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The influence of sewage sludge processing method on the properties of humic substances

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ABSTRACT

Based on the analysis of fractional composition and the quality parameters of humic acids, the quality of organic matter from municipal sewage sludge with varying degrees of processing (unstabilized sludge, chemically stabilized sludge, sludge biologically stabilized under aerobic conditions, and sludge stored in lagoons) was assessed. The total organic carbon (TOC) content in sewage sludge depended on the sludge processing degree. Lime stabilization and composting had a positive effect on TOC content, but the TOC content was lower in stored sewage sludge than in raw sludge. The quality of organic matter in sewage sludge, assessed based on fractional composition, differed significantly from that of soil organic matter. The sludge contained less extractable humic compounds and more humins; the C–HA:C–FA index value was 0.5–0.7 in raw sludge and approximately 1 in lime-stabilized or composted sludge. The degree of humification of their organic matter was low (5.88–15.48%). Regardless of their origin, humic acids from sludge exhibited a similar elemental composition, distinct from that of soils – they contained less C and O and more H and N, indicating a higher proportion of aliphatic structures and a lower degree of aromatic nucleus condensation. Composting municipal sewage sludge is the most effective method of preparing it for use in agriculture and reclamation, as it ensures the formation of stable forms of humus, which promotes carbon sequestration and the sustainable improvement of degraded soil quality.

Keywords: sewage sludge, sewage sludge stabilization, humus fractional composition.

INTRODUCTION

Sewage sludge is a major and unavoidable byproduct of wastewater treatment processes in wastewater treatment plants. It must be removed from these facilities to ensure optimal efficiency (Bauer et al., 2020). The amount of this sludge is constantly increasing worldwide. For example, in the European Union (EU), its production increased by almost 38% from 2005 to 2020. According to EU reports, among European countries, the largest sludge producers are Germany, the United Kingdom, Spain, France, and Poland (Grobelak et al., 2019; Wei et al., 2020). Although alternatives have been explored, wastewater treatment still generates sludge that has not been completely eliminated from the environment. Therefore, a key challenge in sewage sludge management remains determining safe disposal routes.

The main obstacle to sludge management is its complex composition and properties. Raw sludge from wastewater treatment plants varies significantly in composition, depending on the wastewater treatment technology and its input characteristics.

Treatment methods influence, among other things, the decomposition of organic matter, organic carbon content, and the degree of dewatering and drying. As a result, sludge exhibits diverse physical and chemical characteristics, consistency, toxicity, and resistance to substances (Cieślik et al., 2015; Kacprzak et al., 2017). The use of various sludge stabilization methods changes its chemical composition, improves its sanitary condition, and improves its physical properties (Grobelak et at., 2019). Stabilization of sewage sludge can be achieved by using biological, chemical or thermal processes that lead to changes in its physicochemical properties and biological composition.

In chemical stabilization, the most commonly used stabilizing agent is calcium oxide, which creates a mixture containing more dry matter than the sludge itself. The addition of calcium oxide (CaO) to the sludge causes alkalization, resulting in ammonia emissions and a reduction in nitrogen content (Yepez-Ceron et at., 2025). Calcium oxide can be used on both raw and dewatered sludge; however, for ecological reasons, it is recommended to stabilize and sanitize dewatered sludge (Zhou et al., 2025). The mixture created after the addition of CaO has favorable physical properties for transport, storage, and field application. However, due to its high calcium content, its use on soils requiring liming (Yepez-Ceron et at., 2025). Composting is a biological method for stabilizing and simultaneously recovering sewage sludge.

Composting can be used for raw, fermented, mixed, and dewatered sludge with varying degrees of stabilization (Skrzypczak et al., 2024). The composting process involves intensive biochemical transformations, primarily involving aerobic bacteria. These transformation processes include the mineralization and humification of organic matter. During this process, water and carbon dioxide are released, and the temperature of the composted sludge increases to 60–70 °C. As a result, the mass and volume of the sludge are reduced, and pathogenic microorganisms are neutralized. The final product is a relatively stable residue with a high humus content, which serves as a valuable organic fertilizer.

Sewage sludge is rich in a variety of compounds, including organic matter (OM), making it valuable in agriculture and other economic sectors (Gusiatin et al., 2017; Klik et al., 2021). Since 22.3% of soils in Europe alone are degraded and require remediation and restoration, the use of sewage sludge generated in wastewater treatment plants for agricultural purposes is the dominant recovery route, enabling the disposal of approximately 50% of this waste (Eurostat, 2020; Anielak and Kłeczek, 2022). Raw sewage sludge is always treated to improve its quality before being used in agriculture.

Sewage sludge may contain humic materials because, during municipal wastewater treatment, the mineralization of OM is accompanied or immediately followed by humification, meaning that sewage sludge is rich in intermediate decomposition products, primarily "raw" humus. For this reason, sewage sludge can be a rich source of humic substances (HS), which, after recovery, can also be used in fertilization and soil reclamation.

When considering the suitability of sewage sludge as a source of exogenous soil organic matter, it is important to assess not only the OM content but also the fractional composition, i.e., the relative amounts of humic substances. In soil, carbon fractions are dynamic indicators of soil health, ecological balance, and ecosystem resilience in the face of climate and land use changes. These indicators reflect the balance between carbon input and carbon transformation, as well as changes in soil activity and nutrient cycling.

The aim of this study was to assess the quality of organic matter in sewage sludge from municipal mechanical biological wastewater treatment plants. The assessment was based on determining the fractional composition of humic compounds and the quality parameters of extracted humic acids.

MATERIAL AND METHODS

The municipal sewage sludge from which the samples were taken for testing came from mechanical-biological sewage treatment plants of various capacities located in Poland and were characterized by varying degrees of processing. The following were assessed: unstabilized sludge (SS_{NS}), chemically stabilized sludge (SS_{Ca}), biologically stabilized sludge under aerobic conditions (SS_C), and sludge stored in lagoons (SS_S) (Table 1).

