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Properties of Organic Matter in Composts Based on Sewage Sludge

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ABSTRACT

The aim of the research was to assess the quality of organic matter contained in sewage sludge composting products and their co-composting with fly ash and mineral wool. The object of the research were composts produced using stabilized sewage sludge from the municipal sewage treatment plant (SS_1C) and sewage sludge with the addition of 20% (SSF_2C) and 30% (SSF_3C) of fly ash and 5% (SSW_4C) and 10% (SSW_5C) of mineral wool. Selected physicochemical properties, fractional composition of humic compounds, and the degree and rate of humification were determined in compost samples taken after 180 days of composting. The reaction of the evaluated composts was close to optimal for mature composts. Co-composting of sewage sludge with mineral wool and ash increased the sorption capacity in composts compared to SS_1C. Due to the content of available P and Mg, the discussed composts formed the SS_1C>SSF_2C and SSF_3C>SSW_4C and SSW_5C series. However, in terms of available K content: SSF_2C and SSF_3C>SSW_4C and SSW_5C>SS_1C. In the SS_1C compost the organic carbon (TOC) content was slightly higher, but no statistically significant effect of the addition of fly ash and mineral wool on the TOC content in mature composts was confirmed. The addition of ash and mineral wool significantly increased the total nitrogen content. Due to the humification index, the composts formed the series: SSW_4C > SSW_5C > SSF_2C > SS_1C > SSF_3C. The values of the C-KH/C-KF ratio in SS_1C were typical for good quality soils, while in the remaining composts the C-KH/C-KF values were slightly lower. The degree of humification of the assessed composts was characterized by poorly humified organic materials, with the highest values of this indicator found in composts with the addition of mineral wool. The assessed quality indicators of organic matter indicate that the organic matter of composts from sewage sludge with the addition of mineral wool and 100% sludge was of the highest quality.

Keywords: compost, sewage sludge, fly ash, mineral wool, fractional composition of organic matter, humification index.

INTRODUCTION

In response to the observable climate change and environmental degradation threatening Europe and the rest of the world, the European Green Deal Action Plan was created. It is a strategy of remodelling the European Union's economy to make it a region with zero greenhouse gas emissions by 2050. Climate protection is to go hand in hand with the development of competitive industry and maintaining a high standard of living. The adopted regulations and guidelines paid particular attention to soils, assuming that soils in the EU must be restored to "health" by 2050. Content of soil organic matter (SOM) is a critical indicator of soil health and is fundamental to the productive potential of soils and their ability to perform ecosystem services. Studies of SOM initially focused on soil fertility, and later on interactions with heavy metals in the context of soil contamination. Organic matter plays a key role in maintaining the physical, chemical and biological properties of soils, so its content is a key measure of healthy soil [Raviv, 2005; Leroy et al., 2008; Zhai et al., 2022]. Maintaining its content in the soil and its further accumulation are crucial importance for food security and mitigating climate change.

Since the early 1980s, the awareness of the risks and challenges of global warming has been increasing year by year, which translates into research on carbon sequestration in soils as a factor in climate regulation and other ecosystem services of organic matter [Lal, 2004; Hoffland et al., 2020]. Soil organic C in the top 100 cm of the soil layer contains about 50% of the terrestrial C pool [Lal, 2004]. Therefore, SOM is attributed a key role in shaping soil ecosystem functions as a source and potential storage medium for CO_2 [Janzen, 2006; Hoffland et al., 2020].

The soils in Poland contain relatively little OM, as the soil cover is dominated by light soils made from sands of various origins. They are airy, and some of them are permanently too dry. They are characterised by a low colloidal fraction (< 0.002 mm), which does not favour humus accumulation in soils, and the mineralisation processes of organic compounds are aggravated by the rainfall deficits observed in recent years [Siebielec et al., 2020]. Hence the need to take measures to increase the OM content in soils or to maintain its content at current levels [Sobolewski, 2020].

