-fragmented, non-homogenised form with equivalent diameters of 5–100 mm. Taking into account NPK content in the wastes, the thickness of the cultivation layer (0–20 cm) and the soil density (1.5 Mg m^{-3}), the waste doses were 6% for the mining waste (by mass ratio) and 3% for the biogas digestate (by volume ratio). The variation in these ratios was due to differences in the NPK nutrient content of these materials. Hence, after conversion, the doses were 200 Mg ha^{-1} of the mining waste and 60 m^3 ha^{-1} of the biogas digestate [22].

Both materials were initially applied on the surface of the soil. Plots were then ploughed to the depth of ~20 cm. Then, in the process of active harrowing, the soil surface was levelled. Twenty days after waste application, the soil was then subjected to a conventional plough tillage. The soil was cultivated with a conventional tillage method, mouldboard ploughing (18–20 cm), followed by harrowing, and then sowing and harrowing. Before planting each crop, a 0–20 cm deep plough tillage was applied.

Soil specimens were taken between 10 and 20 May 2018, in the winter rye heading phase, in the last year of the experiment. Soil samples were taken from two depths, 0–10 and 10–20 cm.

2.2. Analysis

The soil structure analysis was based on the content of water-stable aggregates. The study required 50 g samples of air-dried soil, sifted through a sieve (mesh size: 10-mm). Next, the soil was wet sieved for 12 min using a set of flat sieves (5 mm and 1 mm meshes), in 1 L cylindrical containers, in six replicates. The containers were rotated at an angle of 45°, with a frequency of two rotations per minute. We focused on soil macroaggregates because they are considered to be most agriculturally valuable, and it was important for us to determine their resistance to the destructive effects of water. The aggregates remaining on each sieve were dried at room temperature and weighed to obtain the shares of water-stable aggregate fractions: 5–10 ($A_{5–10}$), 1–5 ($A_{1–5}$) and <1 mm ($A_{<1}$). The mean weight diameters of the water-stable aggregates (MWD) were calculated from the screening [37]. Soil texture was established by the sieving and sedimentation method [38], and the total organic carbon (TOC) content was measured using of a Shimadzu TOC-VCSH analyser, Kyoto, Japan with an SSM-5000A adapter for solid sample combustion.

2.3. Statistical Analysis

The statistical analysis were the analysis of variance (ANOVA), the Tukey's test and the lowest significant difference test (LSD), with $p < 0.05$ in all tests. The one-way ANOVA concerns the average the soil property values for the 0–20 cm layer. The statistical variation in the results was estimated based on the coefficient of variation, CV = SD (standard deviation)/(arithmetic mean), and the coefficient of correlation (r; n = 60) of the studied soil qualities; the significance level α was set as 0.05. Statistical analyses were conducted in Statistica 11 software by Statsoft and ARSTAT by the University of Life Sciences in Lublin.

3. Results

3.1. Soil Texture (PSD) and Total Organic Carbon (TOC)

The results of the PSD (fractions of sand 2.0–0.05 mm: $PSD_{2.0–0.05}$, silt 0.05–0.002 mm: $PSD_{0.05–0.002}$, and clay < 0.002 mm: $PSD_{<0.002}$) and TOC analyses were shown in the paper by Pranagal et al. [34]. However, due to the strong influence of these features on soil structure, we decided to include this data in this paper as well.

The texture of soil without waste application (treatments I and II) remained unchanged in terms of the PSD—it was loamy sand (LS) [38] and only slightly varied. The mean value of the sand fraction was 75.5%, silt was 21.0%, and clay was 3.5% (Table 2). The waste application caused the PSD to change by several percent. In treatment III (application of carboniferous rock), the analysis of the fine earth particles revealed an increase in the sand fraction content by 3%, a decrease in silt content by 3%, and an increase in clay content by 1%. The greatest changes in the PSD were caused by addition of the biogas digestate (treatment IV). The content of the sand, silt and clay fractions also changed by −7%, +5% and +3%, respectively. Consequently, the soil texture classification changed to a sandy loam (SL) [39].