The basic physicochemical and chemical properties of the tested sewage sludge are presented in Table 2. Laboratory tests included determining the fractional composition of organic matter, isolating and purifying humic acids, and determining their elemental composition.

The fractional composition and separation of humic acids were determined using the Schnitzer method (Griffith and Schnitzer, 1975). The following were determined in the extracted humic acids: ash content – by burning the sample at 550 °C for 24 hours (PN-ISO 1171), elemental composition (C, H and N content – with a CHN Vario EL Cube analyzer from Elementar, O was calculated from the difference). Elemental composition results are presented in atomic percentages on an ashless mass. The functional group content (–COOH and –OH) was determined using the Dragonov and Kucharnka method (Dziadowiec and Gobet, 1999).

Table 1. Characteristics of sewage treatment plants and municipal sewage sludge (Żukowska et al., 2026)

Variant	City	Size of sewage treatment plant (PE – population equivalent)	Average daily flow [m³/d]	Degree of processing	Characteristics of the processing process
SS_{NS1}	Słupsk	200 000	19 647	Raw	Sewage sludge not stabilized
SS_{NS2}	Swarzewo	45 000	5 000		
SS_{Ca1}	Zamość	250 000	25 000	Chemically stabilized	Sewage sludge lime-stabilized
SS_{Ca2}	Sandomierz	29 601	7 500		
SS_{C1}	Tarnobrzeg	55 000	12 000	Biologically stabilized	Sewage sludge stabilized aerobically in the composting process
SS_{C2}	Stalowa Wola	88 240	6 419		
SS_{S1}	Kielce	289 000	51 000	Stored	Sewage sludge stabilized by storage in lagoons
SS_{S2}	Końskie	39 600	4 900		

RESULTS AND DISCUSSION

Due to the significant role of humic substances in shaping soil fertility and their resistance to chemical degradation, supplementing the negative organic matter balance in arable soils and enriching reclaimed soils/soilless formations with organic matter is necessary (Picocolo et al., 2025). Given the insufficient supply of organic fertilizers, the use of organic waste for this purpose could be of great importance for agricultural and environmental practices and may be one of the possible strategies for managing this waste. Within the organic waste category, a significant part is made up of municipal sewage sludge, which, due to its significant content of organic matter and fertilizing components, is traditionally considered a valuable fertilizer.

The organic matter content in sewage sludge varies widely and can range from 25% to 90%, depending on the quality of the treated wastewater and the stabilization technology (Lucia et al., 2025). Our research results confirmed the significant impact of sludge stabilization technology on the organic matter content (Żukowska et al., 2026). The TOC content ranged widely, from 480 $g·kg^{-1}$ in raw sludge, approximately 420 $g·kg^{-1}$ in composted sludge, to 234 $g·kg^{-1}$ in stored sludge (Table 2). When determining the possibility, dose and frequency of using sewage sludge to fertilize agricultural soils, it is extremely important to estimate the level of organic matter stabilization (Kulikowska, 2011). In addition to determining the organic matter content in sewage sludge, it is also important to determine the quality of organic compounds, as the quality of exogenous organic matter introduced into the soil determines the direction of transformation and the properties of new humic compounds formed in the soil (Acharya, 2025).

The chemical composition of raw sewage sludge indicates that it can provide additional organic matter for the soil and nutrients for crops (Pöykiö et al., 2019). Nitrogen compounds and polysaccharides are quite common in the organic matter composition of sewage sludge, which allows them to be treated as humic substances (Wilén, 2003). Studies have shown that organic matter delivered with sewage sludge to the soil can be easily decomposed due to its relatively low lignin and cellulose content, thus improving the biological, chemical and physical properties of the soil (Rorat et al., 2019; Picariello et al., 2020). It is generally believed that the organic matter contained in sewage sludge has properties similar to soil humus, as it can be extracted with solvents used to extract soil humus. However, studies of the quality of organic matter reveal significant differences between their quality and the quality of soil humus compounds (Michalska et al., 2022).

Humic substances (HS), including humin acids (HA) and fulvic acids (FA), are the main organic components of sewage sludge (Wilén, 2003). They are considered important indicators of the biological maturity and chemical stability of the sludge (Li, 2013). During the stabilization process, unstable organic compounds are biologically converted into more stable forms of HS through humification (Watteau, 2011). Quantification of HS is widely used in assessing the quality of sewage sludge intended for agricultural use (El Fels, 2014). Analysis of the fractional composition of humic compounds in sewage sludge shows significant variation depending on the stabilization technology used.

The C content of humic acids (C–HAs), i.e. carbon compounds extractable with 0.5 M NaOH, ranged within wide limits, from 44.40 $g·kg^{-1}$ to

Table 2. Selected properties of sewage sludge (Żukowska et al., 2026)

Propertes	Unit	SS_{NS1}	SS_{NS2}	SS_{Ca1}	SS_{Ca2}	SS_{C1}	SS_{C1}	SS_{S1}	SS_{S2}
pH	in KCl	6.40	6.20	7.90	6.50	5.50	6.10	6.40	6.20
H	$cmol^{+}\cdot kg^{-1}$	7.25	7.25	1.80	1.80	5.98	3.38	2.25	2.80
S		26.16	24.07	19.92	19.63	22.09	18.03	14.42	10.22
T		33.41	31.32	21.72	21.43	28.07	21.41	16.67	13.02
V	%	78.30	76.85	91.71	91.60	78.70	84.21	86.50	78.49
TOC	$g\cdot kg^{-1}$	462.00	480.00	336.00	342.00	414.00	429.00	234.00	330.00
TN		40.25	46.72	23.80	30.52	36.68	35.56	11.55	17.78
C/N	-	11.48	10.27	14.12	11.21	11.29	11.81	20.26	18.56
Cu	$mg\cdot kg^{-1}$	163.00	178.00	77.80	49.70	130.00	164.00	89.40	141.00
Zn		676.00	625.00	672.00	425.00	686.00	825.00	636.00	459.00
Pb		59.30	28.10	28.40	30.50	68.30	39.30	49.40	79.80
Cd		1.70	1.70	1.20	0.80	2.20	2.80	2.10	2.00

123.36 $g\cdot kg^{-1}$ (Table 3). A reliable assessment of the fractional composition of humus compounds is not the total content of individual fractions, but their share in the total pool of organic carbon (% TOC). The obtained results showed that the share of C–HAs in the TOC content of the tested sediments was very small and ranged from 16.16% TOC (SS_{S2}) to approximately 29.80% TOC (SS_{C1}) (Table 3).