An effective tool to increase OM, and thus meet the EU's policy goals for sustainable use of key natural resources and EM, is the recycling of exogenous organic matter (EOM). EOM is all organic material of biological origin applied to the soil for the purpose of fertilisation, amendment or restoration and environmental improvement [Marmo et al., 2004]. The effects of EOM on crop yields, soil carbon accumulation or nitrogen utilisation have been studied quite extensively. However, literature data indicate that further, accurate characterisation of the large diversity of EOMs and the variability in the effects of their application to soil is needed to quantify their potential to store C in soil, especially for EOM that has undergone treatments such as composting or anaerobic digestion [Siebielec et al., 2021]. Due to the varying properties of exogenous biomass bioconverted under aerobic conditions, and the use of different composting technologies, it is important first of all to understand the factors influencing the directions and intensity of organic matter transformation and to assess the relationship between the substrates in the composting process and its fertiliser value.

An example of EOM is sewage sludge, which has great fertiliser potential and should be recycled in accordance with circular economy strategy [Kominko et al., 2018]. Management of organic waste and returning its organic C to the soil can increase the potential for soil C sequestration in the sense of circular economy strategy [Chabbi et al., 2017]. Of the strategies for increasing soil carbon resources is the conversion of organic waste through composting and the application of composts to soil [Ngo et al., 2012]. Composting is the biological decomposition of organic material under aerobic conditions as a result of the enzymatic activity of different groups of microorganisms [Temel, 2023]. As a result of the process, organic matter is transformed into stabilised organic macromolecular humus substances and any pathogens that may be present are eliminated [Muscarella et al., 2023].

Composting can be used to treat sludge prior to disposal, reducing potential environmental pollution, human health risks and high management costs. Legislation specifies that sludge that has undergone compost stabilisation can be safely stored on land and used as a soil additive [Peltre et al., 2015]. However, composting also has certain possible disadvantages, such as long composting times, loss of nitrogen and unstable or immature compost products. Not fully mature compost may not contain humic substances (HS) and may contain more substances that inhibit plant growth, including free ammonia, phenols, heavy metals and organic acids [Fourti, 2013]. Therefore, efficient conversion of organic matter into HS is of great importance for improving composting efficiency and product quality [Chen et al., 2023]. Certain physicochemical properties, including excessive moisture content and low porosity of sewage sludge, can interfere with the proper composting process.

In order to optimise moisture content and aeration, it is advisable to use bulking agents to simultaneously improve the quality of the final product [Vráblová et al., 2024]. Some added substrates are considered as bulking agents because they only act on the physical structure of the compost, but in most cases these substrates also have a direct or indirect impact on other composting parameters and can be considered as additives [Villasenor et al., 2011].

Fly ash and waste mineral wool can be used as structural materials [Żukowska et al., 2021; Myszura-Dymek and Żukowska, 2023]. Fly ash, due to its sorption properties, shows high effectiveness in sludge treatment processes, especially by intensifying the efficiency of the dewatering process [Zheng and Haifeng, 2010; Wójcik et al., 2017]. Research results also indicate that fly ash, due to its alkalising properties [Gomes et al., 2016] and the presence of reactive CaO, can be used as a reagent for sludge hygienization. Adding fly ash to sewage sludge triggers a number of exothermic reactions, resulting in sludge undergoing sterilisation, pasteurisation and disinfection processes [Poluszyńska, 2013]. Filling media commonly chosen to offset the high moisture content of organic waste are fibrous materials [Miner et al., 2001, Eftoda and McCartney, 2004; Doublet et al., 2011], which can absorb part of the leachate. Absorption of leachate can be achieved, among other things, by using dry growing media [Yang et al., 2013]. A post-production waste from a greenhouse under cover used together with sewage sludge can loosen the structure of the compost mixture, thereby optimising water and air properties [Żukowska et al., 2023]. In addition, rockwool substrates are saturated with hydroponic nutrient salts and thus can provide a source of nutrients [Istenič et al., 2024].

The transformation of sludge properties during composting is the subject of numerous studies [Amir et al., 2005; Khalil et al., 2011; Mayur et al., 2019] but there is too little information in the literature on the quality of composts obtained from processes of co-composting sewage sludge with other wastes, especially the quality of the organic matter of composts in the context of its suitability for increasing CO_2 sequestration. The aim of the study was to assess the quality of organic matter in the products of composting sewage sludge and its co-composting with fly ash and mineral wool. The assessment was based on the analysis of the fractional composition of humus compounds and the degree and rate of humification.

MATERIAL AND METHODS

The object of the study was composts, the main component of which was sewage sludge. Stabilised sewage sludge from a municipal sewage treatment plant, fly ash from a power station and mineral wool – a post-production waste from a greenhouse – were used to produce composts. The basic properties of the wastes used to produce the composts are shown in Table 1. The waste was mixed in various proportions (d.m.), and the composition of the compost mixtures is presented in Table 2.

