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Running Title: SOIL PROPERTIES AFTER ADDITION OF COMPOSTS WITH POLYMERS

Analyses of Micromorphological and Physical Properties of Soils after Composts Application with Addition of Polyethylene- and Biocomponent-Derived Polymer Materials

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ABSTRACT

Composts are considered to be one of the best soil amendments. However, the effects of composts with the addition of polymeric materials on the physical, hydraulic and micromorphological properties of soils have not been widely discussed. Changes in the soil physical environment influence the numerous services that soils provide. This paper presents the impacts of the application of composts with the addition of three different polymer materials produced from polyethylene and thermoplastic corn starch (F1, F2, F3) on the physical, hydraulic and micromorphological properties of two types of soils: Cambic Phaeozem and Luvic Phaeozem. The composts with polymer materials have limited or no significant effects on the soil bulk density and porosity. However, the addition of polymers increases the field water capacity by 18% to 82% (Cambic Phaeozem) and by 3% to 6% (Luvic Phaeozem) and the plant available water content by 15% to 23% (Cambic Phaeozem) and by 4% to 17% (Luvic Phaeozem). Our study suggests that the effect of compost with addition of polymer materials on Cambic Phaeozem is more pronounced than on Luvic Phaeozem. The results suggest that the use of modified composts leads to changes in the soil physical properties and micromorphological features. This effect depends on the compost rate. The compost made with the addition of synthetic and natural polymers was found to be a composite mixture that can be successfully used in agriculture.

Key Words: bulk density, corn starch, porosity, soil micromorphology, soil physics, soil water retention

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INTRODUCTION

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Compost is a widely used organic material with beneficial effects on the physical, chemical, and biological properties of soil (Arthur *et al.*, 2012; Adugna, 2016; Aranyos *et al.*, 2016, Mierzwa-Hersztek *et al*., 2018). Fertilisation with compost increases the content of nutrients and improves soil structure, which limits the possibility of sealing, runoff, and erosion (Głąb *et al*., 2018). Additionally, compost amendment reduces the bulk density and increases the water retention capacity and the water availability to plants (Adugna, 2016). Some scientists have argued that the bulk density and porosity of compost play an important role in the modification of the properties of compost-fertilised soil (Aranyos *et al*., 2016; Głąb *et al*., 2018). According to Zhao *et al.* (2015), a reduced size of compost particles results in a decrease of the OM content in soil because of intensive mineralisation processes. It is also known that the use of compost can sometimes lead to adverse changes such as soil water repellence, which is observed in soils with a high OM content (Mierzwa-Hersztek *et al.*, 2019). This phenomenon may take place when the waxy substances of plants and their degradation products or hydrophobic products created by microorganisms are introduced into the organic matter to the soil (Franco *et al.*, 2000). However, the results obtained by Głąb *et al*. (2014) showed that this phenomenon mainly appears in coarse-textured soils. To date, there are no studies describing the effect of composts with the addition of artificial polymer materials with different proportions of biocomponents on the physical properties of soil and its microstructure. Soil micromorphological analysis may help to explain how modified composts affect the structure of soil and, consequently, soil physical quality.

Attempts made in recent years to reduce the risk of degradation of dry and semi-dry soils by stabilising the surface layer with the addition of polymers (e.g., cement polymers, polyacrylamide, polyethylene, polysaccharides, polystyrenes) and biopolymers (e.g., guar gum, xanthan gum, chitosan, sodium alginate) showed positive effects (Maghchiche *et al*., 2010; Biju and Arnepalli, 2016). However, the authors emphasised that the effects of using these materials depend on the inter-phase reaction between the boundary of the soil particle and the polymer particle. Four categories of soil aggregate-polymer interaction were identified: (i) aggregation of soil particles due to polymer addition, (ii) formation of an interconnected network of polymer and clay via cation bridging, (iii) cation-induced interlinking of polymers, and (iv) change in the thickness of the diffused double-layer on clay surfaces and the competing adsorption of polymer molecules and cations onto clay surfaces (Biju and Arnepalli, 2016). These interactions can differ after introducing composts with the addition of artificial polymer materials into the soil. This is because during the composting process, there may be significant changes in the properties of not only the composted biomass but also the artificial polymer. When applied to soils, especially those with limited water retention capacity, it is essential that the material introduced improves the soil properties. Similar to soil density and porosity, soil retention properties strongly depend on the clay fraction and organic matter content in the soil (Paluszek, 2011; Babalola *et al*., 2012; Aranyos *et al*., 2016, Głąb *et al*., 2018). For this reason, the application of composts with the addition of polymer materials can meet these requirements due to their high content of organic matter at various stages of humification (Mierzwa-Hersztek *et al*., 2019).

Therefore, some questions arise: what is the effect of composts produced with the addition of polymer materials with diverse polarity due to different chemical structures on the physical properties of soil and its structure? Does the addition of polymer materials with a different share of corn starch (biocomponent) have a different effect on the soil physical properties? How does the addition of such composts affect different types of soils? We hypothesise that (i) the addition of a polymer component during the composting process modifies the compost value as a soil amendment and (ii) the effect of compost/polymer fertilisation depends on soil characteristics. The aim of the study was to determine the effect of the application of composts with the addition of three different polymer materials produced from polyethylene and thermoplastic corn starch on the physical-chemical properties of two types of soil.

MATERIALS AND METHODS

Feedstocks and composting conditions

Compost was prepared from the biomass of the following plant components: rape straw, wheat straw, shredded maize, and waste material obtained during the shelling of pea seeds. The mixture of components was prepared at a C:N ratio of 30:1, which was assumed to be optimal for the conditions of the composting process. After mixing, the materials were moistened to approximately 45% (w/w). Then, the obtained biomass was amended with 5 % (relative to the dry matter of the mixture) of ground polymer materials (produced at the Central Mining Institute in Katowice, Poland) (Mierzwa-Hersztek *et al.*, 2018). The polymer materials used in the study had different ratios of compatibiliser, polyethylene, and thermoplastic corn starch (Table 1). Composted polymer materials had relatively similar chemical composition. The highest nitrogen content was determined in F2 polymer material, and the lowest in F3 polymer material. F3 polymer material also had the highest contents of phosphorus, potassium, and trace elements.

TABLE 1
Composition of polymer materials used in the composting process.

Polymer material		F1	F2	F3
Polyethylene	% weight	47.5	65.0	30.0
Thermoplastic corn starch		45.0	30.0	60.0
Compatibiliser		7.5	5.0	10.0
C_{total}	g kg^{-1} DM	662±4	728±3	738±4
N_{total}		4.44±1.02	5.45±0.07	4.24±0.09
P_{total}	mg kg^{-1} DM	38.1±0.90	37.7±1.91	68.0±1.10
K_{total}		97.5 ±2.61	96.1 ±2.62	117 ±2
Ca_{total}		229 ±13	154 ±7	146 ±9
Mg_{total}		18.7 ±0.80	15.7 ±0.30	14.1 ±0.40
Na_{total}		34.9 ±0.11	0.32 ±0.02	0.51 ±0.14
Cd_{total}		2.48 ±0.13	1.73 ±0.08	5.13 ±0.09
Cu_{total}		4.21 ±0.12	3.54 ±0.85	6.94 ±0.57
Pb_{total}		3.52 ±0.07	2.61 ±0.01	7.23 ±0.03
Zn_{total}		15.2 ±1.26	12.2 ±1.30	15.7 ±1.00

±standard deviation, n=3; F1, F2, F3 – polymer materials used in the experiment.

Composting of plant biomass with the addition of polymer materials was carried out under laboratory conditions for 180 days in bioreactors of 0.64 m^3 (0.8×1.0×0.8 m) which were equipped with an aeration and leachate discharge system. Aeration of the composted biomass was carried out by injection of air into bioreactors in 0.1 m^3 min^{-1} cycles 4 times a day. Once a week, the composted biomass was mixed to provide better aeration and homogenisation. Up to the 90th day of the process, the biomass humidity was maintained at 50--60% and, then, to the 180th day, at 45--50% (Mierzwa-Hersztek *et al.*, 2018). The basic chemical properties of the investigated compost/polymer mixtures are presented in Table 2.

TABLE 2

Chemical properties of investigated compost/polymer mixtures.

