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Conversion of Sewage Sludge and Other Biodegradable Waste into High-Value Soil Amendment within a Circular Bioeconomy Perspective

Ewa Neczaj [1], Anna Grosser [1,*], Anna Grobelak [1], Piotr Celary [2] and Bal Ram Singh [3]

1 Faculty of Infrastructure and Environment, Czestochowa University of Technology, 42-200 Czestochowa, Poland; ewa.neczaj@pcz.pl (E.N.); anna.grobelak@pcz.pl (A.G.)
2 Central Laboratory for Measurements and Research, 44-335 Jastrzebie-Zdroj, Poland; pcelary@clpb.pl
3 Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life, 1433 Ås, Norway; balram.singh@nmbu.no
* Correspondence: anna.grosser@pcz.pl

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Abstract: Resource recovery from biodegradable waste is essential in order to reach the goals of zero circular economy waste generation and zero greenhouse gas emissions from the waste sector. Waste whose management is a real challenge is sewage sludge, mainly because of high concentrations of heavy metals. The aim of this study was to compare the effectiveness of material stabilization during aerobic stabilization of two feedstocks with sewage sludge obtained from different sources, namely, digestate from a municipal wastewater treatment plant and digestate from a co-digestion process. Moreover, the goal of the experiment was to assess the quality of compost in terms of remediation potential. The composting process was carried out for four different mixtures consisting of the mentioned digestates, municipal solid waste, and grass. A better composting efficiency with digestate from the co-digestion process was observed. In that case, a higher temperature in the thermophilic phase (>55 °C) and a higher organic matter loss ratio (60%) were obtained as compared to the process with digestate from wastewater treatment plant. Taking into account the fertilizing properties and the concentration of heavy metals, all obtained composts met the requirements set out in the Polish Regulation for organic fertilizers. Only the content of Helminth eggs in the composts produced with the digestate from the wastewater treatment plant was above the acceptable level. The research also proved that the produced composts can be used in the phytoremediation process of the degraded area. It was found that all composts caused a significant increase in fescue biomass. The highest yield was achieved for compost produced from a mixture with the addition of 30% sewage sludge from the co-digestion process.

Keywords: circular economy; bioeconomy; sewage sludge; organic waste; co-composting; bioremediation

1. Introduction

According to the circular economy (CE) strategy and the related action plan *Closing the loop* [1] and *New circular economy action plan: For a cleaner and more competitive Europe* [2], Europe should be transformed into a competitive resource-efficient bioeconomy with a very strong position within the waste economic sector. Among others, bioeconomy concepts assume sustainable organic waste management and their conversion into value-added products such as bio-based products, feed, food, and bioenergy. Increased resource recovery from biodegradable waste from the residential, industrial, and commercial sectors is essential in order to reach the CE goals of zero waste generation and zero greenhouse gas emissions from the waste sector.

The paradigm shift to resource recovery is also observed in the wastewater sector. Wastewater treatment plants (WWTPs), in addition to the production of excellent quality effluent, can become Water Resource Recovery Facilities acting as proactive resource producers (Figure 1). Sewage sludge (SS), the by-product of wastewater treatment processes, can be used for biogas generation in the anaerobic digestion (AD) process. In fact, its co-treatment in WWTPs with other biodegradable waste (e.g., fat wastes, organic fraction of municipal waste) in the co-digestion process has been increasing over the last few years [3,4]. Physical and chemical properties of the co-substrates added to AD bioreactors in WWTPs have a significant impact on the co-digestion process and the quality of digestate. Generally, during the co-digestion process, a higher biogas production as well as higher volatile solids degradation are observed [5]. As shown in the study conducted by Grosser [6], co-digestion of sewage sludge, grease trap sludge (GTS), and the organic fraction of municipal solid waste (OFMSW) resulted in an increase in methane yield of 82% and volatile solids removal of 29.5%, compared to the digestion of sewage sludge alone.