The waste was composted in 120 – litre containers for 180 days, monitoring changes in temperature and moisture content. After 180 days, compost samples were taken for laboratory tests.

Table 1. Selected soil properties and materials used. Average values [Żukowska et al.. 2023]

Properties		Sewage sludge	Fly ash	Mineral wool
pH	H_2O	6.3	7.9	6.1
	KCl	6.1	7.9	6.1
d.m.	%	17	–	–
H_h	cmol(+)kg^{-1}	3.38	0.18	5.83
BC		18.03	11.82	8.3
CEC		21.41	12.0	14.19
P total	g·kg^{-1}	18.6	1.0	5.4
K		2.18	2.24	5.82
Mg		5.25	4.35	10.6
Ca		28.2	27.1	27.7
P available	mg·kg^{-1}	12.2	165.0	186.0
K available		13.74	49.0	41.8
Mg available		10.46	181.5	19.6
Cd		2.77	0.51	0.92
Cr		17.2	–	–
Cu		164	29.5	145
Ni		12	–	–
Pb		39.3	25.9	42.0
Zn		825	51.6	367
Hg		0.4	–	–
Salmonella	–	No detected in 100 g	–	–
Number of live parasite eggs	Pcs/kg d.m.	0	–	–

Table 2. Composition of compost mixtures

Variant	Composition of the compost mixture
SS_1C	Compost from sewage sludge (100%)
SSF_2C	Sewage sludge compost (80%) + fly ash (20%)
SSF_3C	Sewage sludge compost (70%) + fly ash (30%);
SSW_4C	Sewage sludge compost (95%) + mineral wool (5%)
SSW_5C	Sewage sludge compost (90%) + mineral wool (10%)

After drying in the composts, the following were assayed:

- pH using the potentiometric method in 1 mol $KCl \cdot dm^{-3}$ [ISO 10390:2005];
- hydrolytic acidity (Hh) and sum of base cations (BC) by Kappen's method [Soil Survey Laboratory Methods Manual, 1996] and the cation exchange capacity (CEC) of the soil was calculated using the formula:

$$CEC = Hh + BC \quad (1)$$

where: CEC – cation exchange capacity, Hh – hydrolytic acidity, BC – base cations.

- the content of available phosphorus (P) and available potassium (K) – using the Egner-Riehm method [Polish Committee for Standardization, 1996], and the content of available magnesium (Mg) – using the Schachtschabel method [Schlichting et al., 1995];
- total organic carbon (TOC) – by the combustion method using the TOC-VCSH apparatus [PN-EN 15936:2013:02] with the SSM-5000A module, and total nitrogen (TN) content – by the modified Kjeldahl method using the Kjeltech TM 8100 distillation apparatus, and the ratio of total organic carbon to total nitrogen (C/N) was calculated.

Organic matter fractionation based on the Schnitzer method was carried out [Griffith and Schnitzer, 1975]. Humins acids (HAs) were extracted using a NaOH solution of 0.5 $mol \cdot dm^{-3}$ (C extracted). By acidifying the HAs extract with sulphuric acid to pH ~ 2, humic acids (HA) were precipitated and dissolved with 0.1 mol $NaOH \cdot dm^{-3}$. The carbon content of the extracted 0.5 mol $NaOH \cdot dm^{-3}$ and C of humic acids (C-HA) was determined using a TOC-VCSH with SSM-5000A module. The carbon of fulvic acids (C-FA) and humin, i.e. non-hydrolysing carbon (Cnh), was calculated from the difference of, respectively:

$$C\text{-}FA = HAs - C\text{-}HA \quad (2)$$

where: C-FA – fulvic acids, HAs – humins acids, C-HA – humic acids.

$$Cnh = TOC - HAs \quad (3)$$

where: Cnh – non-hydrolysing carbon, TOC – total organic carbon, HAs – humins acids.

The results of the fractional composition are presented as the carbon content of the individual fractions (in $g \cdot kg^{-1}$) and as the carbon content of the fraction in the total carbon pool (%TOC). The ratio of carbon in humic acids to carbon in fulvic acids was calculated (C-HA/C-FA).