We noted similar changes in the soil under treatment V (addition of both digestate and rock). The soil texture classification of soil from treatment V also changed to sandy loam (SL) [39]. The shares of sand, silt and clay fractions changed by −4%, +3% and +2%, respectively. However, the soil texture changes caused by waste application were not statistically significant.

Table 2. Total organic carbon (TOC) content, shares of soil textural classes and variability (CV) [34].

Treatment	Depth cm	TOC, g kg^{-1}	Soil Fraction, mm			Soil Texture [38]
			2.0–0.05	0.05–0.002	<0.002	
I	0–10	8.81–9.52	76	20	4	LS
	10–20	7.39–8.08	75	22	3	
II	0–10	8.93–9.71	75	22	3	LS
	10–20	7.62–7.98	76	20	4	
III	0–10	7.79–8.81	78	18	4	LS
	10–20	7.23–7.78	77	18	5	
IV	0–10	13.62–15.69	68	26	6	SL
	10–20	11.78–12.31	69	26	5	
V	0–10	14.23–15.57	71	24	5	SL
	10–20	11.19–12.14	70	24	6	
CV		0.27	0.06	0.13	0.28	

Note: I—control soil (no waste); II—soil fertilized with N, P, K, Mg, Ca and S; III—soil with carboniferous rock; IV—soil with biogas digestate; V—soil with carboniferous rock and biogas digestate; CV—coefficient of variation; TOC—total organic carbon.

The TOC content varied from 7.23 g kg^{-1} (treatment III; 10–20 cm) to 15.69 g kg^{-1} (treatment IV; 0–10 cm) (Table 2). The addition of mining waste caused a statistically insignificant decrease in the TOC content, while the addition of the organic waste (IV and V) caused a statistically significant increase in this parameter (Table 2, Figure 2).

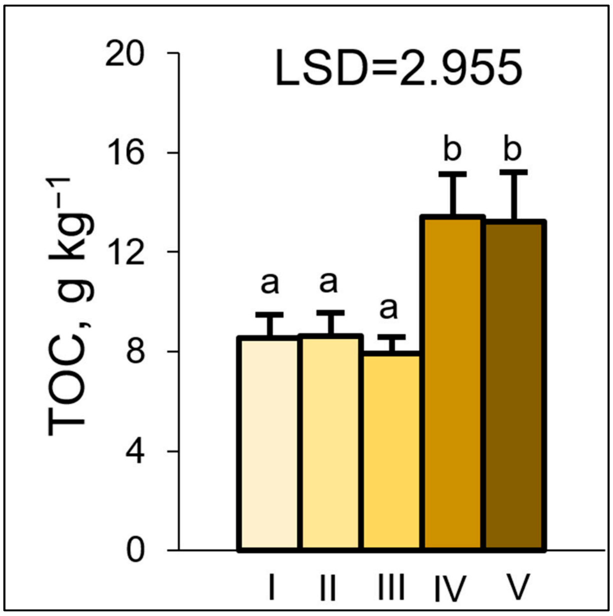

Figure 2. Mean values (0–20 cm layer) of the total organic carbon (TOC) content in the 0–20 cm layer. I–V: treatments (description as in Table 2); letters (a, b) indicate the lowest significant differences (LSD), $p < 0.05$.

The correlation analysis confirmed the significant relationships between the TOC content and water stability of the soil aggregates: large ($A_{5–10}$, r = 0.886), medium ($A_{1–5}$, r = 0.880), and the weighted arithmetic mean of the aggregates' diameters (MWD, r = 0.908) (Table 3).

Table 3. Statistical relationships among the soil properties (based on the correlation coefficients; significance r > 0.4582).