In raw sludge, the average HAs content was 103.79 $g\cdot kg^{-1}$, which constituted 22.03% TOC. Literature data show that the HAs content in raw sludge varies within wide limits and depends on the specificity of the treated wastewater and the course of the treatment process. Similar C-HAs concentrations in unstabilized sewage sludge were obtained by Kulikowska et al., (2019), while in the study by Ayuso et al., (1996), the C–HAs concentration was approximately 56 $g\cdot kg^{-1}$, and in the study by Réveillé et al., (2003), approximately 160 $g\cdot kg^{-1}$. The HA_s content in lime-stabilized sludge was similar to that in raw sludge. An increase in the content of the described compounds was observed in composted sludge. Their share averaged approximately 29% TOC (Table 3).

Generally, in relation to soil organic matter, the lower proportion of humus compounds released from the soil by alkaline solutions, the more stable the organic matter. However, such a low proportion of humus compounds released by 0.5 $mol\cdot dm^{-3}$ NaOH from sewage sludge (for comparison, in mineral soils, these compounds account for approximately 40–60% of TOC) may indicate that the organic matter contained in sewage sludge is a difficult-to-access source of nutrients and energy for soil microorganisms involved in the transformation of soil organic matter. A single introduction of high doses of sewage sludge into the soil may disturb the soil homeostasis and influence the direction of transformation of the organic matter in soils fertilized/reclaimed with sewage sludge.

Ying and Youcai (2011) showed that sewage sludge storage is a stabilization process in which humification also occurs, because they noted an increase in the C–HAs content in the stored sewage sludge in proportion to the storage time. In their own studies, they demonstrated that the C–HAs content in the organic matter composition of stored sewage sludge was 17.56% TOC (on average), which was lower compared to its content in the organic matter composition of raw sludge. The decrease in the C–HAs content is attributed to the long storage period and the leaching of water-soluble humic substances.

Aerobic stabilization of sewage sludge in the composting process is commonly used to process organic matter contained in sludge (Silva et al., 2022). During composting, the organic matter of sewage sludge is transformed by microorganisms, mainly into humic substances (Guo et al., 2019, Zhao et al., 2022). The obtained results showed that the share of C–HAs in composted sewage sludge was higher compared to its share in raw sewage sludge and ranged from 28.5–29.79% TOC (Table 3). In previous studies, the share of humic acids in sewage sludge compost without additives was 24.12% TOC (Myszura 2024). The obtained results are difficult to directly relate to literature data, because most of the results were obtained in model

Table 3. Content of humin acids and humins

Variant	Humin acids (HAs)		Humins (C-NH)	
	$g \cdot kg^{-1}$	% TOC	$g \cdot kg^{-1}$	% TOC
SS_{NS1}	100.00	21.65	362.00	78.35
SS_{NS2}	107.58	22.41	372.42	77.59
SS_{Ca1}	75.75	22.54	260.25	77.46
SS_{Ca2}	93.77	27.42	248.23	72.58
SS_{C1}	123.36	29.80	290.64	70.20
SS_{C2}	121.02	28.21	307.98	71.79
SS_{S1}	44.40	18.97	189.60	81.03
SS_{S2}	53.32	16.16	276.68	83.84
Average	89.90	23.40	288.48	76.61

experiments and under conditions of co-composting of sewage sludge with structural materials such as straw (Kujawa et al., 2014), tree bark (Kulikowska et al., 2021), biochar (Zhang et al., 2015), ash (Klimek et al., 2011). Nevertheless, all studies showed an increase in the proportion of C–HAs in mature composts compared to their content in the starting material. The concentration of humic substances increases markedly during the composting of sewage sludge. During the subsequent cooling and maturation phase, the degradation of complex organic compounds, including proteins, hemicellulose, cellulose, and lignin, takes place. This process results in the formation of low–molecular-weight compounds such as carbohydrates, amino acids, simple peptides, and phenolic substances of low structural complexity. These compounds may be further metabolized by microorganisms as sources of carbon and energy or serve as precursors contributing to humus formation. Lignin degradation products, such as phenols, quinones, and more complex compounds, are the main precursors for the formation of humic substances through polymerization and condensation of N compounds.

The indicator characterizing the quality of humic compounds is the share of humic and fulvic acids among the compounds secreted by alkaline solutions and the value of the carbon ratio of humic acids (C–HA) to carbon of fulvic acids (C–FA).

Among the humic compounds extracted with 0.5 $mol \cdot dm^{-3}$ NaOH from most sewage sludge, the content of fulvic acids exceeded the content of humic acids, and as a consequence the calculated C–HA:C–FA ratio was below 1 (Table 4).

