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Comparing the agrochemical properties of compost and vermicomposts produced from municipal sewage sludge digestate

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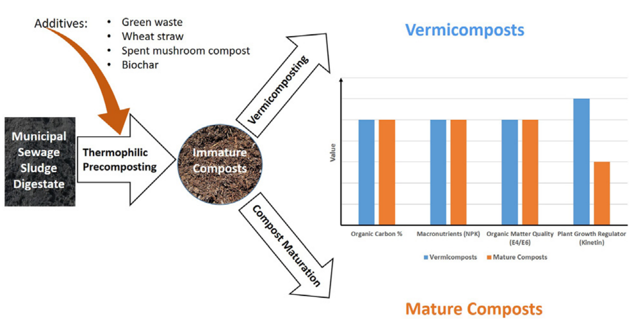
GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this work was to investigate whether the agronomic traits of vermicompost prepared from partially stabilised sewage sludge digestate after thermophilic composting were more favourable than those of conventional compost. The effects of various additives (green waste, spent mushroom compost, wheat straw, biochar) were also tested after 1.5 months precomposting followed by 3 months vermicomposting with Eisenia fetida or by compost maturing. Vermicomposting did not result in significantly more intensive mineralisation than composting; the average organic carbon contents were 21.2 and 22.2% in vermicomposts and composts, respectively. Hence, the average total (N: 2.4%; P: 1.9%; K: 0.9%) and available (N: 160 mg/kg; P: 161 mg/kg; K: 0.8%) macronutrient concentrations were the same in both treatments. The processing method did not influence the organic matter quality (E_4/E_6) either. However, on average the concentration of the plant growth regulator kinetin was more than twice as high in vermicomposts.

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1. Introduction

With the growth of the urban population the quantity of sewage sludge is increasing worldwide. The total sludge volume produced in Europe (in 2010), China (in 2006) and the United States (in 2004) reached 9, 3 and 6.5 million tons dry matter/year, respectively), so the volume of sludge used for energy production via anaerobic fermentation is expected to grow too (Mateo-Sagasta et al., 2015). The digestate resulting from this process, however, still contains a high concentration of organic matter and various plant nutrients, so it is ideal for use in agriculture as a fertiliser (Guilayn et al., 2019). To improve its properties it is worth stabilising the digestate before agronomic use. An aerobic transformation process such as composting or vermicomposting is ideal for biowaste stabilisation. Vermicomposting, in which the transformation of the material is promoted by earthworms and by the bacterial community in their alimentary canal, may be applied as an alternative or supplement to composting (Hait and Tare, 2012).

Fresh sewage sludge digestate is not immediately suitable for vermicomposting, as it is anaerobic and contains materials that are toxic to earthworms, in particular high concentrations of NH_3 and CH_4 (Awiszus et al., 2018). To eliminate these pollutants partial composting with additives at high temperatures is essential to prevent earthworm mortality (Kaushik and Garg, 2003). During this process the material is aerated and stabilised, the moisture content is reduced and the pathogens are inactivated (Yadav et al., 2012; Yadav and Garg, 2016; Malinska et al., 2016).

Several papers discuss the vermistabilisation of sewage sludge (see citations Malinska et al., 2017). However, investigations on vermicomposts made from municipal sewage sludge digestates are very scarce and there are no data on their agronomic value. Information is also lacking on the reproduction characteristics of *Eisenia fetida* in municipal sewage sludge digestates, which is important for the possible large-scale processing of such materials.

Some studies showed that sewage sludge processed by vermicomposting had higher total and available nitrogen and phosphorus concentrations than after composting (Hait and Tare, 2011; 2012; Hanc and Dreslova, 2016). These differences were due to the greater reduction in organic matter during vermicomposting compared to composting. However, as the high-energy, easily decomposable organic matter in the digestate is transformed during the digestion process and as the thermophilic precomposting required before vermicomposting leads to further losses of organic matter, it is questionable whether further conventional compost maturation or vermicomposting of the resulting, relatively stable organic matter in the digestate will lead to any substantial difference in the concentration and availability of the plant nutrients or in the quality of the organic matter. However, the further decomposition of the organic matter in partially stabilised, digested sludge can be catalysed using various additives in the composting or vermicomposting process.

The additives applied during composting and vermicomposting may reduce the unfavourable properties of sewage sludge digestate and give the mixture satisfactory structure and porosity, while modifying the unfavourably low C/N ratio that inhibits microbial processes (Zhao et al., 2016). The additives should also improve the palatability and quality of the food, positively affecting worm activity and thus the quality of the vermicompost (Ndegwa and Thompson, 2000; Vig et al., 2011).

The present work investigated several additives that were expected to enhance the rate of degradation and quality of the final product. One such material is communal green waste, especially plant residues from town parks. However, other organic materials (like spent mushroom compost, straw, biochar) can also be used as bulking materials, with various outcomes. Spent mushroom compost is a waste material (SMC) that improves the decomposition and transformation processes and to some extent the C/N ratio. As a bulking material wheat straw (WS) diminishes the moisture content of the mixture and, as green waste (GW), increases the aeration and C/N ratio (Zhao et al., 2016; Meng et al., 2017). Biochar (BC) has recently been introduced as an amendment for composting and vermicomposting. Due to its properties, BC may have a significant influence on the composting process: it improves aeration and thus the intensity of decomposition and nitrification, and increases the temperature and total microbial biomass (Wu et al., 2017). During vermicomposting, BC enhances the worm reproduction rate and results in the more efficient conversion of the substrate into vermicompost (Malinska et al., 2016).

Data in the literature indicate that vermicomposts contain more humified, stable organic compounds than composts, have an extended fertiliser effect due to slower nutrient release, and contain higher concentrations of plant growth regulators, which exert a positive effect on plant growth (Jack and Thies, 2006). However, composts and vermicomposts can only be properly compared if they are produced using the same mixture of materials (Fornes et al., 2012; Hanc and Dreslova, 2016).