Parameter	Unit	Compost/polymer mixtures				
		CT	C+F1	C+F2	C+F3	C+F3+M
DM	g kg^{-1}	404 ±3.9	396 ±4.0	420 ±4.1	441 ±4.1	465 ±3.7
Ash	g kg^{-1} DM	195 ±6	195 ±9	142 ±2	188 ±4	223 ±2
pH H_2O	-	7.95 ±0.04	7.92 ±0.11	8.06 ±0.02	7.76 ± 0.01	7.32 ±0.18
EC	mS cm^{-3}	3.23 ±0.15	3.02 ±0.24	2.36 ±0.11	3.90 ± 0.14	4.61 ±0.03

± standard deviation, n = 3, CT – control soil (soil without fertilisation), C+F1 - soil fertilised with compost with addition of F1 polymer material; C+F2 - soil fertilised with compost with addition of F2 polymer material, C+F3 - soil fertilised with compost with addition of F3 polymer material, C+F3+M - soil fertilised with compost with addition of F3 polymer material and microbiological inoculum.

Experimental design

The composts produced were tested in a two-year field trial experiment (Małopolska Province, Krakow) in 2016--2017. The experiment was conducted in two locations on two different soil types: Cambic Phaeozem (Arenic) and Luvic Phaeozem (Loamic) (IUSS Working Group WRB, 2015). The soil physical and chemical properties are presented in Table 3.

TABLE 3
Physical and chemical properties of two investigated soils.

Parameter	Unit	Cambic Phaeozem	Luvic Phaeozem
Soil particle fractions (mm):			
1.0-2.0	g kg^{-1}	6	2
0.50-1.0		77	8
0.25-0.5		384	51
0.1-0.25		250	84
0.05-0.1		108	185
0.02-0.05		85	378
0.005-0.02		55	210
0.002-0.005		20	48
<0.002		15	35
Texture		loamy sand	silt loam
Hh	mmol(+) kg^{-1}	15.1 ±1.2	27.3 ±1.5
CEC		118 ±2	130 ±2
pH in H_2O		7.03 ±0.02	6.84 ±0.02
EC	mS cm^{-1}	0.05 ±0.01	0.02 ±0.01
SOC	g kg^{-1}	9.23 ±0.01	9.24 ±0.02
N_{total}		0.84 ±0.03	1.02 ±0.01

± standard deviation, n = 3; Hh – hydrolytic acidity, CEC – the cation exchange capacity, EC – electrical conductivity, SOC – soil organic carbon, N_{total} – total nitrogen content

The experiments used a randomised block design with three replications. The plot area was 1 m^2. The experimental design for both types of soil included 7 treatments: control soil, soil without fertilisation (CT), soil with mineral fertilisers (MF), soil fertilised with compost without addition of polymer material (MF+C), soil fertilised with compost with addition of F1 polymer material (MF+C+F1), soil fertilised with compost with addition of F2 polymer material (MF+C+F2), soil fertilised with compost with addition of F3 polymer material (MF+C+F3), and soil fertilised with compost with addition of F3 polymer material and microbiological inoculum (MF+C+F3+M) (Mierzwa-Hersztek *et al.*, 2014). The compost applications rates per hectare (in the first year) were 5.41 t DM (C), 4.65 t DM (C+F1), 4.65 t DM (C+F2), 4.81 t DM (C+F3) and 4.31 t DM (C+F3+M). These compost rates provided 170 kg N ha^{-1} (EC, 2003). The same N dose (170 kg N ha^{-1}) in the form of ammonium nitrate was also used in the MF treatment. In addition, each treatment (except the control – CT) was amended with supplementary mineral fertilisation with P and K, i.e. up to 40 kg P ha^{-1} and 120 kg K ha^{-1}. The rate of phosphorus (P) was applied once for the first crop in the form of enriched triple superphosphate. Potassium (K) was added in the form of K salt, and nitrogen (N) – in the form of ammonium nitrate. Assuming that three crops are to be harvested, rates of P and N were divided into three equal parts (for each harvest). In the second year of the experiment, mineral fertilisers (100 kg N ha^{-1}, 40 kg P ha^{-1} and 120 kg K ha^{-1}) were applied in each treatment except for the control (CT). After application of composts and mineral fertilisers, seeds of perennial ryegrass (*Lolium perenne* L.) were sown.

Sampling and selected properties of composts and soils

After the second year of the experiment, the soil from the tested area was collected in order to determine its selected physiochemical, chemical, and physical parameters after the application of composts with polymer materials. The soil samples (~0,5 kg) were collected from each plot from the layer 0–20 cm. Three replicate soil samples were randomly excavated in each plot using a soil drill (diameter, 4 cm) and then mixed to produce a composite sample. The samples were air-dried, passed through a 2-mm mesh sieve and stored in the dark at 12–16 ℃ until analysis.

The following parameters were determined in the composts (dried at 70 ℃ and ground in a 2 mm laboratory mill) and soils (2 mm sieved) before and after setting up the 2-year plot experiment: pH – using the pH-meter CP–505 (Elmentron, Zabrze, Poland); electrical conductivity (EC) – using the conductometer CCO–501 (Elmentron, Zabrze, Poland); dry matter (DM) content - after drying the sample at 105 ℃ for 12 hours; ash content - after ashing the sample in a chamber furnace at 550 ℃ for 8 hours; and total nitrogen content - by Kjeldahl’s method using a Kjeltec 1026 System II Distillation Unit apparatus (Foss, Hilleroed, Denmark). The soil organic carbon (SOC) content was analysed using Tiurin's method. The sum of the exchangeable alkaline cations (EAC) and hydrolytic acidity (Hh) were determined by the Kappen method (Jaremko and Kalembasa, 2014). The cation exchange capacity (CEC) was calculated as the sum of Hh and EAC.

Physical and micromorphological soil properties

To determine the selected physical parameters of the soil after application of composts, the air-water relations were identified, and soil micromorphological analyses were performed. These analyses were performed on the soil collected after the second year of the experiment. Undisturbed soil samples were taken into cylinders (100 cm^3 volume) in tree replications from each plots. The following parameters were determined in these soil samples: soil bulk density (BD) was obtained in 100 cm^3 cylinders, soil particle density (Dp) was obtained using the pycnometric method (Blake and Hartge, 1986), total porosity (TP) was calculated on the basis of the soil particle density and bulk density and soil water retention curves were determined at the undisturbed soil samples using Richard’s method with porous plates (Soil Moisture Equipment Corp., Santa Barbara CA, USA). Seven matric potentials were used, namely, –4, –10, –33, –100, –200, –500, and –1500 kPa (Klute and Dirksen, 1986). Soil water retention curves were fitted to the parametric model of van Genuchten (1980) using the RETC program (PC-Progress, Prague, Czech) (van Genuchten *et al*., 1991) (Eq. 2):

$$\theta(h) = \theta r + \frac{(\theta s - \theta r)}{(1+|\alpha \cdot h|^{n})^{1-1/n}} \qquad \text{(Eq. 2)}$$

where θ is the soil water content ($cm^3\ cm^{-3}$), h represents the matric potential (kPa), θs is the saturated water content (assuming equivalence with total porosity (TP)), θr is the residual soil water content, and α and n represent the model parameters. θr is associated with the immobile water present within a dry soil (at $h = \infty$). Based on this method, the following soil quality parameters were calculated: field capacity (FC; defined as the equilibrium volumetric soil water content at –10 kPa matric potential, Marshall *et al*., 1996), permanent wilting point (PWP; volumetric soil water content at –1500 kPa matric potential, Marshall *et al*., 1996), plant available water content (AWC; calculated as the difference between the FC and PWP), sum of macropores (MP; calculated as the difference between TP and PWP), and relative field capacity (RFC; defined by Reynolds *et al*. (2008) as the proportion between FC and TP).