Assessing the effect of sludge processing on the content of humic acids and the C–HA:C–FA ratio, it can be concluded that raw sewage sludge (SS_{NS1} and SS_{NS2}) was characterized by the lowest C–HA:C–FA ratio values (from approximately 0.5 to approximately 0.6). This ratio was slightly higher in stored sludge (approx. 0.85). It should be emphasized that, compared to raw sludge, both the C–HA and C–FA content decreased, and the increase in the C–HA:C–FA value was most likely due to the leaching of water-soluble fulvic acids during storage. In lime-stabilized (SS_{Ca1} and SS_{Ca2}) and composted sludge, the content of humic and fulvic acids was similar, and the C–HA:C–FA ratio was approximately 1. Regarding mineral soils, a C–HA:C–FA ratio close to 1 is typical for soils rich in very good quality humus (e.g., chernozems, rendzinas, black earths) (Mocek, 2015). The addition of CaO influences the alkalization of sludge, which promotes the condensation and polymerization of humus precursors and consequently leads to an increase in the content of humic acids relative to fulvic acids (Kacprzak et al., 2025). Literature data indicate large fluctuations in the content of humic fractions, the trends clearly indicate that the content of fulvic acids decreases and humic acids increases during composting (Zbytniewski et al., 2025), which was also observed in our own research (Table 4).

The discussed changes in the share of carbon compounds released by 0.5 $mol \cdot dm^{-3}$ NaOH were accompanied by changes in the share of compounds constituting the extraction residue, i.e., humin. The share of C_{NH} was very high, on average 70–83% TOC (Table 3). The largest share of the described compounds was found in the organic matter of composted sludge (SS_{C1}) – 85.10% TOC (Table 3). With respect to mineral soils, it is assumed that the extraction residue consists of humic compounds permanently bound to the mineral part of the soil. The obtained results indicate that C_{NH} in sewage sludge is not entirely composed of humic compounds. Peña-Méndez et al. (2005) found that non-extractable humic compounds include polymeric structures of plant cutins, suberins, or unsaturated lipids. The presence of not fully humified organic substances in sewage sludge is confirmed by the calculated values of the degree of humification (Table 4). The percentage share of humic acid carbon in the total carbon pool is taken as the degree of humification of the organic substance (Griszina, 1986). The determined degrees of humification of organic matter in the tested sewage sludge (C–HA in %TOC) ranged from 7.49 to 15.48 (Table 4). According to the criteria proposed by Orlov (after Griszina 1986), humification degrees in the range of 10–20 is characteristic of weakly humified organic matter, and below 10% for very weakly humified. The lowest values of the degree of humification of organic matter (approx. 7–8%) were characterized by raw and stored sewage sludge. Assessing the effect of sewage sludge processing on the degree of humification of organic matter, it was found that, compared to raw sludge with a very low degree of humification, the lime-stabilized (11.35 to 13.85) and composted (14.72 and 15.48) sewage sludge had a higher degree of humification of organic matter, which allows for classifying their organic matter as poorly humified.

Humic acids (HA) are formed by the hydrolysis of organic residues entering wastewater treatment plants along with raw sewage and after secondary and tertiary treatment. To a lesser extent, their formation results from the decomposition of organic matter during biological wastewater treatment and sewage sludge management. Especially throughout thermal or alkaline pretreatment and stabilization processes (Yang and Li, 2016; Eom and Park, 2021; Khakbaz et al., 2021). Despite numerous studies, the final structure of HA has not yet been fully determined due to the high variability of their chemical composition (de Melo et al., 2016; Baveye and Wander, 2019). However, regardless of the source of their formation, the average elemental composition of HA remains relatively constant. Generally speaking, the main elements determining their structure are carbon, oxygen, hydrogen, nitrogen and, to a lesser extent, sulfur (de Melo et al., 2016; Nardi et al., 2021).

In order to thoroughly understand the properties of the organic matter in sewage sludge, substances were extracted from it that behaved like soil humic acids in solvents, and their properties were compared to the properties of humic acids from natural (podzolic) soil. For the comparative analysis (based on the conducted research), the following elemental composition of humic acids extracted from podzolic soil was adopted: 31.98% C; 45.78% H; 2.46% N; and 19.78% O (Żukowska, 2013).

The obtained results showed that, regardless of the sewage sludge stabilization method, the elemental composition of the extracted HAs was little different. At the same time, this composition was found to differ significantly from the elemental composition of humic acids extracted from agricultural soil. HAs extracted from sewage sludge were characterized by slightly lower carbon and oxygen content and higher hydrogen and nitrogen content (Table 5, Figure 1).

In humic acid preparations extracted from sewage sludge, the carbon content ranged from approximately 30 to 32%, hydrogen from

Table 4. Content of humic and fulvic acid

Variant	Humic acid (C-HA)		Fulvic acid (C-FA)		Ratio C–HA:C–FA
	$g \cdot kg^{-1}$	% TOC	$g \cdot kg^{-1}$	% TOC	
SS_{NS1}	34.60	7.49	65.40	14.16	0.53
SS_{NS2}	42.18	8.79	65.40	13.63	0.64
SS_{Ca1}	38.15	11.35	37.60	11.19	1.01
SS_{Ca2}	47.37	13.85	46.40	13.57	1.02
SS_{C1}	64.08	15.48	59.28	14.32	1.08
SS_{C2}	63.17	14.72	57.85	13.48	1.09
SS_{S1}	20.40	8.72	24.00	10.26	0.85
SS_{S2}	24.60	7.45	28.72	8.70	0.86
Average	41.82	9.72	46.33	12.03	0.81

approximately 47 to 51%, nitrogen from approximately 4 to 4.8%, and oxygen from approximately 14 to 17%. Similar results regarding the elemental composition of humic acids extracted from sewage sludge were obtained by other authors (Żukowska and Flis-Bujak, 2002; Reveillr et al., 2003; Li, 2013). The significantly higher nitrogen content in humic acids from sewage sludge, compared to soil humic acids, is particularly noteworthy. The cited authors believe this is due to the incorporation of degradation products of protein compounds present in sewage sludge into the humic acid molecule from sewage sludge.