Based on the above, the aim was to investigate whether vermicomposting has any advantage over compost maturing as regards the quality of the final products prepared from precomposted sewage sludge digestate with various additives. For this purpose composts and vermicomposts were made from the same original materials and the nutrient content and availability, the organic matter quality, and the concentration of plant growth regulators in the composts and vermicomposts were compared. Moreover, the vermicompostability of sewage sludge digestate was also investigated by analysing the reproduction rate and biomass of the worms.

2. Materials and methods

2.1. Materials

The digestate was produced from municipal (secondary) sewage sludge by the wastewater treatment plant of the city of Érd (Hungary, 47° 23′ 31″ N; 18° 54′ 16.3″ E) and had a dry matter content of 18.4 m/m%. The GW was a mixture of various plant materials, mostly from public parks in Százhalombatta with a dry matter content of 73 m/m%. The unchopped WS was a year old and had a dry matter content of 65 m/m%. The SMC was a mixture of cow manure, wood chips and $CaCO_3$, with a dry matter content of 40 m/m%. The BC was a pyrolyzed (450–500 °C for 20 min) mixture of grain husks and paper fibre sludge produced by Sonnenerde GmbH, with a 60% particle size of less than 2 mm. The characteristics of the materials are presented in Table 1. The worm species for vermicomposting was *Eisenia fetida*. The animals were

Table 1
Chemical properties of the materials applied. Values refer to D.M.

Material	pH_{H2O}	OC $m\ m^{-1}$%	$CaCO_3$ $m\ m^{-1}$%	total N $mg\ kg^{-1}$	total P $mg\ kg^{-1}$	total K $mg\ kg^{-1}$	C/N	As $mg\ kg^{-1}$	Cu $mg\ kg^{-1}$	Mo $mg\ kg^{-1}$	Ni $mg\ kg^{-1}$	Zn $mg\ kg^{-1}$
Digestate	6.62	21.9	4.08	39,400	32,509	3370	6	3.38	296	5.27	19.3	795
GW	5.64	35.7	0.98	10,100	1559	8360	35	0.83	12.4	0.867	4.81	59.2
WS	6.08	40.8	0.0	6900	1459	3388	59	0.56	14.7	0.798	2.13	36.7
SMC	7.12	19.9	6.52	19,700	3708	19,806	10	9.03	38.5	2.69	10	145
BC	10.4	27.5	5.75	9590	6742	15,380	29	< dl	15.7	1.66	5.85	53.3

previously bred in sewage sludge digestate and GW compost mixed with marc. The ratio of clitellated worms in the population was 20%.

2.2. Thermophilic composting

Six different mixtures were prepared from the materials. The major component of each mixture was the basic mixture (BM), consisting of sewage sludge digestate and GW in a ratio of 3:1 wet weight. The experiment modelled an operating composting/vermicomposting facility so the mixing ratios were determined by the production rate of the two waste materials in the region, not on the basis of chemical properties, which were therefore not in line with the recommended ideal C/N ratio. The mixtures had the following wet mass ratios: 1) BM 80% + WS 20%; 2) BM 75% + WS 20% + BC 5%; 3) BM 80% + SMC 20%; 4) BM 75% + SMC 20% + BC 5%; 5) BM 100%; 6) BM 95% + BC 5%. The weight of the composting piles was 1.4 t and the volume between 1.1 and 1.4 m^3. Each mixture was formed into a 1 m high heap and covered with geotextile on an open field. During the 43 day thermophilic composting phase (starting on 19th July) the heaps were mixed thoroughly seven times to ensure even decomposition. The core temperature of the mixtures (at 50 cm depth) was monitored daily.

2.3. Vermicomposting and compost maturation

At the end of composting the same volume of material from each piles was filled into 6 l plastic boxes (25 × 25 × 10 cm) in which compost maturation and vermicomposting were carried out for three months in three replications. Due to the different bulk densities of the mixtures the same volume resulted in different weight values.

The mixtures were wetted to 50% relative saturation. The boxes were covered with geotextile and kept at room temperature. The water content was regularly monitored and maintained at the given level. In the vermicomposting boxes the density of worms was 1 worm/35 g DM in each mixture. The average weight of the worms was 0.33 ± 0.11 g. At the end of the maturing and vermicomposting process the materials were dried and ground for analysis.

2.4. Analysis and process control

2.4.1. Worms

Halfway through vermicomposting (six weeks after the start) the number of cocoons was counted in a 200 g sample of the mixtures. The 200 g of the sample was compiled from several subsamples taken from the bulk of the material with a spoon. After counting, the samples were returned to the boxes. At the end of the experiment the total number of worms and the clitellated and non-clitellated individuals were counted and weighed.

2.4.2. Material analysis

The pH was measured in a 1:2.5 soil:water suspension 12 h after mixing (MSZ-08-0206/2, 1978). The organic carbon (OC) content was determined using the modified Walkley-Black method (MSZ-08-0452, 1980).

The pseudo total element concentrations of the materials were determined with the ICP-AES method after microwave teflon bomb digestion with aqua regia (MSZ 21470-50, 2006). The element concentrations in each extract were determined by means of ICP-AES (Jobin-Yvon Ultima 2 sequential instrument), using Merck calibration standards and following the manufacturer's instructions. In each measurement session the extract of a standard soil sample was also analysed as a control. The calibration curves were determined after every 12th sample.

Plant-available P and K concentrations were determined in ammonium-acetate lactate (AL) extract (AL-P_2O_5, AL-K_2O) (Egnér et al., 1960) and the total N content with the Kjeldahl method. The NH_4-N and NO_3-N concentrations were measured from KCl extracts according to Hungarian Standard (Maynard and Kalra, 1993). The $CaCO_3$ content was measured using the Scheibler gas-volumetric method (MSZ-08-0206/2, 1978).