Micromorphological analysis

The techniques of microscopy and image analysis, including micromorphological assessment of soil, are recognised as very useful tools for the direct and comprehensive quantitative and qualitative diagnostics of soil artefacts (Stoops, 2003). Microscopic analysis allows not only the overall assessment of the physical and chemical indicators of soil quality by determining the mineral composition, porosity, amount and quality of the OM (Gerasimova and Lebedeva-Verba, 2010) but also indicates the size and shape of the mesofauna faeces, constituting direct proof of the biological activity of the soil (Stoops, 2003). To identify the microstructures of the tested soils, a soil with an intact structure was collected as a spatial system of mineral-organic components in relation to free space and was treated in an Epovac vacuum chamber (Struers, Ballerup, Denmark) using the Araldite 2020 A/B epoxy resin (Mazurek *et al*., 2016). The obtained soil material was used to prepare 100 µm and 76×52 mm soil slides using the CL50 apparatus (Logitech Ltd, Glasgow, UK). According to Van den Bygaart and Protz (1999), a 76×52 mm slide is a representative sample that is useful for describing the most important micromorphological properties of soils. Observations were carried out using a Nikon Eclipse 400 polarisation microscope. The micromorphological analysis of soil involved the determination of (Stoops, 2003; Mazurek *et al*., 2016): the type of soil microstructure I° and II°, the size and shape of the pores, the presence and share of the mineral and organic components, the presence of artefacts, the biological activity of the tested soils by determining the amount and quality of the soil fauna waste, the degree of organic matter decomposition, the micro-skeletal type as a ratio of coarse (*c*) and fine particles (*f*) adopting a 5 µm limit value, the micro-skeleton coefficient (c/f_5), and the type of soil micro mass (Mazurek *et al*., 2016). The forms of the soil structures and other micromorphological features of the tested soils were described using the nomenclature introduced by Stoops (2003), which is a standard method of describing such results. The forms of the soil structures were described on the basis of a binary image of thin soil slides that were previously completely scanned. The Aphelion v. 3.2 software (ADCIS, Saint-Contest, France) was used for image analysis and porosity determination. The solid phase of the soil was marked in black, and free spaces were marked in white.

Statistical analysis

Analysis of variance for a randomised block design was performed to evaluate the significance of compost mixtures and soil type on soil physical parameters using the statistical software package Statistica ver. 13.0 (StatSoft Inc., Tulsa OK, USA). Means were compared using a Bonferroni test with a level of significance of $P \leq 0.05$. Spearman's rank correlation coefficient and regression analysis were carried out to describe the relationships between soil parameters.

RESULTS AND DISCUSSION

Soil particle density and bulk density

The soil particle density (Dp) determined for both investigated soil types, Cambic Phaeozem and Luvic Phaeozem, was similar and reached an average of 2.56 g cm^{-3} (Table 4). The compost treatments significantly affected the Dp values. The lowest Dp value for Luvic Phaeozem was determined after using only mineral fertilisation (MF). However, for Cambic Phaeozem, the lowest Dp was noticed in the MF+C+F3 treatment. In the treatments with Luvic Phaeozem, the Dp values were more diversified and ranged from 2.44 to 2.59 g cm^{-3}.

Both investigated soils were characterised by significantly different BD values: 1.48 g cm^{-3} for Cambic Phaeozem and 1.39 g cm^{-3} for Luvic Phaeozem (Table 4). Fertilisation of both soils with composts amended with artificial polymer materials did not significantly change the BD values. Bazzoffi *et al*. (2006) also indicated an increase in the BD value in soil fertilised with different doses of composts. On the other hand, Maghchiche *et al*. (2010) and Chen *et al*. (2016) proved that polymer materials can significantly improve the physical properties of soils, especially in sandy soils prone to erosion and periodical water shortages, by improving their air and water parameters. According to Celik *et al*. (2010) and Mierzwa-Hersztek *et al*. (2014), the application of organic matter to the soil has a diluting effect and reduces the soil density. Additionally, Tejada *et al*. (2009) indicated a reduced BD after fertilisation with composts under experimental conditions on a microplot. These authors explained that this is due to the loosening of the soil's compact mineral fraction resulting from the increase in its porosity and structural stability. Kellen *et al*. (2012) indicated a reduced soil density after the application of compost, which clearly shows a beneficial effect of using this type of material on the soil structure. It should be noted that the doses of the composts used in the experiment were responsible for small differences in the BD values between treatments without fertilisation and treatments fertilised exclusively with minerals, as well as treatments with the addition of composts.

The lack of significant differences in BD between individual treatments may also result from establishing a certain state of equilibrium, taking into account soil and meteorological conditions.

As stated by Paluszek (2011), soils with a texture of sands and clayey at the humus level (Ap), in general, have a BD value ranging from 1.50 to 1.70 g cm^{-3}. Arshad *et al*. (1996) determined that the appropriate soil density, which does not have a negative effect on root growth, should not exceed 1.60 g cm^{-3}. None of our treatments exceeded that value. With the use of empirical formulas, Pabin *et al*. (1999) discovered that the BD range in loamy soils should be from 1.38 to 1.53 g cm^{-3}, and in sandy soils, the range should be from 1.48 to 1.65 g cm^{-3}. Considering the optimal values of this parameter indicated by these authors, the results of our investigations conducted with Cambic Phaeozem and Luvic Phaeozem were within the proposed ranges. It was found that the application of composts with the addition of polymer materials did not densify the soil and, consequently, did not deteriorate its air-water relations. According to Weber and Jamroz (2004), the reduced soil compaction after fertilisation with composts is more distinct than the reduced soil density and is observed only in the year of compost application. Other results, i.e., the compaction of sandy soils after compost application, were presented by Arthur *et al*. (2012) and Aranyos *et al*. (2016). These authors explained that this compaction was due to the significant increase in the organic carbon content in the soil and confirmed it by the presence of a strong negative correlation between these two parameters.

We also discovered the presence of a strong negative correlation between the BD and organic carbon content in Cambic Phaeozem ($r=-0.36$; $P \leq 0.05$) and Luvic Phaeozem ($r=-0.43$; $P \leq 0.05$) (Table 5). According to Celik *et al*. (2004), changes in the BD after application of composts depend exclusively on their mineralisation rate. The slower the mineralisation is, the longer the positive effect of the compost fertilisation on the BD. Grosbellet *et al.* (2010) stated that exogenous organic matter has a positive effect on the physical properties of agriculture-use soils, causing the physical protection of aggregates from degradation. These authors indicated that when organic particles break down, they surround the aggregates already present in the soil with a fine film and protect them from degradation.

TABLE 5
Correlation coefficient matrix of soil parameters. The lower triangle shows correlation coefficients (*r*), and the upper triangle shows significances.

	TP	FC	PWP	BD	MP	Dp	AWC	RFC	SOC
TP	1.00			**	**	**		**	*
FC	0.38	1.00					**	*	**
PWP	0.28	0.17	1.00			*			
BD	-0.84	-0.28	-0.03	1.00	**			*	*
MP	0.77	-0.24	0.14	-0.77	1.00			**	
Dp	0.59	0.32	0.51	-0.14	0.36	1.00			
AWC	0.19	0.82	-0.42	-0.24	-0.30	0.01	1.00	*	
RFC	-0.57	0.53	-0.10	0.54	-0.92	-0.24	0.54	1.00	
SOC	0.46	0.61	0.29	-0.51	0.17	0.24	0.39	0.08	1.00

*Significant at $P < 0.05$; ** Significant at $P < 0.01$; TP – total porosity, FC– field water capacity, PWP– permanent wilting point, BD – bulk density, MP – drainage porosity, Dp – soil particle density AWC – plant available water content, RFC – relative field capacity, SOC – soil organic carbon.

Total porosity and macroporosity

Changes in BD after using composts also affected TP. According to Naveed *et al*. (2014), TP linearly followed the organic carbon gradient. In our study, TP depended only on the soil type and not on the type of compost used (Table 4). The TP was 0.422 cm^3 cm^{-3} for Cambic Phaeozem and 0.453 cm^3 cm^{-3} for Luvic Phaeozem. The TP of the tested soils had an optimal range of porosity for mineral soils (0.20 to 0.75 cm^3 cm^{-3}) (Paluszek, 2011). The lack of differences between compost treatments on TP was probably associated with the relatively low compost rates. The results obtained by Babalola *et* *al*. (2012) and Aranyos *et al*. (2016) confirm the increase in TP in soils fertilised with composts. As stated by Aranyos *et al*. (2016), the increase in soil porosity is closely related to the increase in organic matter content. Fertilisation of soil with organic materials at doses from 9 t to 27 t ha^{-1} can increase TP by up to 20%. In the present study, TP was positively correlated with the soil carbon content (Fig. 1). Aranyos *et al*. (2016) also discovered the presence of a negative correlation between BD and air permeability. They showed that an increase in the soil density of 0.1 g cm^{-3} resulted in a significant decrease in the soil air permeability. Grosbellet *et al*. (2011) argued that pore creation resulted from organic matter fractionation and the consumption of organic matter particles by microorganisms. The relationship between the amount of compost used and the changes in TP, BD, and AWC was confirmed by previous reports by Weber and Jamroz (2004). The authors stated that an increase in the TP and AWC was generally observed only at high doses of composts. However, Weber and Jamroz (2004) emphasised that the compost effect on the soil porosity depends on certain factors, mainly on the soil texture and the type of compost used.