Differences in the elemental composition of humic acids extracted from sewage sludge (compared to soil humic acids) were reflected in the atomic ratios of H/C, O/C, N/C, and O/H (Table 6). The atomic ratio of H/C in humic acids extracted from sewage sludge ranged from approximately 1.4 to approximately 1.6, which was higher than that of soil humic acids. According to Van Krevelen (1950), the atomic ratio of H/C is inversely proportional to the aromaticity of humic compounds. H/C ratios of approximately 0.3 are characteristic of systems with highly condensed aromatic rings, values of approximately 0.7 for single-ring aromatic hydrocarbons, values between 0.7 and 1.5 correspond to aromatic systems conjugated with an aliphatic chain of up to 10 carbon atoms, and values of 1.5–1.7 correspond to alicyclic hydrocarbons, while values of approximately 2 are characteristic of paraffins. Using this thesis, it can be concluded that sewage sludge humic acids, compared to soil humic acids, are characterized by a higher proportion of aliphatic structures and a lower degree of aromatic nucleus condensation.

Figure 2 presents diagrams of the H/C and O/C atomic ratios of humic acids from extracted sewage sludge (and, for comparison, from soil). Presenting the elemental composition of humic acids in this form allows for the assessment of

Table 5. Elemental composition of humic acids separated from sewage sludge

Variant	C	H	N	O+S
	Atomic % on an ashless mass			
SS_{NS1}	30.20	48.24	4.37	17.19
SS_{NS2}	31.13	49.73	4.85	14.29
SS_{Ca1}	32.06	47.91	3.79	16.24
SS_{Ca2}	29.87	49.74	4.74	15.77
SS_{C1}	30.16	50.01	4.06	15.23
SS_{C2}	31.57	47.97	3.14	17.32
SS_{S1}	32.34	47.33	4.29	16.04
SS_{S2}	32.52	48.57	4.13	14.78
Average	31.23	48.69	4.17	15.84

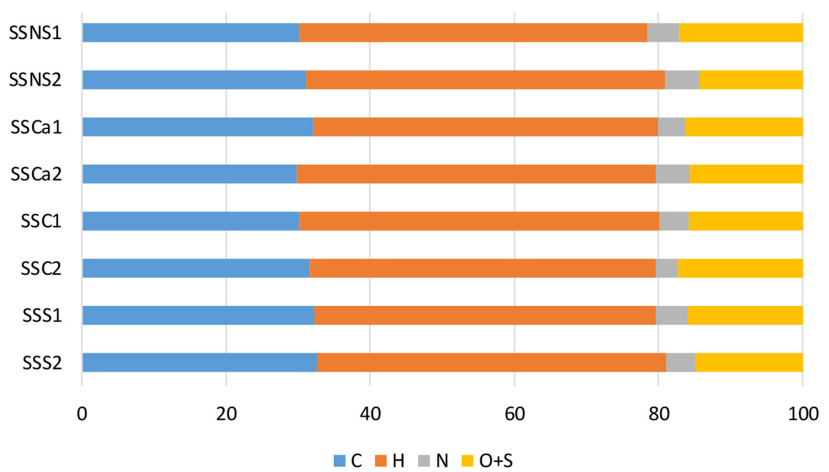

Figure 1. Elemental composition of humic acids separated from sewage sludge

Table 6. Atomic ratio of humic acids separated from sewage sludge

Variant	H/C	O/C	N/C	O/H	Ω
SS_{NS1}	1.60	0.54	0.14	0.36	-0.02
SS_{NS2}	1.60	0.46	0.16	0.29	-0.21
SS_{Ca1}	1.49	0.51	0.12	0.34	-0.13
SS_{Ca2}	1.67	0.52	0.16	0.31	-0.14
SS_{C1}	1.66	0.50	0.13	0.30	-0.24
SS_{C2}	1.52	0.55	0.10	0.36	-0.12
SS_{S1}	1.46	0.50	0.13	0.34	-0.07
SS_{S2}	1.49	0.45	0.13	0.30	-0.20
Average	1.56	0.50	0.13	0.33	-0.14

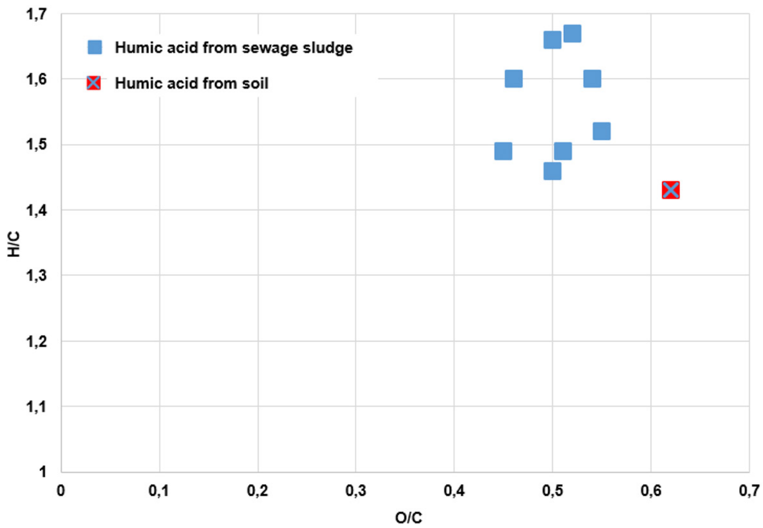

Figure 2. Diagram of the H/C and O/C atomic ratios of humic acids extracted from sewage sludge

differences in their hydrogenation, hydration, oxidation, carboxylation, and methylation (Dębska et al., 2010; Weber et al., 2018).

As can be seen from the diagram, HA extracted from sewage sludge occupy similar positions on the diagram, indicating a very high degree of similarity in their structure. At the same time, compared to humic acids extracted from soil, acids from sewage sludge are more hydrogenated.