All properties were performed in three repetitions. The results were statistically analysed using STATISTICA 13.1 with ANOVA models and Tukey's multiple post-hoc tests (HSD) at a significance level of $\alpha = 0.05$. Ward's method [Malina, 2004] was used to determine sets of factors with high probability. In Ward's agglomeration method, clustering was performed on the basis of Euclidean distance.

RESULTS AND DISCUSSION

Sewage sludge can provide an alternative source of external organic matter for soils [Taskin and Bilgili, 2023]. However, their use, without prior stabilisation, may pose a risk due to the presence of phytotoxic substances and pathogens and the difficulty of applying. One method of stabilising the properties of sewage sludge can be composting. By subjecting sewage sludge to the composting process, a valuable organic fertiliser - compost - can be obtained and the problem of sludge disposal can be partly solved [Nguyen and Shima, 2019].

Compost made from sewage sludge (SS_1C) and composts made from sludge with the addition of fly ash (SSF_2C and SSF_3C) and mineral wool (SSW_4C and SSW_C5) were characterised by a slightly acid reaction (pH values in 1 mol $KCl \cdot dm^{-3}$ ranged from 5.8 to 6.3 (Table 3). The composting process of SS_1C showed a slight reduction in pH (from 6.1 to 5.8 – Tables 1 and 3). Similar results were obtained by Czekała [2008], Krzywy et al. [2000]. The reduction in the pH of composted materials may be caused by calcium losses and/or increased nitrate nitrogen (V) content [Czekała, 2008]. In composts with fly ash and mineral wool added, the pH at 1 mol KCl·dm^{-3} took on values between 5.9 and 6.3 and these values were close to the optimum pH of mature sludge compost [Singh et al., 2023].

The cation exchange capacity (CEC) of the sludge composts ranged from 30.40 cmol(+)·kg^{-1} (SS_1C) to 34.30 cmol(+)·kg^{-1} (SSF_3C) (Table 3). It should be emphasised that CEC was mainly saturated with exchangeable base cations (BC) (Table 3). The lowest BC content 24.19 cmol(+)·kg^{-1} was found in SS_1C. Significantly higher BC content was found in composts with fly ash and mineral wool additions.

The content of available forms of phosphorus, potassium and magnesium in the evaluated composts depended on the composition of the composted substrate (Table 4). In SS_1C, the content of available phosphorus was 30.7 mg·kg^{-1} (Table 4). In SSF_2C and SSF_3C, the content of the component in question was higher (by approx. 1 and approx. 3 mg·kg^{-1}, respectively at 20 and 30% of fly ash content). As reported by Lombard et al. [2011] and Yu et al. [2019], fly ash from thermal power plants, or ash generated during the recycling of sewage sludge, is treated as a waste containing certain elements useful in agricultural production and can, therefore, be added to the soil to improve some of its physicochemical properties [Wyszkowski et al., 2022]. However, in the ashes, only trace amounts of phosphorus are present in a form that is available to plants [Gomes et al., 2016]. In SSW_4C and SSW_5C, the assimilated P content was higher in comparison with the other composts (Table 4), which can be explained by the abundance of post-consumer rockwool from greenhouse crops in assimilable macronutrients [Istenič et al., 2024]. The content of available potassium in the evaluated compost mixtures showed values from 141.5 mg·kg^{-1} to 162.83 mg·kg^{-1}. The highest content of this element was characterised SS_1C and the lowest SSF_3C. The content of available forms of magnesium in all evaluated composts showed values from 157.97 mg·kg^{-1} to 182.29 mg·kg^{-1}. Co-composting of sewage sludge with mineral wool produced composts most abundant in available Mg, due to the significant Mg content of the post-consumer wool [Istenič et al., 2024].

One of the strategies to increase soil carbon stocks is the conversion of organic waste through composting and the application of composts to soil [Ngo et al., 2013]. Carbon and nitrogen are essential nutrients for microorganisms in the composting process. Organic waste provides the necessary carbon and nitrogen for microorganisms [Dogan et al., 2023]. The organic matter content and quality of composts is an important parameter to consider when using them as soil fertilisers [Francou et al., 2005]. Stable organic matter applied to soil emits less carbon than unstable organic matter [Bernal et al., 1998].