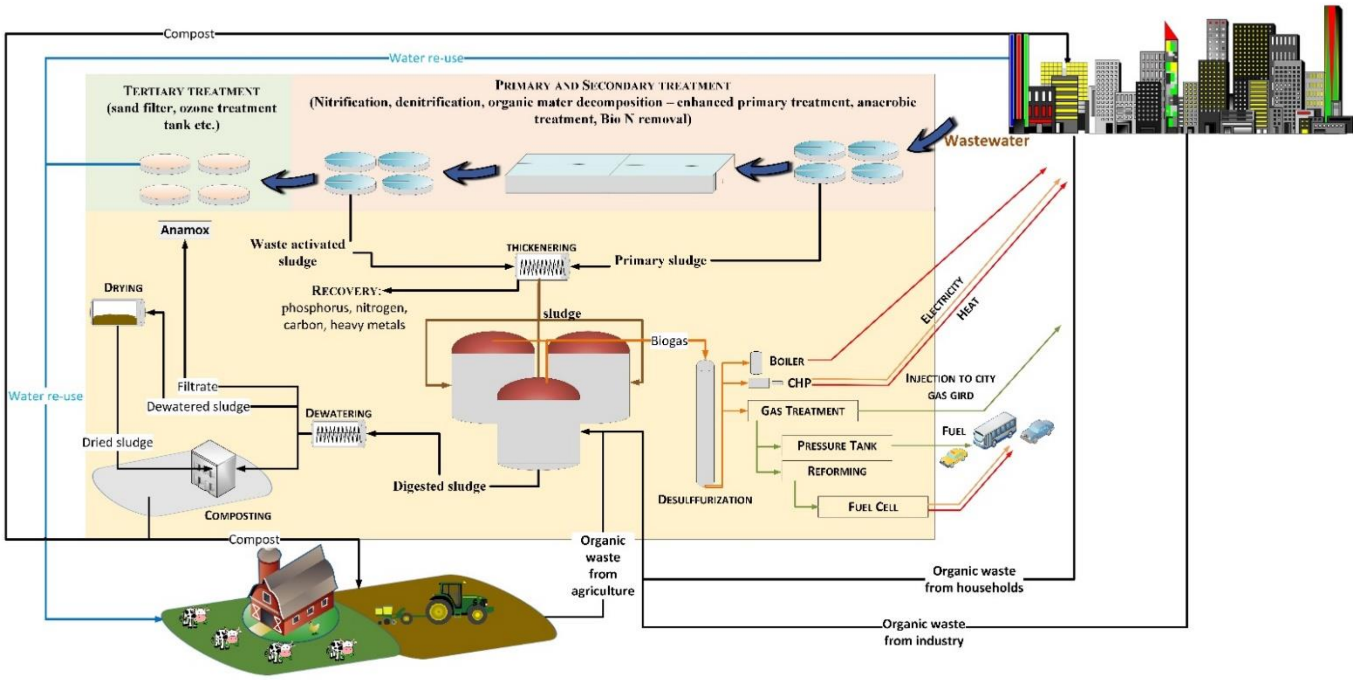

Figure 1. WWTP in the Circular Bioeconomy Concept.

A digestate can be used in agriculture as an organic fertilizer and soil amendment. Another option for digested sludge recovery is its co-treatment with other biodegradable waste and compost production [7]. In recent years, composting has gained acceptance as a very attractive biowaste treatment method owing to its low environmental impact, easy operational procedures, and low technology costs [8]. This is a particularly useful technology for sludge characterized by a high concentration of heavy metals, in which it is common to carry out its treatment with other biowastes, allowing for the dilution of the aforementioned contaminants.

Compost can be used for improving soil quality and its fertility; although the presence of heavy metals can restrict its use because of health or environmental concerns [9,10]. The production of compost from waste materials also involves the estimation of the ecotoxicity of the ultimately obtained products. Subsequently, compost is often used for reclamation of degraded soils in semi-arid areas and as fertilizer for agricultural purposes. It was found that singular applications of organic biosolids can enhance soil reclamation [11]. Urban and anthropogenic soils are usually devoid of vegetation cover and have a soil structure that also enhances the risk of secondary emissions, run-off, and eutrophication. Moreover, they are usually characterized by low moisture content, as well as a low concentration of nitrogen, phosphorus, and carbon [12]. Thus, the application of biosolids is justifiable. According to the Environmental Protection Agency (EPA) [13], "When properly treated and processed, sewage sludge becomes biosolids, which are nutrient-rich organic materials produced at wastewater treatment facilities." Biosolids contain macronutrients and organic carbon essential for plants and can be used both in agriculture and bioremediation [14,15]. Organic matter seems to be essential in the amendment of soil. Application of biosolids causes changes in the soil′s physical properties: it especially increases the soil′s capacity and ensures the retention of higher amounts of nutrients as well as water, which is extremely important in the case of barren, loose, and devastated soils. Kacprzak et al. [16] found that application of municipal solid waste and sewage sludge compost improved soil properties, especially N, P, and C content. Moreover, significant improvement of soil enzyme activity after soil amendment was also observed [17]. It was also found that organic matter from biosolids increases the number of microorganisms in the soil. Scherer et al. [18] observed an increased level of organic carbon of around 50% after repeated sewage sludge and compost application as well as a significant increase in the amount of microbial biomass carbon in soil samples.