The consequence of the higher nitrogen content in HA extracted from sewage sludge, compared to soil HA, were higher N/C ratio values, which indicates a lower degree of maturity of these HA. Changes in the elemental composition of the tested HA, particularly higher hydrogen and nitrogen contents, were reflected in the values of the determined internal oxidation state. The degree of internal oxidation of the tested HA ranged within very wide limits – from -0.02 (SS_{NS1}) to -0.24 (SS_{C1}). This significant variation in the assessed indicator could have been influenced by varying sludge management within the wastewater treatment plant, related to oxygen access and hydration. It should be emphasized that the determined internal oxidation degrees of HA extracted from the tested sludges were significantly lower compared to the internal oxidation degrees of HA extracted from podzolic soil.

CONCLUSIONS

The key role of humic substances in shaping soil fertility and protecting it from degradation necessitates supplementing the organic matter balance. An alternative to the insufficient supply of natural fertilizers may be the use of sewage sludge to enrich agricultural land and reclaimed areas with organic matter. Stabilization methods have a significant impact on the fertilization potential of sewage sludge. The results showed that:

- TOC content in sewage sludge varied within wide limits: from 234 g·kg^{-1} to 480 g·kg^{-1} and depended on the origin and degree of sludge processing: stabilization of sewage sludge with lime and composted had a positive effect on TOC content, in stored sewage sludge, compared to raw sludge, the TOC content was lower,
- the quality of the organic matter of the tested sewage sludges, assessed on the basis of the fractional composition, differed significantly from the quality of the soil organic matter, which was manifested by: a significantly lower share of extractable humic compounds and a significantly higher share of humins, C–HA:C–FA had values of 0.5–0.7 in raw sludge, and approx. 1 in lime-stabilized and composted sludge; the degree of humification of the organic matter of the sewage sludge ranged from 5.88% (stored sludge) to 15.48% (composted), which indicates a very low and poor degree of humification of their organic matter,
- regardless of the origin (type of treatment plant) of sewage sludge, the elemental composition of HA extracted from it was little differentiated and significantly different from the elemental composition of HA extracted from arable soils. Compared to HA from arable soils, humic acids from sewage sludge contained less C and O and more H and N, and the H/C atomic ratio was higher (compared to soil humic acids), which indicates that HA from sewage sludge were characterized by a higher proportion of aliphatic structures and a lower degree of aromatic nucleus condensation.

The most advantageous strategy for preparing municipal sewage sludge for use in agriculture and remediation is aerobic stabilization through composting. Composted sewage sludge was characterized by a relatively high carbon content, which is crucial for improving the organic matter balance in degraded soils. Composting was the only process among those analysed that increased the share of humic acids in the total carbon pool, thanks to which the composted sludge will provide the soil with more stable forms of humus, and not only easily decomposable organic matter. In contrast to raw sludge (susceptible to rapid mineralization) or stored sludge (depleted by the leaching of humic acids), the humus compounds of composted sewage sludge were characterized by optimal quality, which will favor carbon sequestration in the soil and ensure a lasting improvement of the physical and biological properties of the soil.

REFERENCES

1. Acharya B., Priya K., Singh S., Agrahari A., Kumar B., Kumar P., Arya V.P. (2025). Potential use of sewage sludge as fertilizer in organic farming. *Cleaner Waste Systems, 10*. https://doi.org/10.1016/j.clwas.2025.100245
2. Anielak A.M., Kłeczek A. (2022). Humic acids in the digested sludge and their properties. *Materials, 15*, 1475. https://doi.org/10.3390/ma15041475
3. Ayuso M., Hernandéz T., Garcia C., Pascual J.A. (1996). Stimulation of barley growth and nutrient absorption by humic substances originating from various organic materials, *Bioresour. Technol., 57*, 251–257. http://dx.doi.org/10.1016/S0960-8524(96)00064-8
4. Bauer T., Burgman L.E., Andreas L., Lagerkvist A. (2020). Effects of the different implementation of legislation relating to sewage sludge disposal in the EU. *Detritus, 10*, 92–99. https://doi.org/10.31025/2611-4135/2020.13944
5. Baveye P.C., Wander M. (2019). The (bio)chemistry of soil humus and humic substances: why is the “new view” still considered novel after more than 80 years? *Front. Environ. Sci., 7*, 27. https://doi.org/10.3389/fenvs.2019.00027
6. Cieślik M., Namieśnik J., Konieczka P. (2015). Review of sewage sludge management: standards, regulations and analytical methods. *J. Clean. Prod., 90*(2015), 1–15. https://doi.org/10.1016/j.jclepro.2014.11.031
7. de Melo B.A.G., Motta F.L., Santana M.H.A. (2016). Humic acids: structural properties and multiple functionalities for novel technological developments. *Mater. Sci. Eng., 62*, 967–974. https://doi.org/10.1016/j.msec.2015.12.001
8. Debska B., Banach-Szott M., Dziamski A., Gonet S.S. (2010). Chromatographic characteristics (HPLC, HPSEC) of humic acids of soil fertilised with various organic fertilisers. *Chemistry and Ecology, 26*(2), 49–57. https://doi.org/10.1080/02757540.2010.501027
9. Dziadowiec H., Gonet S.S. (1999). Przewodnik metodyczny do badań materii organicznej (in Polish). PTGleb Warszawa.
10. El Fels L., Mohamed Z., El Asli A., Hafidi M. (2014). Assessment of biotransformation of organic matter during co-composting of sewage sludge-lignocelullosic waste by chemical, FTIR analyses, and phytotoxicity tests. *Int. Biodeterior. Biodegrad. 87*, 128–137. https://doi.org/doi:10.1016/j.ibiod.2013.09.024
11. Eom H., Park C. (2021). Investigation of characteristics of effluent DON derived from conventional activated sludge (CAS) and predenitrification biological removal (BNR): in terms of proteins and humic substances. *Environ. Res., 196*. https://doi.org/10.1016/j.envres.2021.110912t