The content of TOC in the evaluated composts was modified to a non-significant extent by the composition of the compost mixtures. In SS_1C, the TOC content was the highest and amounted 424 g·kg^{-1} (Table 5). With an increase in the proportion of additives in relation to the sewage sludge, the TOC content decreased and in SSF_2C and SSW_5C and was approximately 373 g·kg^{-1}. The lower TOC contents in these composts should be explained by the lower TOC content in the composition of the composted mixtures [Myszura-Dymek and Żukowska, 2023].

The content of total nitrogen (TN) was determined by the TN content of the materials used for composting. The highest content of TN was

Table 3. pH and Hh, BC and CEC of composts from the waste composting experiment

Variant	pH 1 mol KCl·dm^{-3}	Hydrolytic acidity (Hh)	Exchangeable base cations (BC)	Cation exchange capacity of the soil (CEC)
		cmol(+)·kg^{-1}		
SS_1C	5.8	6.21±0.03d	24.19±0.06a	30.40±0.03a
SSF_2C	6.1	5.93±0.05c	26.42±0.06c	32.35±0.01d
SSF_3C	6.3	5.03±0.05b	29.27±0.05e	34.30±0.09e
SSW_4C	5.9	5.61±0.03a	25.50±0.08b	31.11±0.11b
SSW_5C	5.8	4.97±0.05a	26.65±0.04e	31.62±0.03c

Table 4. Content of available P, K and Mg in composts from waste composting experiments

Variant	P	K	Mg
	mg·kg^{-1}		
SS_1C	30.71±0.27a	162.83±0.65c	157.97±0.77a
SSF_2C	31.73±0.25ab	151.96±0.77a	165.84±0.62b
SSF_3C	34.02±0.06bc	141.50±0.40b	171.83±0.62c
SSW_4C	32.34±1.76ab	153.60±0.54a	179.33±0.47d
SSW_5C	35.25±0.36c	152.14±0.54a	182.29±0.43e

found in the SS_1C and was 29.45 g·kg^{-1}. In sludge compost mixtures with the addition of other waste substances, the content of TN remained at a lower level. The highest content of TN was found in compost mixtures from sewage sludge with the addition of mineral wool and the lowest in SSF_C3.

In the transformation of organic matter during composting, nitrogen compounds are converted to mineral forms and can be partially volatilised [Czekała, 2008], but the loss of TOC occurs to a greater extent, resulting in a reducing the value of C/N ratio. In the evaluated composts, the C/N ratio ranged from 13.5 g·kg^{-1} (SSW_4C) to 15.3 g·kg^{-1} (SSF_2C and SSF_3C) (Table 5). The C/N ratio in SS_1C was 14.5, indicating a medium degree of maturity in this compost [Garcia et al., 2004]. The addition of mineral waste did not have a targeted effect on the C/N ratio – the ratio was higher in composts with ash addition, while it was lower with wool addition (Table 5). When selecting additives for sludge composting, attention should be paid to the C/N ratio in the starting mixtures to ensure organic matter degradation and prevent N leaching during composting [Doublet et al., 2011].

In conclusion, the differences in TOC content of the evaluated composts were not statistically significant, while statistically significant differences were confirmed for TN content (Table 5). Ward's cluster analysis for TOC, TN, C/N confirmed that the composition of the compost mixture was crucial in shaping these properties (Fig. 1).

The content and structure of humic substances in compost have been studied in numerous studies as the main indicators for assessing compost maturity [Ouatmane et al., 2000; Garcia et al., 2004]. Compost adds humic substances (HS) to the soil [Tomati et al., 2000]. HS, including humic acids, fulvic acids and humins, are part of the SOM which forms humus [Nguyen and Shindo, 2011]. The formation of fertile soil layers rich in humic substances can take decades in nature, but it takes 6–12 months to produce a humic acid-like substance by composting [Amir and Hafidi, 2001]. HS are important in soil restoration processes and can be used to promote nutrient uptake, increase soil porosity, improve nutrient retention and water holding capacity and reduce the presence of pathogens [Schnitzer, 1978]. The content and quality of humic substances in compost is correlated with compost maturity and adds value to the waste material [Nguyen and Shindo, 2011] and is crucial in shaping the potential of composts as exogenous organic matter to support soil carbon sequestration.