Fig. 1

Fig. 1 The relationship between the soil organic carbon content (SOC) and field capacity (FC) and total porosity (TP).

MP is an indicator of the volume of non-capillary pores that are used to gravitationally drain excess water from the soil and for gas exchange between the plant, soil and atmosphere (Arshad *et al*., 1996; Mohammadshirazi *et al*., 2016). It is assumed that the optimum MP values are usually in the range from 0.12 to 0.15 cm^3 cm^{-3}. The MP in the treatments with Cambic Phaeozem was higher than the indicated range and was from 0.21 to 0.25 cm^3 cm^{-3} (Table 4). For the treatments with Luvic Phaeozem, the MP was in the range from 0.058 to 0.095 cm^3 cm^{-3}. The values of MP below 0.10 cm^3 cm^{-3} for arable soils were also obtained by Mazurek (2015). The results of the present investigations showed that, compared to the MF treatment, soil fertilisation with composts with the addition of polymer materials generally reduced the MP values in Cambic Phaeozem and significantly increased this value in Luvic Phaeozem.

TP was also used as one of the parameters to determine the boundary conditions for adjusting the soil water retention curves (van Genuchten *et al*., 1991). The water retention curves are necessary to determine the water-soil constants and are a function of the dependence between the parental potential and soil moisture (van Genuchten *et al*., 1991; Hewelke *et al*., 2013). In our study, differences in retention curves were noted due to the diversity of the properties of both soils (Fig. 2). However, the treatments with the same soil type showed a similar shape of curves in the range of potentials up to -155 kPa.

Fig. 2

Fig. 2 The soil water retention curves based on van Genuchten equation for the investigated treatments.

Field capacity and permanent wilting point

FC and PWP are considered the most important water properties of soils (Arshad *et al*., 1996; Paluszek, 2011; Hewelke *et al*., 2013; Mohammadshirazi *et al*., 2016). In our studies, the treatments showed distinct differences in soil water characteristics (Table 4). The FC in treatments with Cambic Phaeozem ranged from 0.17 to 0.21 cm^3 cm^{-3}. However, for Luvic Phaeozem, the FC values were less varied and reached from 0.36 to 0.38 cm^3 cm^{-3} (Table 4). In Cambic Phaeozem, compost fertilisation significantly increased the PWP value compared to the CT and MF treatments. Deterioration of the PWP parameter was observed in treatments with Luvic Phaeozem. According to Brown and Cotton (2011) and Adugna (2016), the water capacity of the soil depends on the amount of water that is able to infiltrate deep into the soil profile and the amount of water that the soil can hold. It is mainly influenced by soil textural parameters and the organic matter content. Therefore, loamy soils tend to have a much better water retention capacity than sandy soils. The results of Brown and Cotton (2011) revealed a positive correlation between the organic carbon content and FC and a negative correlation with the soil density. This is also confirmed by our results (Fig. 1). In addition, Brown and Cotton (2011) reported that the application of composts to the soil may have a different effect on physical properties, including field water capacity. This is related not only to the type of soil but also to the dose and type of feedstocks from which the compost was produced. For example, Adugna (2016) obtained a significant improvement in water infiltration of sandy soils only after using compost from bovine manure at a dose of 120 t DM ha^{-1}. In our study, the compost doses used in the individual treatments were over 20-fold lower (4.31 – 5.41 t DM ha^{-1}).

Relative field capacity

To determine the soil's ability to retain water and air in relation to the total pore volume, the RFC index is recommended (Reynolds *et al.*, 2008). This coefficient ranged from 0.41 to 0.49 for treatments with Cambic Phaeozem and from 0.79 to 0.81 for treatments with Luvic Phaeozem. For both soil types, the RFC increased when compost with polymer was applied when compared with the CT treatment. As stated by Reynolds *et al*. (2008), the balance between the water capacity and the air capacity in arable soils occurs when the FC-to-TP ratio is in the range of 0.6–0.7. According to these authors, ratio values below 0.6 reduce the intensity of the nitrification process due to a lack of soil water. However, many scientists have indicated that the determination of an optimal air capacity is not easy because FC and air capacity are contradictory properties (Reynolds *et al*., 2008; Paluszek, 2011; Hewelke *et al*., 2013). It is assumed that the balance between water and air in soil is maintained when PWP constitutes approximately 60% of the TP.

Plant available water content

Our investigations revealed that AWC depended significantly on the type of soil on which the experiment was carried out and the type of compost applied (Table 4). This was particularly evident in the treatments with Cambic Phaeozem, where the use of compost significantly increased AWC in relation to the CT and MF treatments (by 15% on average). In the treatments with Luvic Phaeozem, the use of composts with the addition of polymer materials had the opposite effect, i.e., they significantly decreased the AWC parameter (by 6% on average) in comparison with the MF treatment (Table 4). Our results are consistent with those of Weber and Jamroz (2004), who demonstrated that the use of natural and organic fertilisers increases soil water retention, whereas the organic matter content plays an important role in this parameter. For this reason, the beneficial effect of small doses of composts on water retention is usually of short duration, and the increase in the parameter value is more visible in sandy soils and immediately after the introduction of compost. Maghchiche *et al*. (2010), testing various mixtures of composites and polymers, proved that these materials can act in Cambic Phaeozem as a ‘barrier’ protecting against water losses and increasing the efficiency of water use by plants. Additionally, Chen *et al*. (2016) confirmed that the addition of polymer materials to sandy soil significantly improves its structure and the retention of water and nutrients for plants. These authors estimated that the introduction of 0.03--3% of artifiial polymer materials to the soil can increase water retention in sandy soil by 24% to 66% compared to soil without such additions.

TABLE 4

Soil physical parameters of the investigated soil/compost mixtures.

Soil	Treatment	TP (cm^{3} cm^{-3})	FC (cm^{3} cm^{-3})	PWP (cm^{3} cm^{-3})	BD (g cm^{-3})	MP (cm^{3} cm^{-3})	Dp (g cm^{-3})	AWC (cm^{3} cm^{-3})	RFC	SOC (g kg^{-1})
Cambic Phaeozem	CT	0.418	0.173	0.039	1.50	0.247	2.58	0.133	0.412	8.6
	MF	0.406	0.168	0.040	1.52	0.242	2.57	0.127	0.412	9.4
	MF+C	0.423	0.211	0.047	1.49	0.213	2.58	0.163	0.498	11.5
	MF+C+F1	0.432	0.203	0.050	1.48	0.219	2.56	0.153	0.473	12.7

	MF+C+F2	0.450	0.206	0.054	1.42	0.244	2.58	0.152	0.458	12.2
	MF+C+F3	0.403	0.197	0.050	1.50	0.207	2.51	0.147	0.491	12.9
	MF+C+F3	0.423	0.201	0.053	1.47	0.224	2.56	0.149	0.476	10.8
Luvic Phaeozem	CT	0.452	0.358	0.114	1.41	0.094	2.57	0.244	0.794	11.7
	MF	0.433	0.380	0.096	1.37	0.058	2.44	0.283	0.876	12.2
	MF+C	0.457	0.371	0.096	1.39	0.089	2.57	0.275	0.812	12.6
	MF+C+F1	0.457	0.368	0.111	1.39	0.095	2.58	0.257	0.805	12.4
	MF+C+F2	0.454	0.367	0.099	1.40	0.088	2.57	0.268	0.809	13.6
	MF+C+F3	0.458	0.366	0.106	1.40	0.095	2.59	0.260	0.799	13.1
	MF+C+F3	0.456	0.366	0.115	1.39	0.094	2.57	0.251	0.803	12.8
Means for treatments										
	CT	0.435	0.265	0.077	1.45	0.170	2.58	0.189	0.603	10.2
	MF	0.420	0.274	0.068	1.44	0.150	2.50	0.205	0.644	10.8
	MF+C	0.440	0.291	0.072	1.44	0.151	2.58	0.219	0.655	12.1
	MF+C+F1	0.445	0.285	0.081	1.43	0.157	2.57	0.205	0.639	12.5
	MF+C+F2	0.452	0.286	0.076	1.41	0.166	2.58	0.210	0.633	12.9
	MF+C+F3	0.430	0.282	0.078	1.45	0.151	2.55	0.204	0.645	13.0
	MF+C+F3	0.440	0.284	0.084	1.43	0.159	2.56	0.200	0.639	11.8
Means for soils										
Cambic Phaeozem		0.422	0.194	0.048	1.48	0.228	2.56	0.146	0.460	11.2
Luvic Phaeozem		0.453	0.368	0.105	1.39	0.087	2.56	0.262	0.814	12.6
LSD (0.05)										
Treatment		ns*	0.0275	0.0015	ns	0.0106	0.0153	0.0038	ns	1.73
Soil		0.01102	0.0014	0.0028	0.0266	ns	ns	0.0020	0.0175	0.92
Treatment × Soil		ns	0.0389	0.0040	ns	0.0280	0.0216	0.0054	0.0462	ns

Significant at $P < 0.05$; ns – not significant; TP – total porosity, FC– field water capacity, PWP– permanent wilting point, BD – bulk density, MP – drainage porosity, Dp – soil particle density AWC – plant available water content, RFC – relative field capacity, SOC – soil organic carbon.