Properties	TOC	$PSD_{2.0–0.05}$	$PSD_{0.05–0.002}$	$PSD_{<0.002}$	$A_{5–10}$	$A_{1–5}$	$A_{<1}$
$PSD_{2.0–0.05}$	−0.431						
$PSD_{0.05–0.002}$	−0.428	−0.842 *					
$PSD_{<0.002}$	0.393	−0.881 *	−0.897 *				
$A_{5–10}$	0.886 *	−0.451	−0.102	0.054			
$A_{1–5}$	0.880 *	−0.631 *	−0.310	0.259	0.909 *		
$A_{<1}$	−0.870 *	−0.791 *	0.578 *	0.638 *	−0.815 *	−0.940 *	
MWD	0.908 *	−0.468 *	0.288	0.436	0.948 *	0.979 *	−0.917 *

Note: TOC—total organic carbon content; $PSD_{2.0–0.05}$, $PSD_{0.05–0.002}$, $PSD_{<0.002}$—soil size fraction content (diameters: 2.0–0.05 mm, 0.05–0.002 mm, <0.002 mm, respectively); $A_{5–10}$, $A_{1–5}$ and $A_{<1}$—water-stable aggregate content by diameter; MWD—mean weight diameters of the water stable aggregates; r *—significant correlation coefficients.

3.2. The Content of Water-Stable Soil Aggregates ($A_{5–10}$, $A_{1–5}$, and $A_{<1}$) and the Weighted Arithmetic Mean of the Aggregate Diameters (MWD)

In our study the content of water-stable aggregates with sizes of 5–10 mm ($A_{5–10}$) varied from 0.2% (treatment III; 0–10 cm) to 3.6% (treatment IV; 0–10 cm), and the soil was characterised by high statistical variation, CV = 0.82 (Table 4). The mean values calculated for the 0–20 cm soil layer in the treatments were 0.6% (I), 0.6% (II), 0.5% (III), 2.6% (IV), and 2.4% (V). The addition of the biogas digestate to the soil (IV) and both organic and mining waste (V) caused a significant increase in the water stability of $A_{5–10}$. The differences between treatments I–III and treatments IV and V were statistically significant (Figure 3a). The content of $A_{5–10}$ was positively correlated with TOC, r = 0.886 (Table 3).

Table 4. Variability, content and mean weight diameter of the aggregates.

Property	Soil Layer cm	Treatment					CV
		I	II	III	IV	V	
$A_{5–10}$, %	0–10 10–20	0.5–0.9 0.3–0.8	0.4–0.9 0.3–0.8	0.2–0.9 0.2–0.8	1.9–3.6 1.8–3.2	1.7–3.1 1.6–3.2	0.82
$A_{1–5}$, %	0–10 10–20	8.9–11.3 9.4–12.1	8.3–10.1 8.6–10.2	7.4–8.6 8.1–8.8	15.9–17.3 16.7–17.8	16.1–17.3 16.8–17.9	0.32
$A_{<1}$, %	0–10 10–20	88.6–91.1 89.1–90.7	89.7–90.8 89.9–90.7	91.3–92.1 91.1–91.9	79.8–80.7 79.6–80.5	80.1–81.3 79.7–80.9	0.06
MWD, mm	0–10 10–20	0.73–0.84 0.74–0.83	0.73–0.82 0.72–0.83	0.75–0.81 0.69–0.78	1.07–1.15 1.04–1.13	1.03–1.11 1.06–1.14	0.19

Note: I–V as in Table 2; $A_{5–10}$, $A_{1–5}$ and $A_{<1}$—soil water-stable aggregates content at various diameters; MWD—mean weight diameters of water-stable aggregates; CV—coefficient of variation.

The content of $A_{1–5}$ was characterised by a similar distribution as the $A_{5–10}$ case (Figure 3b). Statistical variation in the results was much lower, CV = 0.32, while the content of $A_{1–5}$ was several times higher than that of $A_{5–10}$ (Table 4). The lowest content of $A_{1–5}$ was noted in the 0–10 cm layer in treatment III (7.4%), and it was the highest (17.9%) in the 10–20 cm layer in treatment V. A comparative analysis of the mean values of $A_{1–5}$ for the 0–20 cm layer revealed differences between treatments that were similar to those in the case of $A_{5–10}$. The content of $A_{1–5}$ in treatments I (10.4%), II (9.3%) and III (8.2%), compared to treatments IV (16.9%) and V (17.0%), was significantly lower (ANOVA-LSD) (Figure 3b). The presence of water-stable aggregates with dimensions of 1–5 mm ($A_{1–5}$) correlated positively with TOC (r = 0.880) and negatively with the $PSD_{2.0–0.05}$ fraction (r = −0.631) (Table 3).