Currently, it is a challenge to balance out waste management with the remediation of soils. Organic matter can be provided to soils from different sources, and it is very important to take into account the concentration of toxic elements in the compost or soil amendments that could pose a serious risk to the environment.

Soil amendments can vary extensively in their properties and chemical composition. Nevertheless, agricultural application of sewage sludge compost without a good stabilization process can have negative effects and, hence, compost quality is significantly related to its stability [19]. The impact of composts produced using sewage sludge on plant vegetation and soil properties is quite well known. However, there are no literature reports on the properties of sewage sludge composts derived via the co-digestion process. This is an important aspect because components acting as co-substrates added to the bioreactors during co-digestion can also affect the quality of composts and consequently affect plant growth. For example, the impact of long chain fatty acids (LCFAs) on the effectiveness of the composting process is still unknown, while LCFAs are well-known inhibitors of the co-digestion process with fat rich waste.

The novelty of the submitted manuscript is assessing how sources of sewage sludge (i.e., from anaerobic digestion or anaerobic co-digestion) as well as their share in the mixture affect the composting process and, subsequently, the compost quality in terms of its potential feasibility in the remediation process. The experiment was conducted over a period of several months and divided into two diverse stages. Stage 1 corresponded to composting of sewage sludge with municipal solids waste and grass. In the second stage of the research, composts obtained at stage 1 were used in the remediation process of degraded soil.

2. Materials and Methods

2.1. Substrates

The following raw materials were used in the laboratory trials: sewage sludge (SS1) from a municipal WWTP (dewatered digestate from an anaerobic digester), sewage sludge (SS2) from a co-digestion process (dewatered digestate from a laboratory reactor), OFMSW, willow stems acting as a bulking agent (BA), and grass (G) from green urban areas. The composition of the composting mixtures is presented in Table 1, while their characteristics are shown in Table 2. Moreover, in Table 3 LCFA content in the digested sludge used in the experiments is presented.

Table 1. Composition of the compost mixture (%, *w*/*w*).

Feedstock	SS		G	OFMSW	BA
	SS1	SS2			
R1	20%	-	60%	15%	5%
R2	-	20%	60%	15%	5%
R3	30%	-	50%	15%	5%
R4	-	30%	50%	15%	5%

SS1–digested sewage sludge from a local municipal wastewater treatment plant. SS2–digested sludge from a co-digestion process carried out at laboratory scale (anaerobic co-digestion of sewage sludge with OFMSW and grease trap sludge, described in detail by Grosser et al. [6]). OFMSW–organic fraction of municipal waste prepared according to the recipe described in studies by Grosser et al. [6]. G–grass from green urban areas. BA–bulking agent.

Table 2. Characteristics of raw materials.