The humus compounds extracted by alkaline solutions are considered [Kononova, 1968] to be active organic substances that provide a potential source of energy and nutrients for soil microorganisms. In composts, humic substances play an important role in the course of many processes occurring during composting [Amir et al., 2005]. Moreover, humus content and humus quality are the most commonly used properties to assess

Table 5. TOC, TN content and C:N ratio in composts from the waste composting experiment

Variant	TOC	TN	C/N
	g·kg^{-1}		
SS_1C	424 ±11.31a	29.45 ±1.83c	14.5
SSF_2C	374 ±29.53a	24.62 ±1.13ab	15.3
SSF_3C	357 ±25.10a	23.40 ±0.80a	15.3
SSW_4C	369 ±27.19a	27.31 ±0.82bc	13.5
SSW_5C	373 ±8.99a	26.88 ±0.69abc	13.9

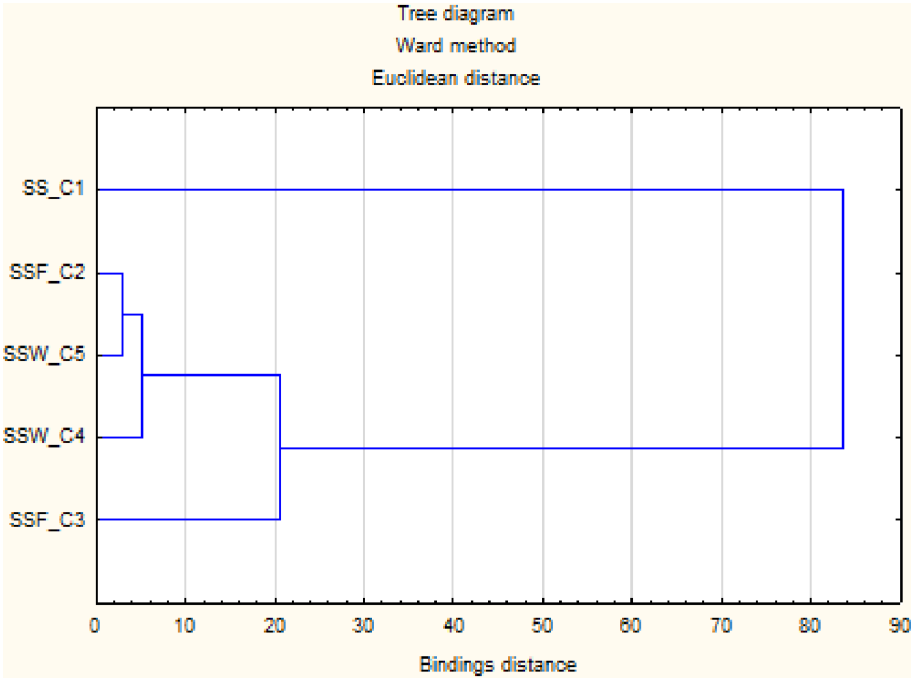

Figure 1. Ward's tree dendrogram for TOC, NT and C/N

compost stability [Roy et al., 2018; Rivers et al., 2021; Mahapatra et al., 2022]. The content of humic compounds extracted by 0.5 mol NaOH·dm^{-3}– humic acids in the assessed composts from sewage sludge and other wastes ranged from 76.80 g·kg^{-1} (SSF_3C) to 102.47 g·kg^{-1} (SS_1C) (Table 6). In assessing the fractional composition of organic matter, the percentage of separated fractions in the pool of total organic carbon is more meaningful than the content of separated fractions. In SS_1C, the proportion of humins acids in the total carbon pool was 24.12 % TOC. The addition of 20% fly ash to the composted sewage sludge had no effect on the contribution of the described humic connections to the carbon pool, neither did the 10% addition of mineral wool (Table 6). SSF_3C was characterised by a significantly lower proportion of humus compounds extracted by 0.5 mol NaOH·dm^{-3}, and these connections accounted for 21.62% TOC. The addition of mineral wool at a dose of 5% significantly increased the proportion of the described fraction (to 27.48% TOC). The proportion (%) of humic compounds extracted with alkaline solutions in the total carbon pool is assumed to be an indicator that can be used to assess the degree of humification of organic matter processes occurring during composting [Shan et al., 2010; Hu et al., 2022]. The higher the value of this index, the more advanced the humification processes are. The results obtained and the performed Ward's cluster analysis (Figure 2) indicate that the composts assessed for their humification index formed a sequence: SSW_4C > SSW_5C > SSF_2C > SS_1C > SSF_3C.