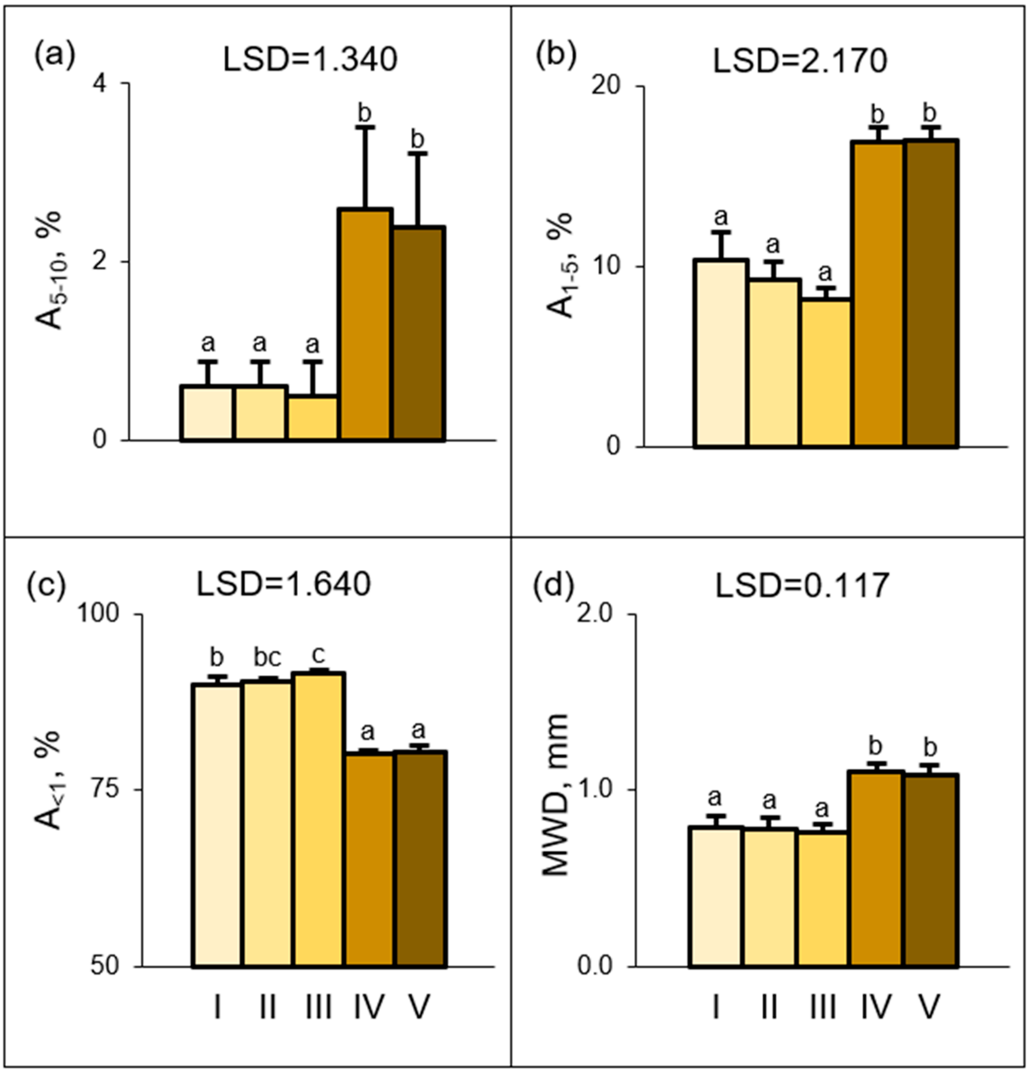

Figure 3. Mean values (0–20 cm layer) of the soil water-stable aggregates content: (**a**) $A_{5–10}$, (**b**) $A_{1–5}$ (**c**) $A_{<1}$ and (**d**) MWD; I–V: treatments; letters (a, b, c) indicate the lowest significant differences (LSD), $p < 0.05$.