The quality of humic substances was determined in two steps: the extraction and fractionation of the humus fractions were carried out as described by Stevenson (1994), and spectral characterisation (E_4/E_6) of total humic matter, fulvic acids and humic acids was measured according to the method of Chen et al. (1977).

Plant hormones: auxin (indole-3-acetic acid (IAA, 3-IAA)), kinetin and gibberellin, were analysed with the HPLC technique according to Klimas et al. (2016).

2.4.3. Statistical analysis

The data were analysed for treatment effects using one-way analysis of variance (ANOVA). The variance was calculated for all the treatments. Significant differences between the treatments were calculated at the $p < 0.05$ level. In the regression analysis, *, ** and *** indicate significance at $p < 0.05$, 0.01 and 0.001, respectively. Statistica v.13 (StatSoft Inc.) software was used for all the statistical evaluations.

3. Results and discussion

3.1. Process parameters

3.1.1. Thermophilic composting

Composting performed prior to vermicomposting was to stabilise the material, inactivate pathogenic microorganisms and decrease the high NH_3 concentration that was toxic to the worms.

During the composting process, the core temperature in each treatment reached at least 60 °C (Fig. 1). Fluctuations in the temperature were the result of mixing and weather conditions. Mixtures containing WS reached the thermophilic phase (> 45 °C) in two days. This period was nine days for BM + BC, 11 days for BM and BM + SMC + BC and two weeks for BM + SMC. The temperature of the composting pile is related to aeration, the availability and energy of the nutrients in the composting material, indicating that the SMC applied was poor in readily available nourishment for microorganisms, in contrast to data in the literature (Meng et al., 2017). The highest core temperature (> 70 °C) and the fastest temperature increase (reaching 70 °C in four days) was recorded for mixtures containing WS, presumably due to the better aeration (Meng et al., 2017). If the temperature is permanently above 65 °C spore-forming bacteria become predominant and most bacteria become inactive (Gray et al., 1971). However, due to the size of the pile the whole volume of the material was not at the temperature measured in the core, so the decomposition processes may have continued in the outer parts. The thermophilic phase lasted for 39 days in the materials containing WS, 24 days in the BM + SMC, BM + SMC + BC and BM + BC mixtures and only 21 days in BM.

Regarding the 43 days of composting the average temperature of mixtures with BC was slightly, ($p = 0.046$) higher than that without BC (50 and 49 °C, respectively). However, in the first 20 days of composting the difference was greater ($p = 0.000$): the average temperature reached 53 °C in mixtures with BC and 49 °C without BC. Between the 21st and 43th day the mixtures with BC were slightly cooler (48 °C) than the other mixtures (49 °C) as average ($p = 0.010$). Thus, the addition of BC resulted in a more intensive decomposition in the thermophilic phase but in the cooling phase, the degradation process resulted in less heat in these mixtures due to the depletion of easily degradable organic compounds (Wu et al., 2017).

The fall in temperature at the end of the thermophilic composting period indicates the depletion of easily decomposable organic materials in the mixtures (Meng et al., 2017).

3.1.2. Vermicomposting

Assuming that one worm consumes half of its weight per day, the

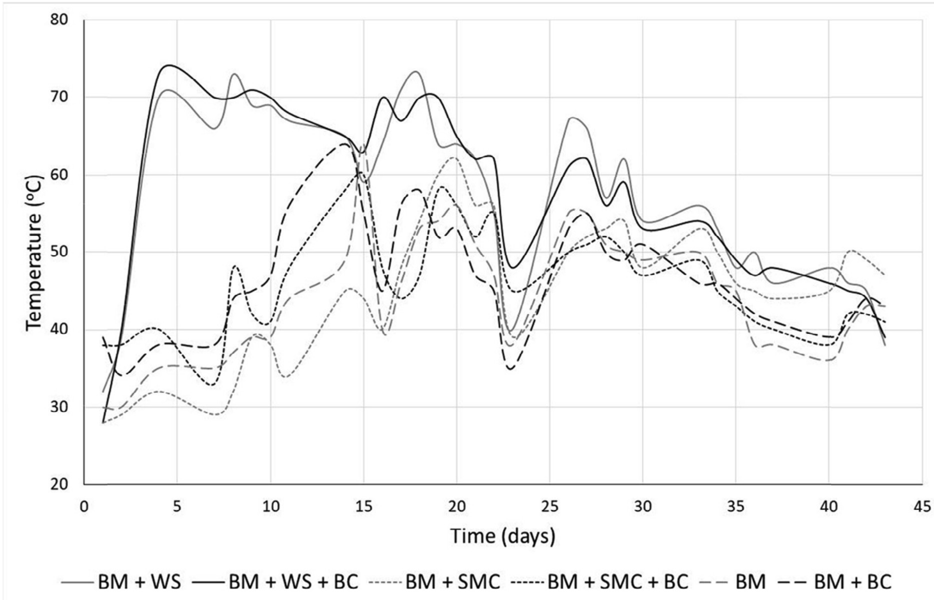

Fig. 1. Changes in core temperature in the compost piles.

total dry weight of the mixture in one box was sufficient for up to about 90 days, not counting the juveniles and assuming that the total amount of organic material is edible for worms (Malinska et al., 2016). It can thus be expected that by the end of the experiment the total amount of consumable organic material will have been depleted and converted into earthworm casts. After three months the worm biomass had probably passed its peak value (Malinska et al., 2016). It is unlikely that the potentially toxic elements (PTE) in the additives had a negative effect on the life functions of the earthworms in the various mixtures, as the sewage sludge had the highest PTE concentration (Table 1).