In the evaluated compost mixtures, the predominant fraction of humus compounds was non-hydrolysing carbon (Cnh) (Table 6). The content of this fraction ranged from about 267.80 g·kg^{-1} to about 321.53 g·kg^{-1}, which accounted for about 72.52% TOC (SSW_4C) to about 78.32% TOC (SSF_3C). Such a high proportion of Cnh in the tested composts indicates the presence of not fully mummified organic matter. The highest share of Cnh was found in compost from SSF_3C [Żukowska et al., 2012]. The lowest, among the evaluated composts, share of the described fraction was characterised by SSW4_C composts.

Taking into account the proportion of Cnh and the degree of humification of the organic matter, it can be concluded that the organic compounds of the SSF_3C were the least processed in the composting process. In terms of these indicators, the organic matter of composts from sewage sludge with mineral wool added and from 100% sewage sludge had the best quality. Within humic connections separated by 0.5 mol NaOH·dm^{-3}, the content of fulvic acids (C-FA) slightly exceeded that of humic acids (C-HA), and the C-KH/C-KF ratio took values below 1 (Table 7). In SS_1C, the proportion of humic and fulvic acids determined

Table 6. The share of humic compounds extracted by 0.5 mol NaOH·dm^{-3} from the waste composting experiment

Variant	Content of humus compounds extracted by 0.5 mol NaOH·dm^{-3}		Non-hydrolysing carbon (Cnh)	
	g·kg^{-1}	% TOC	g·kg^{-1}	% TOC
SS_1C	102.47±10.46a	24.12±1.93ab	321.53±5.32a	75.88±1.93ab
SSF_2C	92.13±10.96a	24.56±1.03ab	281.87±18.78a	75.44±1.03ab
SSF_3C	76.80±1.70a	21.62±1.86a	280.53±25.85a	78.38±1.86b
SSW_4C	101.53±9.72a	27.48±1.43b	267.80±19.95a	72.52±1.43a
SSW_5C	95.47±6.11a	25.59±1.05ab	277.20±3.68a	74.41±1.05ab

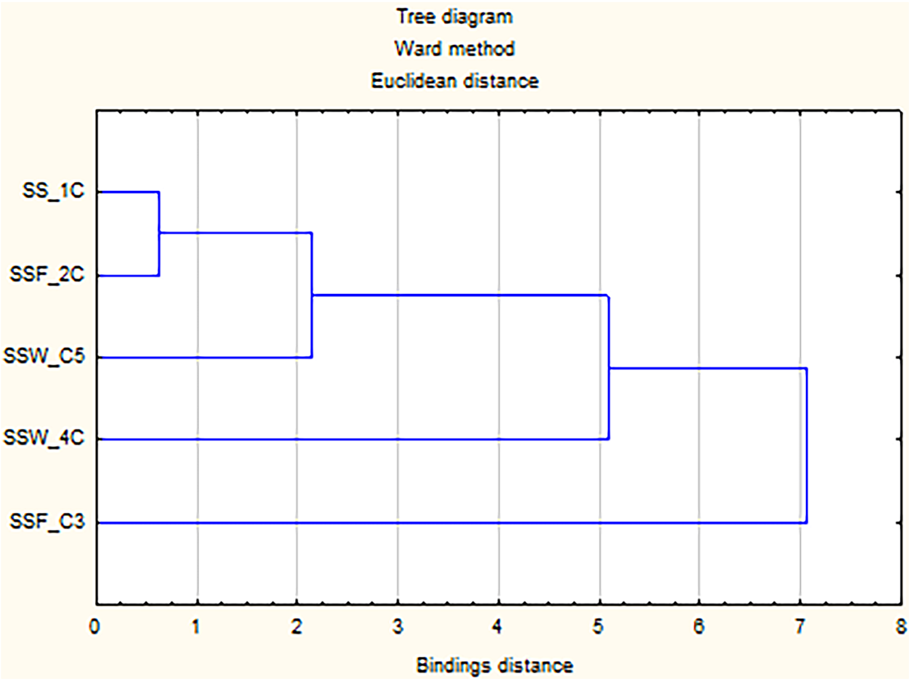

Figure 2. Ward's tree dendrogram for content of humus compounds extracted by 0.5 mol NaOH·dm^{-3} and Cnh