The AWC values obtained in the present study were in the range specified by these authors. In accordance with the range proposed by Walczak *et al*. (2002), treatments with Cambic Phaeozem had a medium retention of AWC, and treatments with Luvic Phaeozem had a high retention of AWC. Craul *et al*. (1999) demonstrated that fine-textured soils have the best retention capacity because they are rich in humus and possess a durable aggregate structure. The authors also assumed that 0.200 cm^3 cm^{-3} is a limit value above which there are perfect conditions for the maximum growth and functioning of plants.

Permanent wilting point

Our results do not clearly confirm the influence of the type of compost with the addition of polymer materials on permanent wilting point (PWP) (Table 4). For Cambic Phaeozem, a significant increase was determined in PWP compared with the MF and CT treatments. The highest value was determined for the treatment with compost with additions of the F3 polymer materials (MF+C+F3). In the case of Luvic Phaeozem, a significant increase in this parameter was determined in all treatments compared to MF. The application of compost to the soil did not cause any changes in PWP. It should be emphasised that the addition of polymer materials to the composted biomass of plants did not decrease the PWP value. According to Walczak *et al*. (2002), the PWP for fine and medium-textured soils should range from 0.050 to 0.150 cm^3 cm^{-3}. The parameter values obtained in our study were within this range (except for the PWP value determined for CT, MF and MF+C treatments with Cambic Phaeozem).

Micromorphological analysis

To assess the impact of management practices on the soil environment, it is necessary to quantify the modifications in the soil structure. Soil micromorphological investigations are a useful tool for the general interpretation of soil quality by assessing soil physical, chemical and biological properties (Stoops, 2003, Gerasimova and Lebedeva-Verba, 2010; Wierzbicka-Miernik *et al.*, 2015; Mazurek, 2015). Because this assessment is carried out in intact soil, it is possible to distinguish many pedogenic traits of the sample, including the illuvial displacement of the colloidal fraction, type of microstructure, presence of iron or carbonate concretions, degree of mineralisation, share of biogenic pores, or degree of decomposition in organic matter (Gerasimova and Lebedeva-Verba, 2010; Wierzbicka-Miernik *et al*., 2015). Additionally, based on the size and shape of soil mesofauna faeces, quantitative and qualitative assessments of its composition are possible (Stoops, 2003; Mazurek, 2015). The so-called groundmass, which constitutes a general description of the coarse and fine materials (and the free spaces between them), is also assessed. For the parameters described, a 5 μm boundary was adopted, as the commonly used range is from 3 μm to 20 μm (Stoops, 2003; Mazurek, 2015). A coarse fraction (>2 mm) was individually separated from the tested material due to the important role of the identification of the skeleton material (sandstones, silica rocks). Considering that microscopic diagnostics of the individual elements of fine material are very difficult, their features, occurrence, spatial organisation, and b-fabric are described on the basis of selected optical properties, such as interference colours, colour, and transparency.

Detailed microscopic analysis showed that preparations made of Cambic Phaeozem, regardless of the compost used, did not significantly change the portions of the individual soil fractions, which were visible primarily in the form of mineral composition, consisting mainly of differently rounded (subangular) grains of quartz and feldspar (Table 6, Fig. 3). They ranged in size from 20 μm to 500 μm, with an average size oscillating at approximately 200 μm. To a lesser extent, mica and clay minerals were available. Locally, larger fragments of silica rock were visible in the images of thin sections (Fig. 3).

TABLE 6

Micromorphological properties of light and medium soils after the second year of the experiment.

Soil	Treatment		Voids	Porosity (%)	Decomposition degree of OM	Related distribution pattern		Organic matter		Antropogenic material		Mineral material Minerals			Rock fragments		Ground-mass	Pedo-features	
		Microstructure I/II level				type	c/f$_5$ ratio	plant tissues	decomposed organic material	black carbon	polimer material	quartz	feldspar	clays	sandstone	cherts	b-fabric	Fe nodule	excrements
Cambic Phaeozem	CT	g/s	cxpv	5	VH	cfe	3/1	+	++	+	-	+++	+	+	+	-	un	+	+
	MF	g/s	cxpv/cm	17	VH	cfe	4/1	+	+++	+	-	+++	+	+	+	-	un	++	+
	MF+C	g/s	cxpv/spv	8	VH	cfe	3/1	+	++	+	-	+++	+	+	++	-	un	+	+
	MF+C+F1	g/s	cxpv	15	VH	cfe	3/1	+	++	+	-	+++	+	+	+	+	un	+	+
	MF+C+F2	g/s	cxpv	8	VH	cfe	2/1	+	+++	+	+	+++	+	+	+	-	un	+	+
	MF+C+F3	g/s	cxpv	6	VH	cfe	3/1	+	+++	+	+	+++	+	+	+	-	un	+	+
	MF+C+F3+M	g/s	cxpv	10	VH	cfe	3/1	+	++	+	-	+++	+	+	+	-	un	-	+
Luvic Phaeozem	CT	sab/ch/ver	cdpv/ch	15	VH	dsp	2/1	+	+++	+	-	++	+	+	-	-	un, str	+	++
	MF	sa/ch/cr	cdpv/ch	10	VH	dsp	2/1	+	+++	-	-	++	+	+	+	-	un, str	+	++
	MF+C	sa/ch	cdpv/ch	20	VH	dsp	2/1	+	+++	+	-	++	-	+	+	+	un, str	+	+
	MF+C+F1	sab/ch	cdpv/ch	17	VH	dsp	2/1	+	+++	-	-	++	+	+	+	-	un, str	+	+
	MF+C+F2	sa/ch	cdpv/ch	22	VH	dsp	2/1	++	+++	+	+	++	+	+	+	-	un, str	+	++
	MF+C+F3	sa/ch/ver	cdpv/ch	15	VH	dsp	2/1	+	+++	_	-	++	+	+	+	-	un, str	+	++
	MF+C+F3+M	sab/ch	cdpv/ch	8	VH	dsp	2/1	+	+++	+	-	++	+	+	+	-	un, str	++	+

- absent, + present, ++ common, +++ very common;
Voids: cpv - complex packing voids, spv – simple packing voids;
Microstructure: c – crumby, sa – subangular, s – spongy, g – granular;
Type of c/f related distribution: ssp – single spaced porphyric, op – open porphyric, dsp - double spaced porphyric, dse – double spaced enaulic, cp - close porphyric, cfe – close fine enaulic;
Decomposition degree of organic matter: VH – very high H – high M- moderate L- low, VL – very low;
b-fabric: un – undifferentiated, str - locally striated.
C – control soil (soil without fertilisation), MF - soil with mineral fertilisers, MF+C - soil fertilised with compost without addition of polymer material, MF+C+F1 - soil fertilised with compost with addition of F1 polymer material; MF+C+F2 - soil fertilised with compost with addition of F2 polymer material, MF+C+F3 - soil fertilised with compost with addition of F3 polymer material, MF+C+F3+M - soil fertilised with compost with addition of F3 polymer material and microbiological inoculum.

Fig. 3

Fig. 3 Soil microstructures of 0–10 cm soil layer after compost/polymer treatments.