The suboptimal C/N ratio of the composts had no negative effect on the physiology of *Eisenia fetida* (Ndegwa and Thompson, 2000). Under these circumstances the animals invest more energy in growing than in reproducing (Aira et al., 2006). No earthworm mortality was detected in any of the materials. Six weeks after the start of vermicomposting the average cocoon number was statistically the same in each mixture with the exception of BM + SMC + BC, which had a lower cocoon number than BM (Fig. 2). The data suggest that additive-free BM was the best medium for initial reproduction, though the difference was not significant. In contrast to earlier findings, BC addition did not affect the cocoon number (Malinska et al., 2017).

After three months of vermicomposting the highest increase in the number of earthworms (five times the initial number) was observed in the BM (Fig. 3). The addition of SMC or WS significantly reduced the

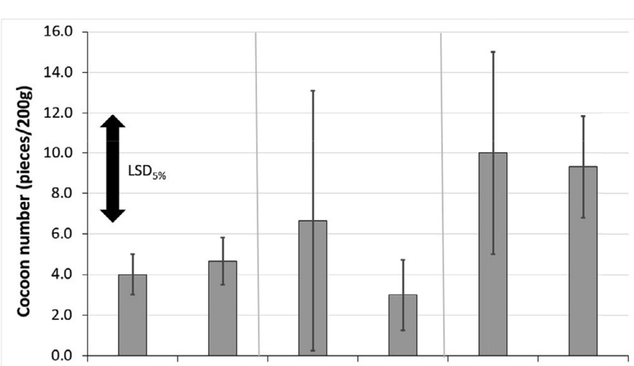

Fig. 2. Cocoon number in the mixtures 6 weeks after the start of vermicomposting.

number of earthworms compared to BM, but it was still at least twice the initial value. Earlier studies also showed that WS is not an ideal medium for the reproduction of epigeic earthworms (Manna et al., 1997). SMC probably contained materials that were unfavourable for earthworms, but the addition of BC significantly reduced this negative effect. A 450% increase in earthworm number was recorded in the SMC + BC mixture, though the earthworms remained small and the number of clitellated worms was only 4%. Judging by the worm population data, BC appears to have bound the SMC component that was unfavourable for the earthworms, thus promoting rapid reproduction until the food source was exhausted.

The increase in the number of worms was not directly proportional to the increase in worm biomass. In mixtures containing SMC and WS there was a significantly lower increase in total worm biomass than in BM. In the latter, BC resulted in a significantly smaller worm biomass compared to BM itself.

All in all the average individual worm weight decreased by the end of the experiment and in none of the mixtures was it as high as the initial 0.33 g. Three factors could be responsible for this: the number of juveniles, the inverted ratio of the population density to the mass increase of individual worms (Yadav and Garg, 2016) and the exhaustion of the food supplies. In response to BC addition there was always a drop in the average individual worm weight.

The proportion of juveniles and the quantity of food available is also indicated by the proportion of clitellated worms in the population. The presence of a clitellum indicates that the worms are capable of reproduction. *Eisenia fetida* worms usually become sexually mature within 40–60 days. A clitellum cannot be observed on juvenile earthworms and may also disappear from sexually mature worms if the medium in which they live does not contain sufficient food or the population density exceeds a certain value (Yadav and Garg, 2016). The number of clitellated worms is the result of all these factors. The highest and lowest values were recorded in mixtures containing WS and SMC, respectively: the decisive factor in the former was the low proportion of juveniles and in the latter the high number of juveniles and the exhaustion of the food supplies.

In summary it can be stated that SMC and WS were unfavourable for the worms from the point of view of population and biomass growth. BC did not promote reproduction or weight increase, but mitigated the negative effect of SMC on worm biomass. Based on earthworm parameters, the best conditions for vermicomposting were provided by BM