in the 0.5 mol NaOH·dm^{-3} NaOH extract was similar, and the C-KH/C-KF ratio was 0.97 (Table 7). According to Kononova [1968], the C-KH/C-KF ratio is an indicator of the quality of humus compounds and the higher its value, the more resistant the humus compounds are to decomposition and the more stable they are. The obtained value of the C-KH/C-KF ratio for sludge compost is characteristic of soils of good quality. It is presumed that composts with such a high C-KH/C-KF ratio will promote carbon sequestration in the soils into which they are introduced [Bekier et al., 2023]. The sludge composts with added waste were characterised by a slightly lower C-HA content with a tendency towards a higher C-FA content (compared to SS_1C) (Table 7). Taking the C-KH/C-KF ratio as an indicator of organic matter quality, it can be concluded that composting sewage sludge with fly ash and mineral wool also had a beneficial effect on the quality of the newly formed humus compounds. The C-KH/C-KF ratio in these compost mixtures took on values ranging from 0.86 to 0.93. The significantly lower value of the C-KH/C-KF ratio was characterised by compost from SSF_2C, SSW_4C and SSW_5C. The humification degree is an extremely important indicator in assessing the quality of organic matter in composts. To assess the degree of humification of composted organic waste, the indicator proposed by Orlov [Grishina, 1986] was used, i.e. the percentage of humic acids in the total carbon pool (Table 7). A degree of humification above 10 is characteristic of poorly mummified organic materials [Grishina, 1986]. The degree of humification of organic matter SS_1C was 11.87, while the others ranged from 10.39 (SSF_3C) to 13.17

Table 7. The content of humic and fulwic acids in the compounds extracted from 0.5 mol·dm^{-3} NaOH and the C-KH/C-KF ratio

Variant	Content of humic acids (C-HA)		Content of fulvic acids (C-FA)		C-KH/C-KF ratio
	g·kg^{-1}	% TOC	g·kg^{-1}	% TOC	
SS_1C	50.37±4.86b	11.87±0.88ab	52.10±5.60a	12.28±1.00a	0.97
SSF_2C	42.60±4.41ab	11.39±0.29ab	49.53±6.57a	13.24±3.05a	0.87
SSF_3C	37.10±0.57a	10.39±0.77a	39.70±1.24a	11.12±1.09a	0.94
SSW_4C	46.43±4.13ab	12.58±0.28b	53.50±7.40a	14.49±1.20a	0.88
SSW_5C	49.13±3.80ab	13.17±0.72ab	52.67±6.75a	14.12±1.50a	0.88

(SSW_5C). Although the degree of humification of the evaluated composts fell into the same category, it should be noted that the highest values of this indicator were found for composts with the addition of mineral wool.

CONCLUSIONS

The composition of the composted mixtures had a key impact on shaping the properties of the assessed composts. The pH of composts based on sewage sludge was close to optimal for mature composts. Co-composting of sewage sludge with mineral wool, regardless of its share and ash, in proportion to its share in the compost mixture, increased the sorption capacity compared to 100% sewage sludge compost. Due to the content of available phosphorus and magnesium, the discussed ingredients formed the series sewage sludge 100% > sewage sludge + fly ash 20 and 30% > sewage sludge + mineral wool 5 and 10%. However, in terms of the available potassium content: sewage sludge + fly ash 20 and 30% > sewage sludge + mineral wool 5 and 10% > sewage sludge 100% >. In composts (SSF_2C, SSF_3C, SSW_4C, SSW_5C) the TOC content was slightly lower, but no significant effect of the addition of fly ash and mineral wool on the TOC content in the mature compost was statistically confirmed. Statistically, a significant impact of the addition of fly ash and mineral wool on the TN content in composts was confirmed. Due to the humification index, i.e. the percentage of carbon fractions released from 0.5 mol NaOH·dm^{-3}, the evaluated composts formed the series: SSW_4C > SSW_5C > SSF_2C > SS_1C > SSF_3C. The values of the C-KH/C-KF ratio in the compost from sewage sludge 100% were typical for good quality soils In other composts, C-KH/C-KF had slightly lower values. The degree of humification of the assessed composts was characteristic of poorly humified organic materials, but the highest values of this indicator were found in composts with the addition of mineral wool. The largest share in the fractional composition of organic matter in composts was non-hydrolysing carbon. The assessed quality indicators of organic matter indicate that the organic matter of composts from sewage sludge with the addition of mineral wool and 100% sewage sludge was of the best quality.

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