The content of aggregates with dimensions <1.0 mm ($A_{<1}$) was characterised by low variation, CVs = 0.06. The lowest content of those aggregates (79.6%) was noted in the soil with the addition of the biogas digestate (IV; 10–20 cm), and it was the highest (92.1%) in the soil mixed with mining waste (III; 0–10 cm). The content of $A_{<1}$ was calculated by subtracting the shares of $A_{5–10}$ and $A_{1–5}$ from 100% (Table 4). Therefore, the changes in the content of $A_{<1}$ and its correlations were opposite in relation to $A_{5–10}$ and $A_{1–5}$. Comparison of the mean values for the 0–20 cm layer revealed that the content of $A_{<1}$ was influenced by the application of the organic waste (IV) or both organic and mining wastes (V). The lowest statistically significant difference of $A_{<1}$ content was noted in the soils under treatments IV and V (Figure 3c). The mean levels of $A_{<1}$ (0–20 cm) in the treatments were 89.9% (I), 90.3% (II), 91.6% (III), 80.2% (IV), and 80.5% (V). An estimation of the correlation showed a negative relationships between $A_{<1}$ content and the TOC value (r = −0.870), and with the $PSD_{2.0–0.05}$ fraction (r = −0.791), but positive correlations with the $PSD_{0.05–0.002}$ fraction (r = 0.578) and $PSD_{<0.002}$ fraction (r = 0.638) (Table 3).

The MWD values were subject to only a small statistical variation, CV = 0.19. The smallest MWD was noted in treatment III in the 10–20 cm layer (0.69 mm), and the largest was noted in treatment IV in the 0–10 cm layer (1.15 mm; value range VR = 0.46 mm) (Table 4). The mean values for the 0–20 cm layer in the treatments were 0.79 mm (I), 0.78 mm (II), 0.76 mm (III), 1.10 mm (IV), and 1.09 mm (V). The following visible changes in soil quality caused by waste application were observed: (i) negative—treatment III; (ii) positive—treatments IV and V. Compared to treatments I, II, and III, the stability of the soil aggregates in treatments IV and V was significantly higher (Figure 3d). The MWD significant correlations were noted in the case of the TOC (r = 0.908; positive one), similarly to $A_{5–10}$ and $A_{1–5}$, and the $PSD_{2.0–0.05}$ fraction (r = −0.468; negative one) (Table 3).

4. Discussion

4.1. Changes in Soil Texture and Total Organic Carbon

The largest PSD changes caused by the addition of biogas digestate (treatment IV) were surprising because the digestate was used in liquid form. However, reclassification of soil texture after waste application is a common phenomenon, especially in the case of soils with similar texture classes [40,41].

The carboniferous rock consists of loams, mudstones and claystones. However, addition of this material did not cause significant changes of the silt and clay shares. Yang et al. [10] showed that mineral amendments (natural clay mineral attapulgite) might influence the PSD by decreasing the content of sand and increasing the silt and clay shares. The lack of significant changes in our case may have been due to the form of the applied material, i.e., non-fragmented rock. It could be assumed that with time, the rock will undergo physical weathering and disintegrate into smaller fine earth particles. Then, more significant changes in soil texture might be noticeable. The changes in the PSD in soil amended with carboniferous rock and/or post-fermentation sediments (III, IV, V) had an undeniable impact on the soil qualities, especially on its structure. It is widely known that PSD changes cause further changes to other soil properties [29,40,42,43]. A particularly strong relationship exists between the content of the fine fractions and the TOC content—the more silt and clay in the soil, the more TOC [44].

Changes in the TOC content usually result in numerous modifications to the physical properties of the soil, influencing the openness of soil pores and the difficulty of performing tillage treatments [5,27,45–48]. A TOC content decrease could cause a deterioration of the soil water properties and conditions of soil–atmosphere gas exchange. On the other hand, an increase in the TOC content has a positive effect on the physical properties of the soil [29,49–53]. Soil organic carbon facilitates the formation of a stable aggregate structure, as it stabilises bonds between fine earth particles. Therefore, because high TOC soil aggregates are less susceptible to the destructive force of water, soil is thus more resistant to water erosion [54–56]. The statistically significant changes in TOC content in soils from treatments I–V, observed four year after the waste application, proves that the effects are long-lasting. An increase in carbon content is especially visible while using organic waste. In our study, the TOC value increased after application of biogas digestate. Cai et al. [9] noted a TOC increase after applying organic waste, biochar and manure, while Lilli et al. [11] observed a similar response after applying sewage sludge and olive-mill-waste.