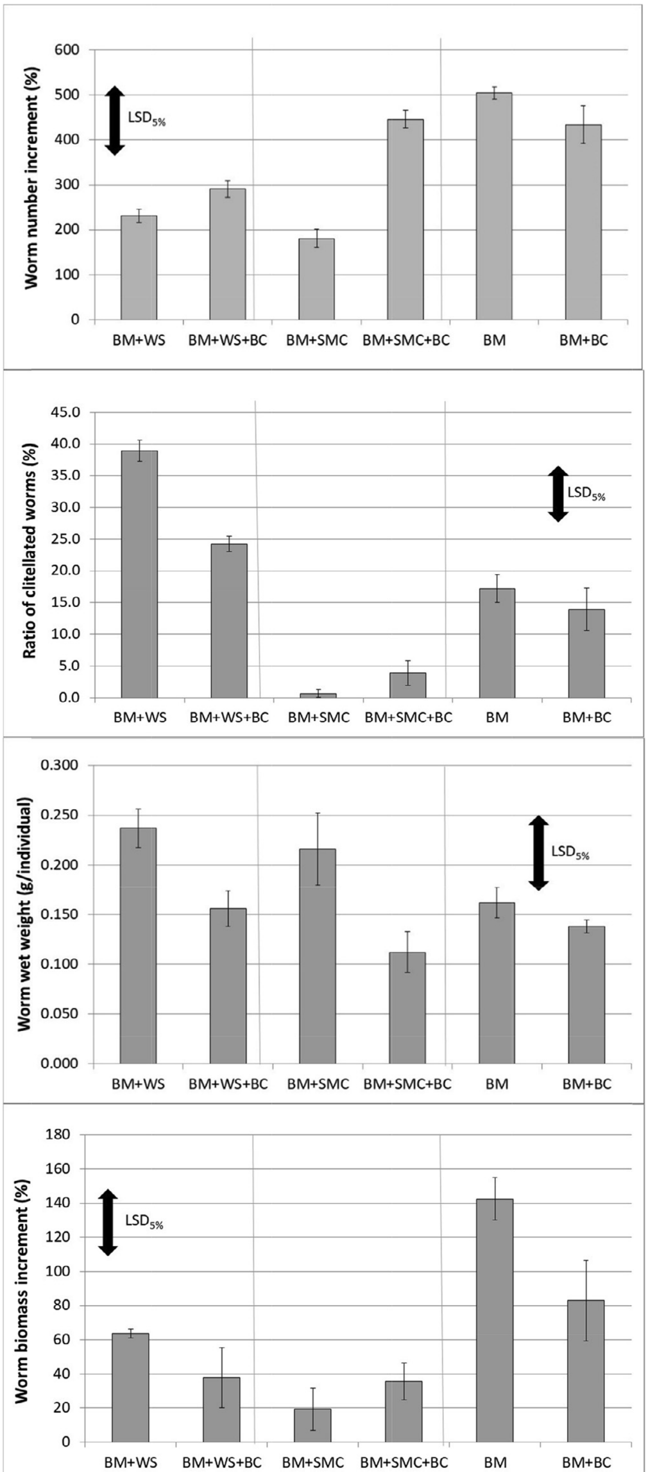

Fig. 3. Differences in worm number, total worm biomass increment, clitellated worm ratio and individual worm weight between the different mixtures after 90 days of vermicomposting.

and BM + BC.

3.2. Compost and vermicompost properties

3.2.1. Immature compost

At the end of the thermophilic composting phase (43 days) the pH of each mixture was close to neutral (pH 6.8–7.0). The OC concentration varied over a range of 21–28%, reaching higher values in mixtures containing BC and WS (Table 2).

The main difference between the composts was in the concentration and ratio of nitrogen forms. The concentration of NO_3-N exceeded that of NH_4-N in all the composts, indicating the completion of the nitrification process. An exceptionally high mineral N concentration was detected in mixtures containing WS. WS promoted the aeration of the mixture, so nitrification processes took place more intensively than in the other mixtures. BC also stimulated nitrification by providing better aeration and ensuring a better habitat for microbes, thus lowering the concentration of NH_4-N and raising that of NO_3-N. The anion adsorption ability of BC may also have contributed to the higher NO_3-N concentration (Verheijen et al., 2010).

The total N concentration was lower in mixtures containing BC. This could be attributed to the slightly higher composting temperature in these mixtures, which led to NH_3 loss during the thermophilic composting phase (Meng et al., 2017). However, according to other literature data BC supposed to reduce NH_3 emission during composting (Wu et al., 2017). Moreover, BC had the lowest total N concentration among the materials, so the N concentration of the mixtures decreased, after BC addition.

The better aeration and more intensive decomposition induced by WS application was manifested a 15% higher plant-available P concentration in BM + WS and BM + WS + BC than in the other mixtures. The plant-available K concentration was higher in mixtures containing SMC due to the high K content of this material.

3.2.2. Vermicompost and mature compost

3.2.2.1. pH and EC. The pH values in the final materials were statistically different, but were similar from the practical point of view, ranging from 6.54 to 6.86 (Table 3). When mixtures with the same composition were compared, a significant but very slight increase in acidity in the vermicompost compared to the compost (0.21 and 0.03 pH units) was only observed for mixtures containing WS. This could be attributed to the greater mineralisation occurring due to worm activity and to the release of organic acids (Fornes et al., 2012).

The EC value was higher in vermicompost than in compost made from the same material. However, this difference was only significant in three cases. The increase in EC in response to vermicomposting led to a rise in the concentrations of soluble organic materials and soluble salts as a consequence of decomposition processes (He et al., 2016).

3.2.2.2. Organic carbon. Compared to immature compost, a certain reduction in OC % (1–17%) was observed in all the mixtures except BC + SMC during compost maturation and vermicomposting. The extent of this decline was significantly influenced by the additives, with mean decreases of 2% for BM + SMC, 5% for BM + BC, 10% for BM + WS, 12% for BM, 13% for BM + SMC + BC and 16% for BM + WS + BC. SMC itself not only had a negative effect on the earthworms, but also inhibited decomposition processes, in contradiction to earlier findings (Meng et al., 2017). The effect of WS on the mineralisation process can be attributed mainly to better aeration, since its high lignin content, which restricts the availability of polysaccharides, makes it resistant to decomposition (Harper and Lynch, 1981). BC also influenced transformation processes: the average OC decreased in mixtures with and without BC by 12 and 8%, respectively, which is in accordance with the findings of Malinska et al. (2017). However, its effect is contradictory as it hindered mineralisation in the BM + BC mixture compared to BM.

On average vermicomposting led to a significantly greater decline in OC (12%) than conventional composting (7%). The more intensive mineralisation induced by earthworms, however, only resulted in significant differences in OC in two cases: there was a significant reduction in OC concentration in BM + SMC and BM + BC vermicomposts compared to the relevant composts (4 and 9%, respectively).

This suggests that BC and earthworms enhanced the decomposition processes in precomposted sewage sludge digestates to only a limited

Table 2
Chemical properties of the starting mixtures and immature composts.

Material	Starting mixture			Immature compost							
	OC m m^{-1}%	Total N m m^{-1}%	C/N	pH_{H2O}	OC m m^{-1}%	Total N m m^{-1}%	C/N	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	AL-P_2O_5 mg kg^{-1}	AL-K_2O mg kg^{-1}
BM + WS	38.1	2.91	13.1	6.77	25.9	2.47	10.5	1030	1426	8947	6989
BM + WS + BC	35.8	2.42	14.8	6.82	28.0	2.33	12.0	357	1570	8245	6636
BM + SMC	35.2	2.32	15.2	6.92	21.4	2.37	9.0	105	988	7323	8026
BM + SMC + BC	32.1	2.49	12.9	6.95	23.7	2.13	11.1	63.1	1019	7071	8269
BM	31.4	2.38	13.2	6.89	22.7	2.43	9.3	84.1	848	7436	6769
BM + BC	38.1	2.91	13.1	6.89	23.2	2.21	10.5	56.1	1191	7395	6889

extent. In both cases this can be attributed to microbiological stimulation and better aeration (Sanchez-Monedero et al., 2018; Vinceslas-Akpa and Loquet, 1997).