All preparations obtained from treatments with Cambic Phaeozem had the granular microstructure I °, which determined the formation of pores with complex packing voids (Fig. 3). In some cases, larger pores in the form of chambers were observed. Aggregates in the images of thin slides showed a poor separation of soil material, resulting mainly from sandy graining. The lower-level structure had a spongy nature, determined by the presence of mostly well-decomposed organic matter. In general, the surface porosity of the studied soils with grain size structures of a clay was relatively small and ranged from 5% to 17% (Table 6). According to the division proposed by Pagliai *et al*. (2004), treatments with Cambic Phaeozem can be classified as compact (CT, MF+C, MF+C+F2, MF+C+F3) or moderately porous (MF, MF+C+F1, MF+C+F3+M) soil.

Micromorphological features indicating the progression of the soil-forming process are primarily related to the accumulation and decomposition of organic matter (Pagliai *et al*. 2004; Gerasimova and Lebedeva-Verba, 2010; Wierzbicka-Miernik *et al*., 2015; Mazurek, 2015). The organic matter visible in the images of all the tested preparations (obtained from soils with a grain size structure of light clay) showed a high degree of decomposition and an anisotropic character (Fig. 3). However, the highest degree of organic matter decomposition among treatments with Cambic Phaeozem was determined in MF, MF+C+F2, and MF+C+F3 (Table 6). In all preparations, poorly decomposed plant residues with visible tissue structures were locally present. In the microscopic image of preparations obtained for treatments with Cambic Phaeozem, there were also many soil fauna faeces, constituting evidence of high biological activity.

The slides prepared from treatments with Cambic Phaeozem were dominated by the close fine enaulic micro-skeleton index (Table 6). Sandy soil material created an advantage of coarse soil material over fine soil, which translated into a high micro-skeleton index c/f_5. The highest value of this parameter was determined in the treatment with mineral fertilisation (c/f_5=4/1). This means that in the basic mass of the soil collected in this treatment, there was 4 times more coarse material than fine material. In treatments fertilised with compost with addition of artificial polymer materials, c/f_5 was generally 3:1. The tested fine soil mass had a dark, almost black colour and showed neither distinct variation nor the formation of bands. These were mainly humus substances.

Among the treatments with Cambic Phaeozem, the presence of anthropogenic materials in the form of fragments of non-decomposed polymer materials was found only in the images of the MF+C+F2 and MF+C+F3 treatments (Fig. 3). Additionally, carbides were discovered in images of all treatments with Cambic Phaeozem. The presence of numerous trivalent iron nodules (of anorthic type) was a characteristic feature of the treatments with Cambic Phaeozem, which indicated periodic difficulties associated with the infiltration of rainwater. This phenomenon was especially visible in the MF soil, but it was not observed in the MF+C+F3+M soil (Table 6).

Preparations made of treatments with Luvic Phaeozem had a typical structure for soils with a silt particle size (Fig. 3). The microstructure of these treatments was classified as subangular and subangular blocks (Table 6). The lower microstructure level indicates the presence of a tubular-type microstructure, which is related to the high activity of mesofauna (earthworms and vaseworts) in the treatments with Luvic Phaeozem. Among the analysed treatments, the activity of earthworms was clearly noticeable in the soil from the treatment in which no fertilisation was applied (CT) (Fig. 3). The variant of the vermicular structure and the formation of a characteristic aggregate-based microstructure could be distinguished in this preparation.

The mineral composition of treatments with Luvic Phaeozem (irrespective of the fertilisation applied) was determined by the predominant share of quartz fragments, mainly in angular forms. More rarely, in the case of larger crumbs, subangular grains were found (Table 6). The size of the quartz fragments in the majority of preparations ranged from 20 μm to 100 μm. Additionally, in each of the preparations (except the MF treatment), feldspars and mics were found. Clay minerals that form complexes with humus substances were also present in the micromass in each image made for treatments with Luvic Phaeozem. The above structure types were characterised by poor to moderate separation of soil material. Complex pores were the free spaces in the areas of the analysed treatments. Some pores were partially or completely filled with manure from soil animals (Fig. 3).

The surface porosity of treatments with both types of soil was strongly diversified and ranged from 8% to 22%, regardless of the fertilisation applied. A porosity level of ≤10% (characteristic for soils with a compact structure) was determined in all Cambic Phaeozem treatments (except for MF+C+F1) and in the MF and MF+C+F3+M treatments with Luvic Phaeozem. Other treatments had moderate porosity. According to Pagliali *et al*. (2004), total soil porosity of 10% is the lower limit for good-quality soils. Investigations also revealed that some pores of the tested soils contained poorly decomposed plant residues, and in pores of biogenic nature, larger spaces were visible in the form of highly branched pores and chambers (Fig. 3). However, neither clay liners nor crystalline structures were found in the pores.

Treatments with Luvic Phaeozem had a high micro-skeleton index with a double-spaced porphyric system. However, larger grains (mainly of quartz) were relatively far from each other. The average ratio of larger parts to micromass ($c/f_{5\mu m}$) was 3:1 (Table 6). The visible micromass on the structure of the selected brown surface areas was generally humic substances combined with mineral parts (clay minerals) in the state of strong dispersion (Fig. 3). In regard to pedofeatures, for soils from individual treatments located on the sample of agronomic Luvic Phaeozem, many anorthic-type nodules were found that were composed of trivalent iron compounds with a characteristic brown colour. The highest amount of Fe nodules in the images of the thin slides was determined in soil of the MF+C+F3+M treatments with Luvic Phaeozem. This was confirmed by the results relating to the deteriorated porosity in this treatment (Fig. 3). According to Pagliai *et al*. (2004), the use of external organic matter in the form of compost and manure improved soil porosity and aggregation. Better aggregation indicated that the addition of organic materials plays an important role in preventing the formation of soil crust. These results confirm that it is possible to adopt alternative tillage systems to prevent physical soil degradation and that the use of organic materials is necessary to improve the quality of the soil structure.

CONCLUSIONS AND PERSPECTIVE

The investigated composts with the addition of polymer materials (with different amounts of thermoplastic corn starch and polyethylene) improved water retention and increased soil retention in a given type of soil. Materials made from synthetic and natural polymers were found to be a composite mixture that can be successfully used in agriculture, especially to improve the structure of sandy soils.

The data obtained suggest that the use of composts leads to changes in the soil retention capacity and improves soil accessibility to plants, whereas the dose of these composts is a factor determining the compost effectiveness. It should be emphasised that the Cambic Phaeozem soil had a stronger reaction to the composts applied. This was due to the filling of large spaces in the soil with finer material, and therefore, the water retention increased. This correlation was also confirmed by the results of micromorphological investigations and the obtained soil retention curves.

Our study suggests that composts with the addition of polymer materials can be widely used, among others in the reclamation of degrades areas, e.g. through soil sealing (as structure-forming material), in soilless cultivation of horticultural plants (e.g. high income crops grown in pots or mats under roofs). Composts with the addition of polymer materials can also be used in the ornamental plants market (perennials, shrubs, trees, flowers), as this industry requires very large volumes of substrates, including those based on biodegradable polymer composts. Costs of producing composts from post-consumer polymer materials may be higher than in the case of composting natural materials. However, the added value here is the attempt to close the carbon cycle and achieve its longest possible time of binding in soil to reduce CO_2 emissions. Then, the profits and losses can be balanced (reuse of post-consumer materials) and a clear economic assessment confronts environmental aspects.