12. Eurostat. Sewage Sludge Production and Disposal from Urban Wastewater. https://ec.europa.eu/eurostat/web/environment/water (accessed 15 March 2026).
13. Griffith S.M., Schnitzer M. (1975). Analytical characteristics of humic and fulvic acids extracted from tropical volcanic soils. *Soil Science Society of America Journal, 39*(5), 861–867.
14. Griszina L.A. (1986). *Humus formation and humus state (Gumusoobrazovanie i gumusnoje sostojanie).* PCV. Iż. Moscov. Universiteta.
15. Grobelak A., Grosser A., Kacprzak M., Kamizela T. (2019). Sewage sludge processing and management in small and medium-sized municipal wastewater treatment plant-new technical solution. *Journal of Environmental Management, 234*, 90–96. https://doi.org/10.1016/j.jenvman.2018.12.111
16. Guo X., Liu H., Wu S. (2019). Humic substances developed during organic waste composting: Formation mechanisms, structural properties, and agronomic functions. *Science of The Total Environment, 662*, 501–510. https://doi.org/10.1016/j.scitotenv.2019.01.137
17. Gusiatin Z.M., Kulikowska D., Klik B. (2017). Suitability of humic substances recovered from sewage sludge to remedy soils from a former As mining area – a novel approach. *J. Hazar. Mater., 338*, 160–166. https://doi.org/10.1016/j.jhazmat.2017.05.019
18. Kacprzak M., Baran J., Fijalkowski K. (2025). Emerging sewage sludge treatment technologies for land carbon sequestration: a comprehensive review. *J Mater Cycles Waste Manag, 27*, 2866–2886. https://doi.org/10.1007/s10163-025-02369-3
19. Kacprzak M., Neczaj E., Fijałkowski K., Grobelak A., Grosser A., Worwag M., Rorat M., Brattebob H., Almåsc A., Singh B.R. (2017). Sewage sludge disposal strategies for sustainable development *Environ. Res., 156*(2017), 39–46. https://doi.org/10.1016/j.envres.2017.03.010
20. Khakbaz A., Goi D., Bravo C., Contin M. (2021). Thickening and storage of sewage sludge contribute to the degradation of LAS and EOX and the humification of organic matter. *Water., 13*, 933. https://doi.org/10.3390/w13070933
21. Klik B., Gusiatin Z.M., Kulikowska D. (2021). Quality of heavy metal-contaminated soil before and after column flushing with washing agents derived from municipal sewage sludge. *Sci. Rep., 11*, 15773. https://doi.org/10.1038/s41598-021-95441-5
22. Klimek A., Chachaj B., Kosakowski L. (2011). Influence of sewage sludge composts with straw or ash on oribatid mites (Acari, Oribatida) from pine forest liter in laboratory conditions. *Biological Lett., 48*(1), 19–27. https://doi.org/10.2478/v10120-011-0002-z
23. Kujawa S., Nowakowski K., Tomczak R.J., Dach J., Boniecki P., Weres J., Mueller W., Raba B., Piechota T., Rodríguez Carmona P.C. (2014). Neural image analysis for maturity classification of sewage sludge composted with maize straw. *Computers and Electronics in Agriculture, 109*, 302–310. https://doi.org/10.1016/j.compag.2014.08.014
24. Kulikowska D. (2011). *Przemiany materii organicznej w procesie kompostowania oraz wskaźniki dojrzałości kompostu* (in Polish). In: I. Wojnowska-Baryła (Ed.), Trendy w biotechnologii środowiskowej. Cz. 2 (110–132). Uniwersytet Warmińsko-Mazurski w Olsztynie.
25. Kulikowska D., Bernat K. (2021). Waste willow-bark from salicylate extraction successfully reused as an amendment for sewage sludge composting. *Sustainability, 13*, 6771. https://doi.org/10.3390/su13126771
26. Kulikowska D., Gusiatin Z.M., Bułkowska K., Kierklo K. (2015). Humic substances from sewage sludge compost as washing agent effectively remove Cu and Cd from soil. *Chemosphere, 136*, 42–49. https://doi.org/10.1016/j.chemosphere.2015.03
27. Kulikowska D., Klik B.K., Gusiatin Z.M., Jabłoński R. (2019). Sewage sludge can provide a washing agent for remediation of soil from a metallurgical area. *Catena, 173*, 22–28. https://doi.org/10.1016/j.catena.2018.09.049
28. Li H., Li Y., Li C. (2013). Characterization of humic acids and fulvic acids derived from sewage sludge. *Asian J. Chem. 25*, 10087–10091. https://doi.org/10.14233/ajchem.2013.15162
29. Lucia C., Badalucco L., Corsino S.F. (2025). Management and valorisation of sewage sludge to foster the circular economy in the agricultural sector. *Discov. Soil 2*, 80. https://doi.org/10.1007/s44378-025-00105-9
30. Michalska J., Turek-Szytow J., Dudło A., Surmacz-Górska J. (2022). Characterization of humic substances recovered from the sewage sludge and validity of their removal from this waste. *EFB Bioeconomy Journal, 2*. https://doi.org/10.1016/j.bioeco.2022.100026
31. Mocek A. (2014). Gleboznawstwo (in Polish). Wydawnictwo Naukowe PWN.
32. Myszura-Dymek M. (2024). Properties of organic matter in composts based on sewage sludge. *Journal of Ecological Engineering, 25*(7), 70–81. https://doi.org/10.12911/22998993/187964
33. Nardi S., Schiavon M., Francioso O. (2021). Chemical structure and biological activity of humic substances define their role as plant growth promoters. *Molecules, 26*, 2256. https://doi.org/10.3390/molecules26082256
34. Peña-Méndez E.M., Havel J., Patočka J. (2005). Humic substances – compounds of still unknown structure: applications in agriculture, industry, environment, and biomedicine. *J Appl Biomed. 3*(1), 13–24. https://doi.org/10.32725/jab.2005.002
35. Picariello E., Pucci L., Carotenuto M., Libralato G., Lofrano G., Baldantoni D. (2020). Compost and sewage sludge for the improvement of soil chemical and biological quality of Mediterranean