3.2.2.3. Nitrogen. The digestate was the main source of N in the mixtures, since it had the highest total N concentration. A slight increase was observed in the total N concentration of the mature composts and vermicomposts (2.39% N on average) compared to immature compost (2.32% N on average), which could be attributed to the decrease in OC concentration. The greatest nitrogen loss occurred during the thermophilic phase of composting, with no substantial losses during the following stages (Chowdhury et al., 2014). On average the total N concentration was the highest in mixtures containing WS (2.47%) (Table 3). The high hemicellulose content and high C/N ratio of WS may result in more intensive OC decomposition and an increase in the relative amount of N in the mixture (Zhao et al., 2016). For the same treatment and material composition, BC significantly reduced the total N concentration except in the case of BM + WS compost. Among the materials BC had the lowest total N concentration, so when it was added to the mixtures the N concentration decreased and the lowest total N concentration (2.19%) was observed in the BM + SMC + BC compost and vermicompost. The only case when vermicompostation affected the total N concentration of the material was BM + WS, where vermicompost had 2.58% N compared to 2.48% in the compost. The total N content was expected to increase more during vermicomposting than during composting due to the more intensive mass reduction caused by organic material loss and the metabolic activity of microorganisms (Hait and Tare, 2012). However, Hanc and Dreslova (2016) reported statistically identical total N concentrations in sewage sludge after composting and combined composting-vermicomposting. In the present experiment the main component of each mixture was the twice stabilised digestate, so vermicompostation probably did not result in a higher mineralisation rate in this matrix than compost maturation.

In the course of maturation and vermicomposting there was an average reduction of 78% in the concentration of NH_4-N and 91% in that of NO_3-N compared with the immature compost. This was due partly to the formation of more stable N compounds and partly to the fact that the mineral nutrients arising from the decomposition of soluble and easily degradable carbon sources during the intensive thermophilic stage were assimilated by microbes (Barrington et al., 2002). However, there was no difference in the NH_4-N and NO_3-N concentrations of vermicomposts and mature composts with the same material composition which contradicts the observations of Hait and Tare (2012), who reported a decrease in NH_4-N and an increase in NO_3-N in vermicomposted sewage sludge compared to composting. In contrast, Hanc and Dreslova (2016) reported lower NO_3-N in sewage sludge vermicompost than in compost. The present results suggest that worm activity did not affect the ammonification and nitrification processes, probably due to the fact that most of the organic compounds were stabilised. In the final materials the NH_4-N concentrations varied from 60 to 70 mg kg^{-1} except for BM + SMC + BC compost and vermicompost, which had lower values. The NO_3-N concentration in the materials was in the range of 61–152 mg kg^{-1}, with the highest NO_3-N values for the BM and BM + BC mixtures on average (127 mg kg^{-1}).

The ratio of inorganic nitrogen forms is an important parameter for assessing the maturity of composts (Das et al., 2011). On the basis of the NH_4-N/NO_3-N ratio, composts are defined as very mature (< 0.5), mature (0.5–3.0) and immature (> 3.0), so the BM + SMC + BC compost and vermicompost could be classified as very mature and the others as mature.

The C/N ratio in the materials ranged from 8.2 to 10. A C/N ratio of below 15 is indicative of composts with good quality and maturity, making them ideal for practical application. The vermicomposts exhibited lower C/N ratios than the relevant composts, but this difference was only significant for the BM + BC mixture. Due to its resistance to decomposition, materials containing BC had higher C/N ratios, though these differences were not always significant.

3.2.2.4. Phosphorus and potassium. The total and plant-available P concentrations were both related to the mixture composition and not the treatment method (Table 3). The highest total P concentration was found in BM (2.18%) and the lowest in the BM + SMC + BC mixture (1.67%). BC application decreased the total P value due to the retention of P in the pores, which could not be extracted with aqua regia (Gul and Whalen, 2016). Contradictory data can be found in the literature on the change in total P concentration during the vermicomposting of sewage sludge compared to composting, some authors reporting higher levels of P in vermicomposts (Hait and Tare, 2011; 2012; Yadav et al., 2012), while others found no change (Hanc and Dreslova, 2016). Most of the P content of the investigated mixtures originates from the digestate, the total P concentration of which was an order of magnitude higher than that of the other components (Table 1). There was less than 1% difference between the AL-P_2O_5 concentrations of composts and vermicomposts made from the same mixture. It can be postulated that, as in the case of N, the vermicomposting of previously stabilised materials did not result in higher mineral P concentration compared to composting. The highest AL-P_2O_5 concentration (8512 mg kg^{-1} on average) was found in mature composts and vermicomposts with WS, being about 19 and 27% higher than that of mature BM + SMC and BM composts and vermicomposts, respectively. The higher concentration of mineralised P could be the consequence of more intensive decomposition during the thermophilic composting phase, due to the better aeration provided by WS (Meng et al., 2017). Compared to immature compost, mature compost and vermicompost containing BM and SMC had lower mineral P concentration due to the ageing of the material (Adler and Sikora, 2003). As in the case of total P, BC addition decreased the AL-P_2O_5 values significantly in mature composts and vermicomposts, but this change was not significant in the case of BM compost and vermicompost.

As in the case of N and P, the total and available K concentrations were expected to increase after vermicomposting compared to composting (Yadav et al., 2012). However, earthworm activity caused no

Table 3
Properties of vermicomposts and mature composts.