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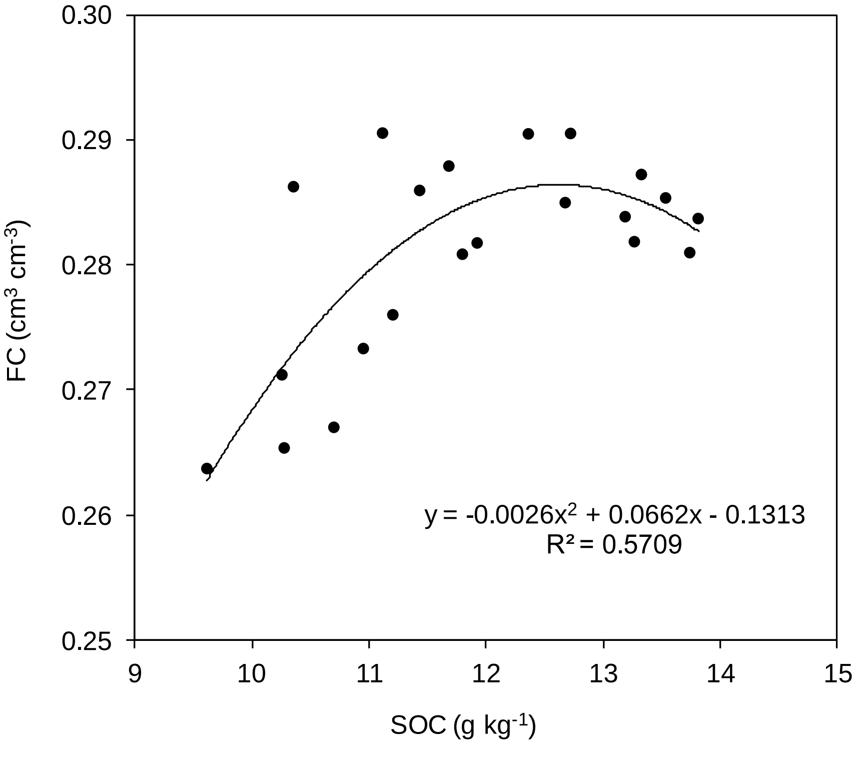


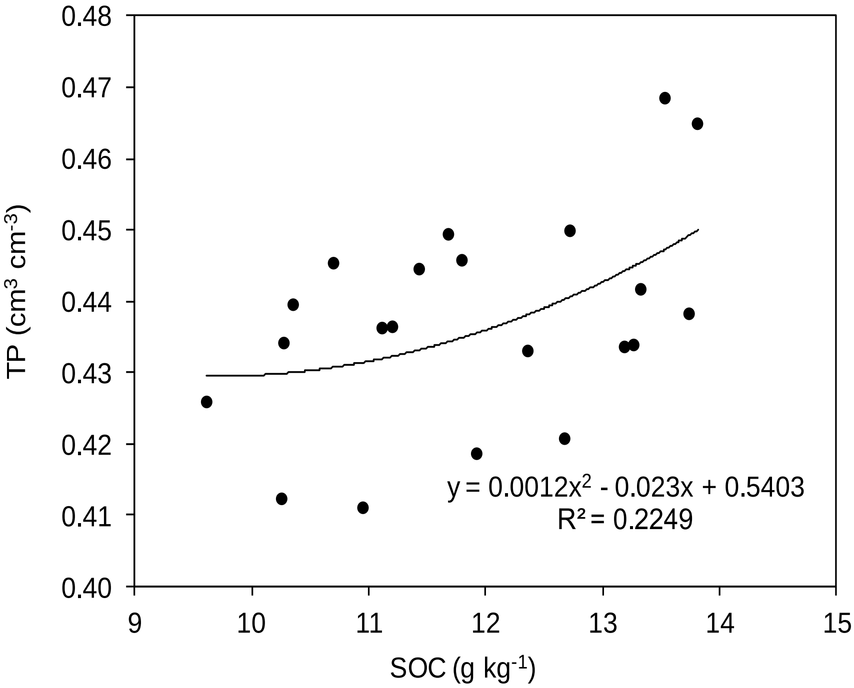
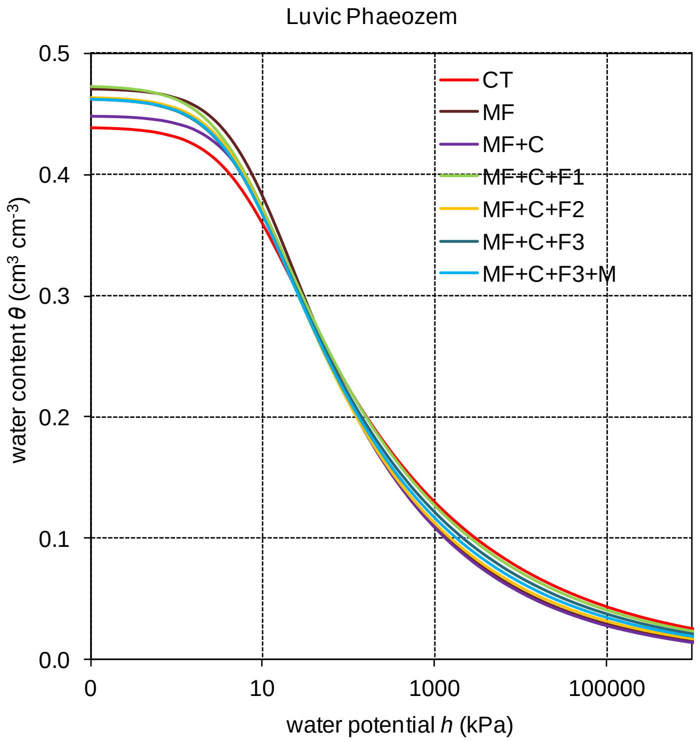


Fig. 1 The relationship between the soil organic carbon content (SOC) and field capacity (FC) and total porosity (TP).



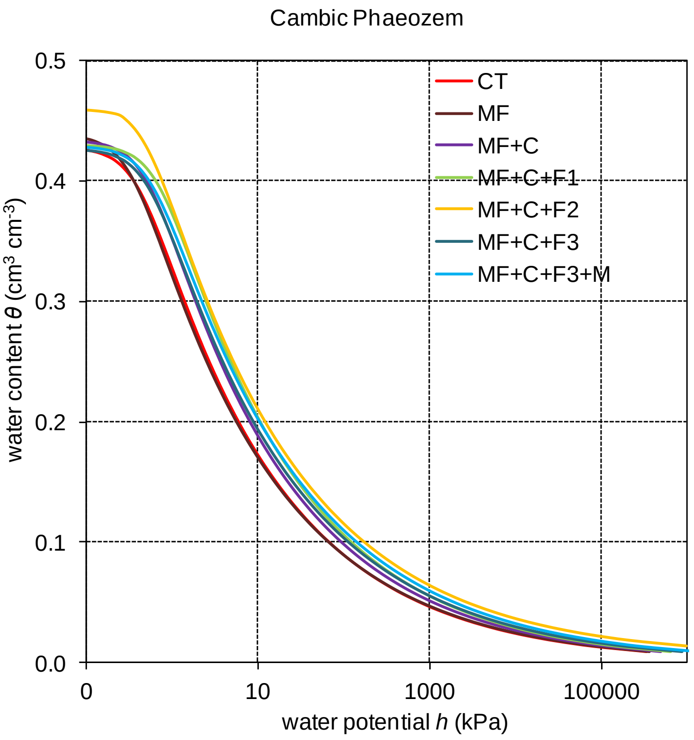
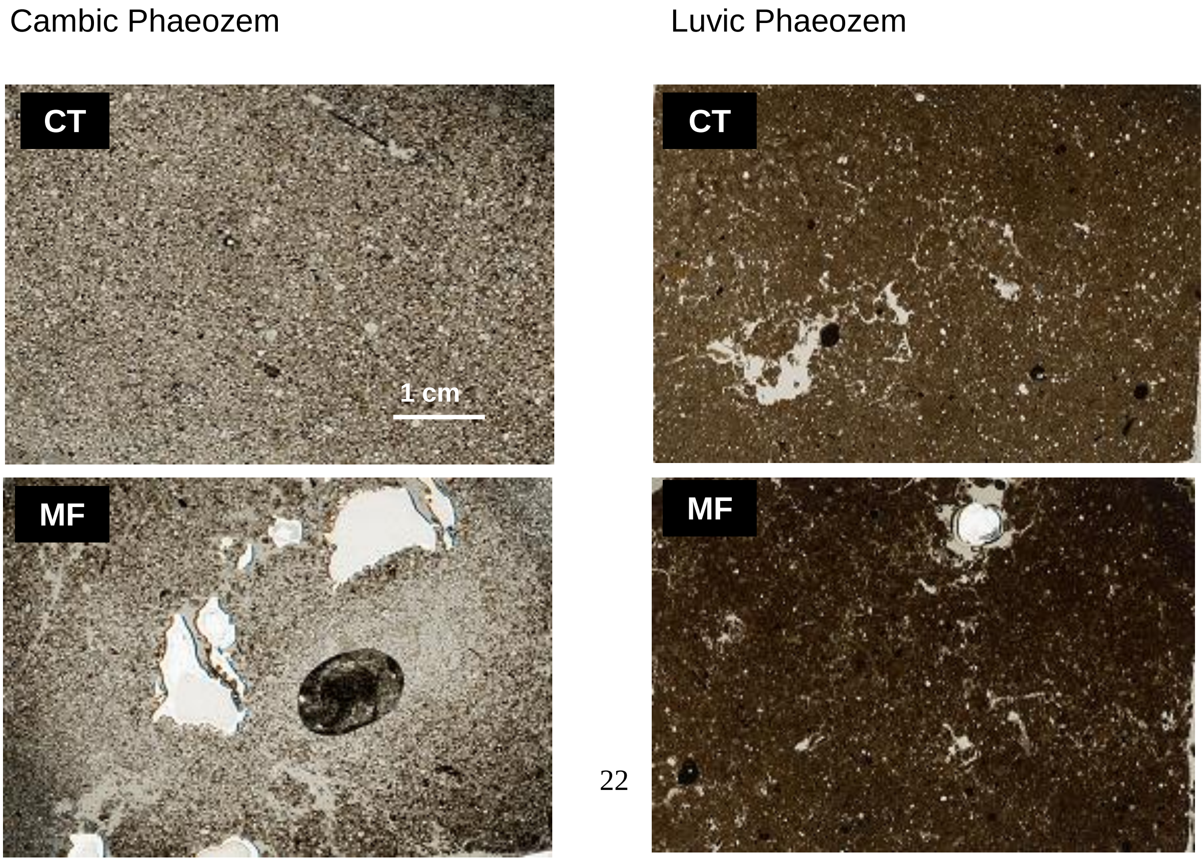
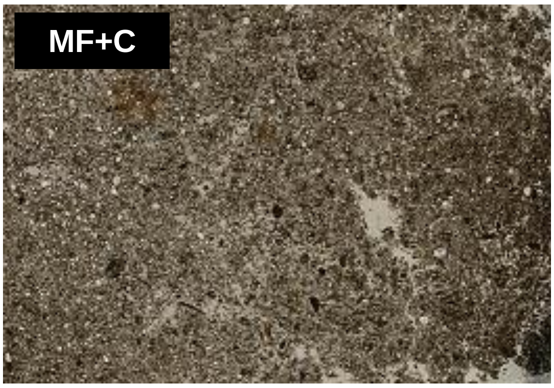