4.2. Changes in the Aggregate Content

Macroaggregates are considered a good indicator of soil structure durability and quality [32,57,58]. The content of large aggregates (5–10 and 1–5 mm), resistant to the destructive effect of water, has a beneficial effect on the air–soil–water–plant relation [59–61].

According to our results, the addition of organic waste into soil has a beneficial effect on soil structure, i.e., it caused an increase in the macroaggregate content (up to 1.45% in the case of $A_{5–10}$ and 7.25% for $A_{1–5}$). Similar results were obtained by Cai et al. [9] who applied biochar and poultry manure separately and combined causing a significant increase in the water-stable aggregate share (by up to 28.7%). Moreover, the water stability could be significantly increased (by 8–15%) by the addition of phosphogypsum and turkey litter [62] as well as sewage sludge and olive mill waste (an increase in macroaggregates by 16.4% and a decrease in microaggregates by 3.3%) [11].

Our results differed considerably from the values presented by Paluszek [50], according to whom, the mean content of water-stable aggregates with dimensions of 5–10 mm in soils with a PSD of loamy sands is 7.9%. Our correlation analysis confirmed the relationships between the water stability of aggregates and other soil properties [26,44,59]. The cited works show that the presence of A_{1-5} in soil is the most favourable for plant growth.

The results of A_{1-5} obtained in our study were similar to the mean values presented in the study by Paluszek [50]. The author concluded that the content of A_{1-5} in soils developed from loamy sands was 11.6% on average. However, those results ranged broadly between 2.2% and 24.0%. The correlation analysis indicated the same relationships as in the case of A_{5-10}. According to Paluszek [50], the average content of $A_{<1}$ in soils with the PSD of loamy sands is 80.5%. Compared to the results of our study, this corresponds precisely with the content of $A_{<1}$ in the soil with the simultaneous addition of both wastes—treatment V.

The MWD of aggregates is an indicator commonly used by soil scientists. It represents the stability of soil aggregates to the disintegrating effect of water, taking into account the mutual quantitative relations among the fractions of aggregates. The MWD is highly useful in the estimation of (i) the stability of soil structure, (ii) soil susceptibility to crusting, and (iii) soil susceptibility to water erosion [19,63].

Based on abundant data, Paluszek [50] calculated the mean MWD for sandy soil (loamy sand), which amounted to 1.15 mm. Compared to the overall mean value from our study (MWD = 0.90 mm), it was notably higher, and the range of the values obtained by Paluszek [50], i.e., VR = 2.38 mm, was several times higher as well (the MWD values fell within the range 0.31–2.69 mm). According to the classification proposed by Le Bissonnais et al. [64], soil aggregates in treatments I, II and III were unstable and conducive to soil surface crusting. Whereas the soil in treatments IV and V was characterised as a medium stability of aggregates and a lower susceptibility to the soil surface crusting. It should be emphasised that the formation of a soil surface crust contributes to, for example, an increase runoff of rainfall, and thus intensifies the threat of water erosion [65].

Cai et al. [9] showed that the MWD value can be successfully increased by organic waste amendment. However, based on this study, biochar (increase by ~17%) is more effective than manure (increase by 9%). However, application of both types of wastes had antagonistic effects, the positive changes in the MWD caused by biochar were reduced by manure addition. In our case, application of mining waste negatively influenced the MWD value. Therefore, it would be worth considering research into the use of biochar and mineral materials as soil amendments. Biochar might be more effective in reducing the negative MWD changes caused by mineral waste than biogas digestate.