Treatment	pH-H_2O	EC mS cm^{-1}	OC m m^{-1}%	Total N m m^{-1}%	C/N	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	Total P mg kg^{-1}	AL – P_2O_5 m m^{-1}%	Total K mg kg^{-1}	AL – K_2O mg kg^{-1}
BM + WS											
Mature compost	6.77 ± 0.06	4.62 ± 0.26	23.4 ± 1.1	2.49 ± 0.03	9.42 ± 0.36	70.7 ± 3.8	118 ± 14.7	2.02 ± 0.08	8522 ± 66	8462 ± 518	7467 ± 282
Vermicompost	6.56 ± 0.01	5.41 ± 0.12	23.4 ± 0.8	2.58 ± 0.01	9.08 ± 0.31	69.3 ± 9.6	68.5 ± 29.3	1.97 ± 0.06	8502 ± 223	8620 ± 137	7534 ± 113
$LSD_{5\%}$	0.13*	0.48*	n.s.	0.09*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
BM + WS + BC											
Mature compost	6.57 ± 0.03	4.80 ± 0.63	23.7 ± 1.1	2.42 ± 0.04	9.75 ± 0.38	60.4 ± 4.6	61.2 ± 25.3	1.73 ± 0.07	7951 ± 150	8721 ± 19	7353 ± 117
Vermicompost	6.54 ± 0.01	5.96 ± 0.09	23.1 ± 1.7	2.38 ± 0.03	9.41 ± 0.73	70.9 ± 2.1	73.5 ± 17.3	1.77 ± 0.04	7972 ± 221	8755 ± 218	7474 ± 120
$LSD_{5\%}$	0.02*	1.49*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	44**
BM + SMC											
Mature compost	6.74 ± 0.03	5.81 ± 0.02	21.0 ± 0.6	2.48 ± 0.03	8.47 ± 0.27	52.6 ± 1.6	89.1 ± 34.7	2.00 ± 0.07	6986 ± 175	8937 ± 90	8979 ± 70
Vermicompost	6.77 ± 0.04	6.43 ± 0.16	20.2 ± 0.4	2.45 ± 0.04	8.21 ± 0.09	70.6 ± 8.4	79.1 ± 10.9	1.99 ± 0.02	6842 ± 183	8832 ± 78	9035 ± 153
$LSD_{5\%}$	n.s.	0.39*	0.8*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
BM + SMC + BC											
Mature compost	6.74 ± 0.03	5.51 ± 0.48	21.8 ± 1.2	2.19 ± 0.05	9.93 ± 0.74	37.4 ± 1.1	90.2 ± 8.0	1.67 ± 0.03	6034 ± 154	10623 ± 151	9216 ± 32
Vermicompost	6.75 ± 0.01	5.66 ± 0.32	19.9 ± 1.0	2.19 ± 0.03	9.09 ± 0.38	42.7 ± 2.0	92.3 ± 24.5	1.68 ± 0.05	6078 ± 139	10284 ± 425	9145 ± 356
$LSD_{5\%}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
BM											
Mature compost	6.86 ± 0.04	4.03 ± 0.43	20.6 ± 1.2	2.43 ± 0.13	8.51 ± 0.88	68.7 ± 7.3	152 ± 46.5	2.16 ± 0.07	7063 ± 46	7562 ± 138	7494 ± 361
Vermicompost	6.80 ± 0.05	4.79 ± 1.11	19.7 ± 0.7	2.41 ± 0.06	8.17 ± 0.51	72.0 ± 4.9	110 ± 14.4	2.19 ± 0.02	7014 ± 208	7954 ± 90	7462 ± 90
$LSD_{5\%}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	380*	n.s.
BM + BC											
Mature compost	6.82 ± 0.05	5.51 ± 0.14	22.8 ± 1.3	2.27 ± 0.03	10.1 ± 0.46	76.2 ± 18.2	124 ± 33.2	1.98 ± 0.06	6898 ± 186	8258 ± 440	7651 ± 17
Vermicompost	6.72 ± 0.03	5.94 ± 0.41	20.7 ± 1.4	2.33 ± 0.02	8.85 ± 0.67	60.1 ± 0.8	121 ± 12.3	1.99 ± 0.02	6770 ± 53	8202 ± 188	7821 ± 142
$LSD_{5\%}$	n.s.	n.s.	1.6*	n.s.	0.84*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$LSD_{5\%}$ all treatments	0.06***	0.78***	1.9***	0.08***	0.88***	12.1***	41.4***	0.08***	285***	434***	298***

n.s. = not significant; *, ** and *** indicate significant differences at $p < 0.05$, 0.01 and 0.001, respectively.

Table 4
E_4/E_6 ratio of total humic matter, humic and fulvic acids in vermicomposts and mature composts.

Material	Humic fractions		
	Total humic matter	Fulvic acid	Humic acid
BM + WS			
Mature compost	5.65 ± 0.85	11.8 ± 1.26	3.65 ± 0.59
Vermicompost	6.34 ± 0.18	16.2 ± 3.20	6.12 ± 1.13
$LSD_{5\%}$	n.s.	n.s.	n.s.
BM + WS + BC			
Mature compost	5.91 ± 0.32	14.4 ± 1.03	3.48 ± 0.13
Vermicompost	6.96 ± 0.2	15.2 ± 1.07	4.89 ± 0.84
$LSD_{5\%}$	n.s.	0.5*	n.s.
BM + SMC			
Mature compost	6.54 ± 0.37	7.73 ± 0.65	5.64 ± 0.27
Vermicompost	6.73 ± 0.57	7.60 ± 0.66	5.97 ± 0.15
$LSD_{5\%}$	n.s.	n.s.	n.s.
BM + SMC + BC			
Mature compost	7.10 ± 0.46	8.80 ± 0.62	5.94 ± 0.54
Vermicompost	7.62 ± 0.06	9.37 ± 0.23	6.31 ± 0.06
$LSD_{5\%}$	n.s.	n.s.	n.s.
BM			
Mature compost	6.07 ± 0.08	15.3 ± 5.59	5.67 ± 0.88
Vermicompost	5.85 ± 0.41	9.27 ± 0.84	5.25 ± 0.21
$LSD_{5\%}$	n.s.	n.s.	n.s.
BM + BC			
Mature compost	6.08 ± 0.13	14.5 ± 1.10	4.91 ± 0.26
Vermicompost	6.45 ± 0.07	10.0 ± 0.23	5.30 ± 0.15
$LSD_{5\%}$	0.34*	2.30*	0.30*
$LSD_{5\%}$ all treatments	0.65***	3.34***	0.94***

n.s. = not significant; *, ** and *** indicate significant differences at $p < 0.05$, 0.01 and 0.001, respectively.