agroecosystems. *Sustainability, 13*, 26. https://doi.org/10.3390/su13010026

36. Piccolo A., Drosos M. (2025). The essential role of humified organic matter in preserving soil health. *Chem. Biol. Technol. Agric. 12*, 21. https://doi.org/10.1186/s40538-025-00730-0
37. PN-ISO 1171:2002 - wersja polska *Paliwa stałe.* Oznaczanie popiołu.
38. Pöykiö R., Watkins G., Dahl O. (2019). Characterization of municipal sewage sludge as a soil improver and a fertilizer product. *Ecol. Chem. Eng. S., 26*, 547–557. https://doi.org/10.1515/eces-2019-0040
39. Réveillé V., Mansuy L., Jardé E., Garnier-Sillam E. (2003). Characterisation of sewage sludge derived organic matter: lipids and humic acids, *Org. Geochem., 34*, 615–627. https://doi.org/10.1016/S0146-6380(02)00216-4
40. Rorat A., Courtois P., Vandenbulcke F., Lemiere S. (2019). *Sanitary and environmental aspects of sewage sludge management.* M.N.V. Prasad, P.J. de Campos Favas, S.V. Mohan (Eds.), Industrial and Municipal Sludge. Emerging Concerns and Scope for Resource Recovery, Butterworth-Heinemann, United States. 155–180.
41. Silva R.D.S., Jalal A., Nascimento R.E.N.D., Elias N.C., Kawakami K.C., Abreu-Junior C.H., Oliveira F.C., Jani A.D., He Z., Zhao F. (2022). Composted sewage sludge application reduces mineral fertilization requirements and improves soil fertility in sugarcane seedling nurseries. *Sustainability, 14*, 4684. https://doi.org/10.3390/su14084684
42. Skrzypczak D., Trzaska K., Gil F., Izydorczyk G., Chojnacka K. (2024). Guidelines for efficient nitrogen preservation in sewage sludge-based fertilizers. *Sci. Total Environ., 947*. https://doi.org/10.1016/j.scitotenv.2024.174460
43. Van Krevelen D.W. (1950). Graphical-statistical method for the study of structure and reaction processes of coal. *Fuel, 29*, 269–284.
44. Watteau F., Villemin G. (2011). Characterization of organic matter microstructure dynamics during co-composting of sewage sludge, barks and green waste. *Bioresour. Technol. 2*, 9313–9317. https://doi.org/10.1016/j.biortech.2011.07.022
45. Weber J., Chen Y., Jamroz E. (2018). Preface: humic substances in the environment. *J Soils Sediments, 18*, 2665–2667. https://doi.org/10.1007/s11368-018-2052-x
46. Wei L., Zhu F., Li Q., Xue C., Xia X., Yu H., Zhao Q., Jiang J., Bai S. (2020). Development, current state and future trends of sludge management in China: based on exploratory data and CO_2-equivaient emissions analysis *Environ. Int., 144*. https://doi.org/10.1016/j.envint.2020.106093
47. Wilén B.M., Jin B., Lant P. (2003). The influence of key chemical constituents in activated sludge on surface and flocculating properties. *Water Res., 37*, 2127–2139. https://doi.org/10.1016/S0043-1354(02)00629-2
48. Yang Y., Li H. 2016. Recovering humic substances from the dewatering effluent of thermally treated sludge and its performance as organic fertilizer. *Front Environ. Sci. Eng., 10*, 578–584. https://doi.org/10.1007/s11783-015-0827-5
49. Yepez-Ceron O.D., McCarthy P., Patterson S., Casey E., Dereli R.C. (2025). The role of calcium in anaerobic treatment: The good, the bad and the ugly. *Water Research X, 28*. https://doi.org/10.1016/j.wroa.2025.100381
50. Ying Z., Youcai Z. (2011). Stabilization process within a sewage sludge landfill determined through both particle size distribution and content of humic substances as well as by FT-IR analysis. *Waste Management & Research: The Journal for a Sustainable Circular Economy, 29*(4), 379–385. https://doi.org/10.1177/0734242X10384309
51. Zbytniewski Z., Buszewski B. (2005). Characterization of natural organic matter (NOM) derived from sewage sludge compost. Part 1: chemical and spectroscopic properties, *Bioresource Technology, 96*(4), 471–478. https://doi.org/10.1016/j.biortech.2004.05.018
52. Zhang J., Lü F., Zhang H., Shao L., Chen D., He P. (2015). Multiscale visualization of the structural and characteristic changes of sewage sludge biochar oriented towards potential agronomic and environmental implication. *Sci Rep., 5*. https://doi.org/10.1038/srep09406
53. Zhao B., Wang Y., Sun H., Xu Z. (2022). Analysis of humus formation and factors for driving the humification proces during composting of different agricultural wastes. *Front. Environ. Sci., 10*, 954158. https://doi.org/10.3389/fenvs.2022.954158
54. Zhou Y., Huang C., Wang Y., Zhao X., Luan H., Zhang S. (2025). Time-dependent effects of calcium oxide on urban sludge dewatering in temporary lagoons and its application in sustainable urban development. *Front. Earth Sci. 13*, 1605262. https://doi.org/10.3389/feart.2025.1605262
55. Żukowska G. (2013). *Wskaźniki jakościowe substancji organicznej gleb o zróżnicowanym nawożeniu i zmianowaniu* (in Polish). Monografie Komitetu Inżynierii Środowiska, Polska Akademia Nauk.
56. Żukowska G., Flis-Bujak M. (2002). Properties of humic acids of light soil fertilized with sewage sludge. *Polish Journal of Soil Science, 35*, 37–43. https://doi.org/
57. Żukowska G., Myszura-Dymek M., Bik-Małodzińska M. (2026). The content of mineral forms of nitrogen in light soil fertilized with various doses of sewage sludge. *Journal of Ecological Engineering. 27*(1), 29–39. https://doi.org/10.12911/22998993/208824