Parameter		Substrate				
		G	SS1	SS2	BA	OFMSW
Moisture	(%)	73.30 ± 0.1	70.6 ± 1.54	82.70 ± 2.1	10.81 ± 0.02	56.58 ± 2.12
Volatile solids	(% TS)	78.80 ± 1.2	58.6 ± 0.21	53.20 ± 1.8	89.19 ± 1.29	54.22 ± 0.76
Total solids	(%)	26.70 ± 0.02	29.4 ± 1.23	17.30 ± 0.1	95.79 ± 0.5	43.42 ± 0.34
pH	(-)	7.56	7.8	7.20	6.81	7.60
P	(mg/g TS)	4.20 ± 2.30	3.11 ± 6.54	2.90 ± 3.1	bdl	5.20 ± 0.30
N	(mg/g TS)	13.80 ± 1.53	21.25 ± 2.45	25.30 ± 1.98	3.28 ± 0.1	12.76 ± 2.49
TC	(mg/g TS)	347.80 ± 1.76	336.0 ± 2.87	364.0 ± 0.68	452.6 ± 1.67	443.2 ± 0.11
Cr	(mg/kg TS)	3 ± 0.21	250 ± 37.5	220 ± 24.2	7 ± 0.42	45 ± 3.6
Cd	(mg/kg TS)	bdl	3 ± 0.24	2.8 ± 0.22	1.6 ± 0.14	9 ± 0.9
Ni	(mg/kg TS)	1.5 ± 0.15	135 ± 13.5	118 ± 8.26	bdl	49 ± 4.41
Pb	(mg/kg TS)	bdl	75 ± 6.75	72 ± 6.48	bdl	bdl
Hg	(mg/kg TS)	bdl	bdl	bdl	bdl	bdl

bdl—below detection limit.

Table 3. Long Chain Fatty Acid concentration in the digestated sludges (based on Grosser et al. [6]).

	Kind of LCFA	mg/g TS		mg/g TS	mg/g TS		mg/g TS		mg/g TS	mg/g TS
		av.	SD	max	min		av.	SD	max	min
AD of Ss	C10:0	0.04	0.01	0.06	0.03	AcD of Ss, GTS and OFMSW	0.03	0.01	0.05	0.01
	C12:0	0.10	0.03	0.12	0.06		0.09	0.03	0.16	0.03
	C14:0	0.50	0.11	0.64	0.36		1.56	0.47	2.98	0.71
	C16:0	6.58	1.38	8.42	5.12		21.79	4.26	32.82	14.26
	C18:1	2.47	0.90	3.68	1.55		11.30	2.27	15.92	5.68
	C18:0	0.55	0.02	0.57	0.52		0.61	0.08	0.77	0.53

The characteristics of two investigated degraded soils are presented in Table 4. The soil from the area of the zinc smelter was characterized by low moisture content, low pH and nutrients content, and a high concentration of cadmium (Cd), lead (Pb), and zinc (Zn). The second degraded soil was collected from the external dumping site of a brown coal opencast mine. This type of soil exhibits a poorly defined soil profile, with high pH and permeability, and a very low content of humic material and heavy metals. Both soil samples were collected from surface soil horizons (deep 20 cm).

Table 4. Selected chemical and physical parameters of the soils.

Parameter	Soil from the Area of the Zinc Smelter (Soil M) ± SD	Soil from Brown Coal Post-Mining Area (Soil B) ± SD
pH in H_2O	5.39 ± 0.01	8.12 ± 0.01
pH in 1 M KCl	5.03 ± 0.01	7.90 ± 0.02
CEC [cmol(+)/kg TS]	3.21 ± 0.13	24.93 ± 0.20
C total [g/kg TS]	13.51 ± 0.03	4.15 ± 0.05
N Kjeldhal [mg/kg TS]	599.00 ± 19.00	106.250 ± 9.00
P total [mg/kg TS]	179.00 ± 1.23	132.00 ± 1.00
Zn [mg/kg TS]	1751.00 ± 57.00	14.00 ± 1.05
Cd [mg/kg TS]	28.78 ± 1.23	0.29 ± 0.01
Pb [mg/kg TS]	1696.00 ± 87.00	1.20 ± 0.05

2.2. Experimental Procedure

The laboratory experiment was divided into two stages as shown in Figure 2 (composting, remediation). Insulated lid-covered 5 l composters equipped with a temperature control system, aeration, and leachate collecting system were filled with four different feedstock mixtures. Experiments were performed in triplicate.