Fig. 2. The soil water retention curves based on van Genuchten equation for the investigated treatments.

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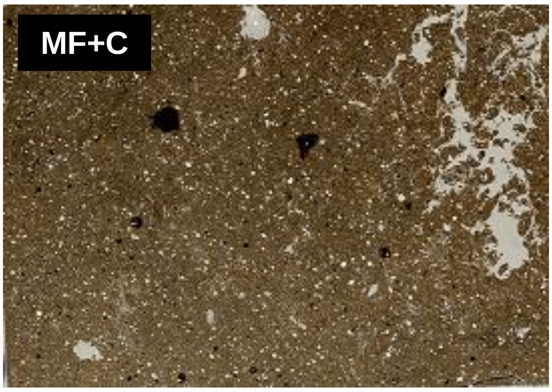
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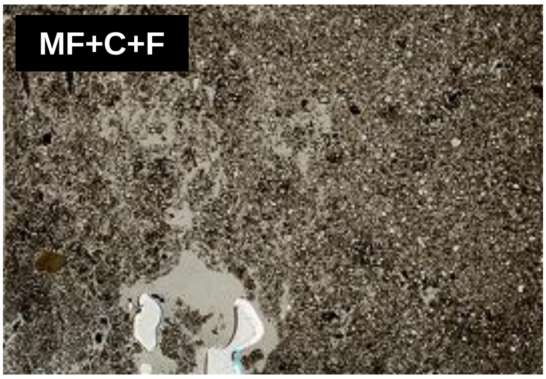
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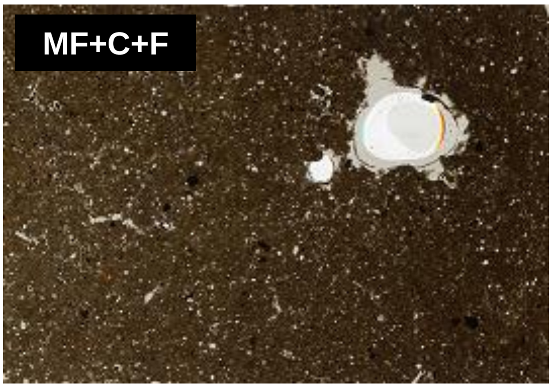
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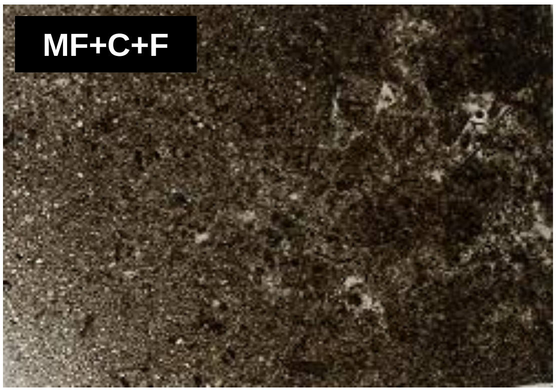
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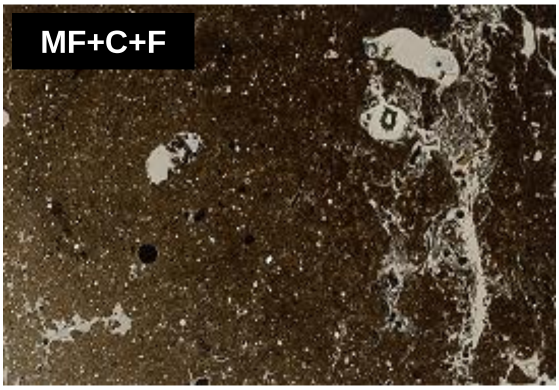
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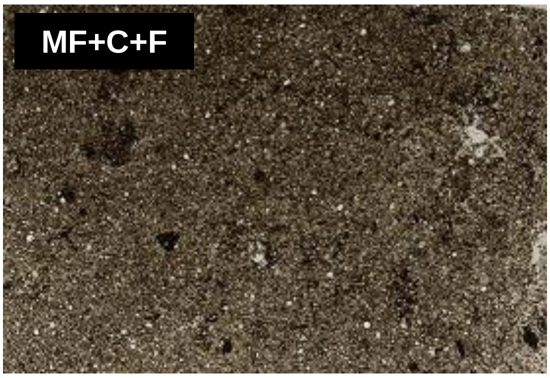
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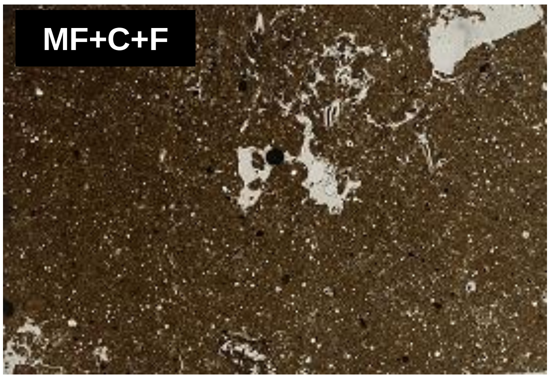
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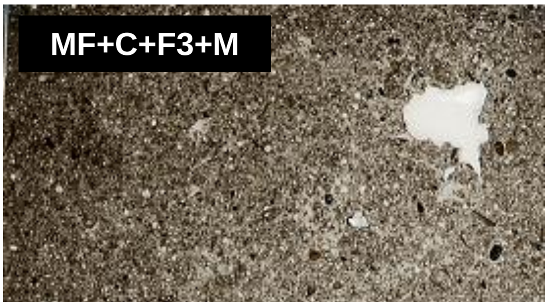
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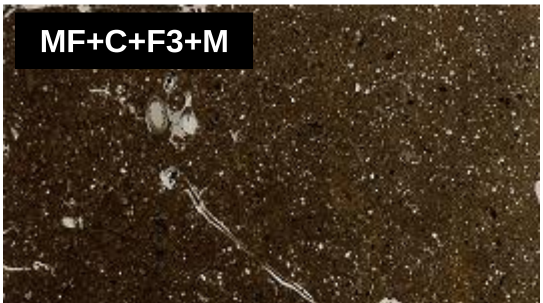
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Fig. 3. Soil microstructures of 0–10 cm soil layer after compost/polymer treatments.