The application of carboniferous rock in the non-fragmented form to soil (treatment III) increased the susceptibility of aggregates to the disintegrating effect of water. Whereas the addition of the organic waste (IV), or both organic and mining one (V), had a beneficial impact on the quality of the soil aggregate structure. The effect of these changes can be considered long-lasting, as the differences resulting from the application of the tested materials were still visible four years after their application. Similar observations were noted in a 20-year study by Meena et al. [14]—the best effects in terms of improvements in soil aggregates water stability were obtained with treatments of permanent grass cover and in soil to which organic compost had been added systematically. Fiorini et al. [64] emphasised that an increase in soil aggregate stability is fastest when the initial soil organic matter (SOM) content is low and the dominant particle size fraction is sand. The dominant role of SOM in the formation of soil aggregates and the maintenance of their stability has been indicated by many authors, e.g., Domżał and Pranagal [66], Ojeda et al. [59], and Pranagal et al. [26].

The presented results show a highly important function of SOM in the shaping of the soil aggregate structure. The water stability of soil aggregates changes dynamically under various environmental factors, e.g., mechanical tillage of soil, excessive soil compaction, the use of monocultures in crop plant cultivation, accelerated mineralisation of SOM, disturbed air–water–soil relations, etc. It should be stressed that the stability of soil aggregates is also subjected to seasonal dynamics. This results from changes in soil moisture and temperature. The stability of soil aggregates is determined by freeze–thaw and cyclic wetting–drying processes and by the activity of soil microorganisms, biological binding agents and mycelium hyphae. The least stable aggregates are observed in early spring, and the most stable in late summer [14,55,67].

Nowadays, a growing population requires more environmental resources. Thus, the amount of waste produced is large [68]. Food demand is increasing as well, so we need fertile soils that can produce high yields [69]. The most effective are mineral fertilisers; however, they have a negative impact on the environment, especially water bodies [70]. Moreover, inorganic fertilisers change the chemical soil quality, while physical properties remain the same. Our study, as well as studies by other authors investigating waste application into soil [9–11,71], show that introduction of waste can not only improve the chemical soil properties but also the physical ones, in our case the PSD and water-stability of aggregates. Changes in physical properties are more permanent and, in the process, influence soil chemical characteristics, for example, sorption, which makes the use of mineral fertilisers more effective. Therefore, application of waste, in our case mining material and biogas digestate, has two advantages: managing environmentally burdensome waste and permanently improving the physical properties of soils.

5. Conclusions and Recommendations

Our study showed that application of carboniferous rock and/or biogas digestate to soil influence the soil structure in a positive way. Basic soil properties, such as particle size distribution and total organic carbon content, have improved in soil with the addition of waste (IV application of the organic waste and V application of both organic and mining waste), compared to treatment I and II (both without waste). The PSD improvement was caused by higher shares of the silt and clay fractions and the increased TOC content. Changes in the PSD and TOC had a beneficial effect on soil aggregation and on the content of water-stable soil aggregates.

The application of carboniferous rock (III) had a negative impact on soil quality, and the MWD value compared to the control soil decreased on average by 0.03. However, this deterioration of the soil properties might only be temporary—weathering will disintegrate fragments of rock into finer fractions, i.e., silt and clay, improving the soil texture and other properties. It needs to be stressed that the content of large water-stable aggregates (with dimensions of 5–10 and 1–5 mm) can be used as a sensitive indicator for the assessment of changes taking place in the soil. On the other hand, the addition of biogas digestate improved the MWD value (by ~0.3 for treatments IV and V).

Our results show that natural utilisation of wastes has to be undertaken very cautiously. Mining waste should be applied after prior fragmentation, especially in the case of sandy soils. On the other hand, the degree of digestate hydration should be reduced. The differences among different treatments were often statistically significant. The changes in soil quality were permanent and still visible four years after their application.

Author Contributions: Conceptualization, J.P.; methodology, J.P. and S.L.; validation, S.L.; formal analysis, J.P.; investigation, J.P.; resources, J.P.; writing—original draft preparation J.P.; writing—review and editing, J.G.-I.; visualization, J.G.-I.; supervision J.P.; project administration, J.P.; funding acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research was financed from the budget of the Ministry of Science and Higher Education for Science in Poland 2016–2020.

Data Availability Statement: Data will be available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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