substantial change in the total and available K concentration in the present experiment. Although the AL-K_2O concentration was significantly higher in the BM + WS + BC vermicompost, in practice the difference was negligible, being only 1.6%. The concentration of K, like that of N and P, was not higher after vermicomposting than after conventional composting, as the transformation processes were not significantly more intensive in the former.

The total K concentration was the highest in BM + SMC + BC compost and vermicompost (1.05%) because of the high K content of the two additives (Table 1). The plant-available K concentration was the highest in mixtures containing SMC (9094 mg kg^{-1} as average) due to the high K content of this material (Table 1).

3.2.2.5. Organic matter quality. The quality of the organic matter is just as important for the stability and maturity of the compost as its quantity (Haddad et al., 2015). The E_4/E_6 ratio used to characterise humus quality indicates the intensity of humification in vermicomposts (Li et al., 2011). The smaller the ratio the more mature the compost is, and the larger and more complex the molecules that make up the humus. A higher E_4/E_6 ratio, on the other hand, indicated the presence of smaller, aliphatic molecules often containing several functional groups (Stevenson, 1994).

Spectral analysis of the total humic matter quantity gave E_4/E_6 ratios between 5.7 and 7.6. This wide range of values reflects the great heterogeneity of the molecules (Table 4). The E_4/E_6 ratio of the humic acids averaged 4.9 in the composts, with a higher value of 5.7 in the vermicomposts. However, the difference was only significant in the case of the BM + BC mixture. The humic acids detected in the experimental mixtures exhibited a degree of condensation and humification similar to that recorded by Li et al (2011), also in sewage sludge vermicomposts.

The fulvic acids in the experimental mixtures had a wide range of E_4/E_6 ratios (7.6–16.2). Based on the composition of the mixture, the most complex fulvic acid molecules were found in mixtures containing SMC, with an average E_4/E_6 ratio of 8.4, while on average more complex fulvic acid molecules were found in vermicomposts (E_4/E_6 = 11.3) than in composts (E_4/E_6 = 12.1). When the materials were analysed separately, however, significantly better fulvic acid composition was only found in BM + BC vermicompost compared to BM + BC compost. By contrast, in the case of BM + WS + BC the compost contained significantly more complex fulvic acids.

The results suggest that the vermicomposting of twice-stabilised digestate-based materials had no substantial influence on the quality of the organic matter compared to composting. Contradictory results were obtained in earlier studies on the effect of earthworm activity on humus quality. Campitelli and Ceppi (2008) reported that composts had a higher humification level than vermicomposts, while Savala et al. (2003) demonstrated a close significant correlation between earthworm activity and humus quality when vermicomposting was carried out using *Eisenia fetida*.

3.2.2.6. Plant growth hormones. Data in the literature suggest that one advantage of vermicomposts over composts is their higher plant growth hormone content (Jack and Thies 2006). Among the compounds investigated gibberellin could not be detected in the samples. Auxin was present in the nanogram range and kinetin in the microgram range (Table 5). These concentrations were several orders of magnitude smaller than those found in other vermicomposts (Ravindran et al., 2016; Tomati et al., 1988). Kinetin was always present in higher concentrations in vermicomposts, but the difference was only significant in two cases. Its concentration was five times higher in BM + WS vermicompost and almost seven times higher in BM + SMC vermicompost than in compost. There was no clear trend in the case of auxin. Higher auxin concentrations were recorded in the vermicompost for the BM + SMC mixture and in the compost for BM + WS and BM, but the difference was only significant in the latter case. For the proper evaluation of the effects of the materials on plant growth further analyses, including germination tests and plant growth monitoring are necessary.

4. Conclusions

After vermistabilisation no substantial differences in the macronutrient content and availability or organic matter quality was observed in a twice-stabilised digested then thermophilically precomposted sewage sludge compared to conventional composting.

Table 5
Plant growth hormone concentrations in vermicomposts and mature composts. (Materials containing BC were not analysed.)

Treatment	BM + WS		BM + SMC		BM	
	Indole-3-acetate ng kg-1	Kinetin µg kg^{-1}	Indole-3-acetate ng kg-1	Kinetin µg kg^{-1}	Indole-3-acetate ng kg^{-1}	Kinetin µg kg^{-1}
Mature compost	16.9 ± 4.5	91 ± 22.5	11.2 ± 1.6	115 ± 51	35.8 ± 8.5	548 ± 74
Vermicompost	9.10 ± 4.9	487 ± 62	22.9 ± 8.0	704 ± 171	10.9 ± 6.0	602 ± 78
$LSD_{5\%}$	n.s.	207*	n.s.	450*	8.7*	n.s.

n.s. = not significant; *, ** and *** indicate significant differences at $p < 0.05$, 0.01 and 0.001, respectively.

However, there was a higher concentration of the plant growth regulator kinetin in vermicomposts. Probably aeration or a shorter composting period before vermicomposting could be a better pre-treatment for sludge digestates.

Though only slight differences could be found between composts and vermicomposts for the above chemical properties, a more profound evaluation will be needed of their indirect effects as soil additives (on plant maturity, yield properties, soil structure, water regime).

Declarations of Competing Interest

None.

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