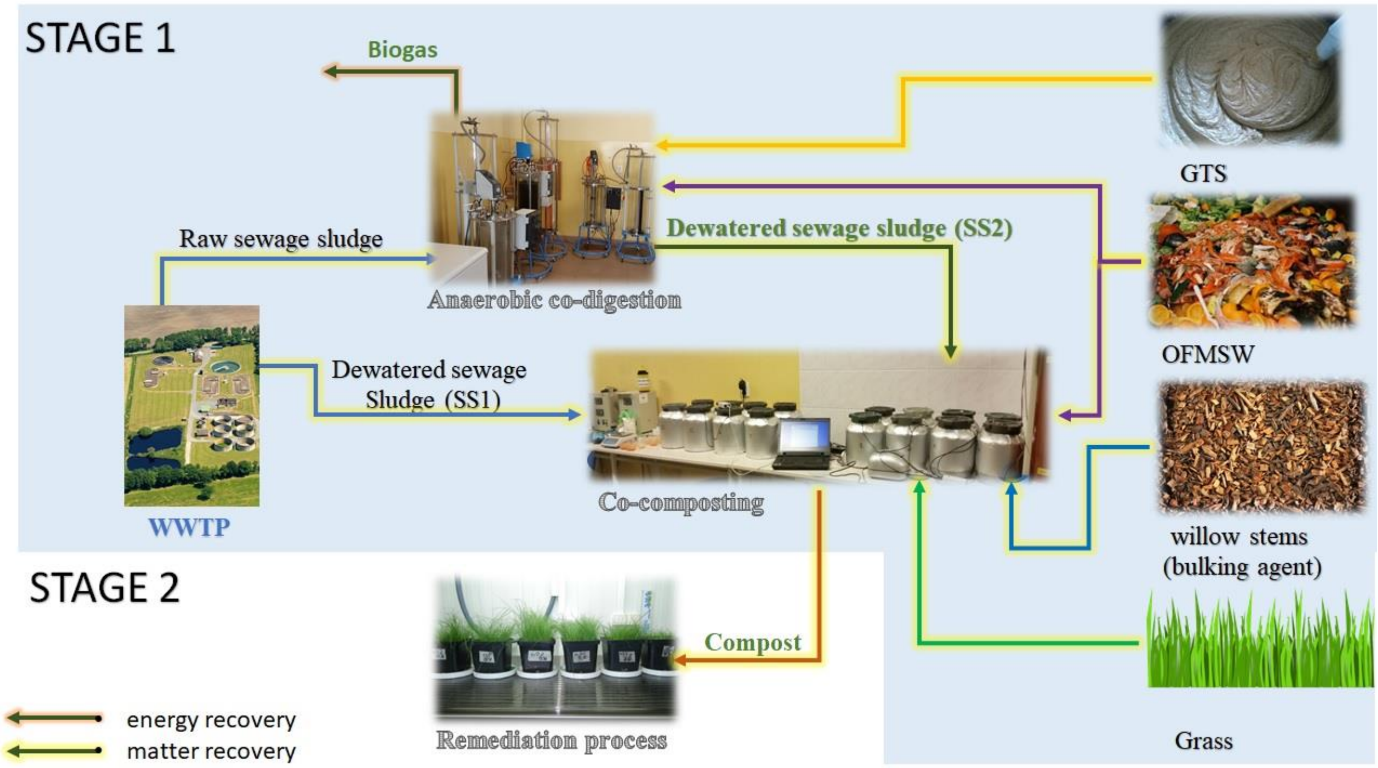

Figure 2. Experiment scheme (blue background: stage 1, composting process; white background: stage 2, remediation process).

The stabilization process in the bioreactors lasted for 4 weeks, while the maturation step was carried out in 5 l plastic bags for 6 weeks. The mature compost was then used for remediation of the degraded soils. A dose of 15 Mg TS/ha of compost was applied to two types of soil: soil M (the zinc smelter, Silesia region (50°30′27.1″ N 18°56′09″ E)) contaminated soil, and soil B (brown coal post-mining area, (51°15′54″ N 19°4′41″ E)). The dose of compost was calculated based on previous research (Placek et al., 2019).

Next, the fescue grass (*Festuca arundinacea* Schreb.) was sown in pots (4 g of grass seeds per each pot, 10 kg of soil for each pot). Pots with and without the compost were used as controls. The remediation experiment was conducted in a phytotron chamber for 4 months under the following conditions: artificial light (350 µmol/m^2 s^1), relative humidity of 70%, and daytime temperature of 20 °C, and nighttime temperature of 14 °C. After vegetation in a phytotron chamber, the generated biomass was weighed and analyzed.

2.3. Sample Analysis and Results Calculation

Total (TS) and volatile solids (VS), pH, total nitrogen (TN), and total carbon (TC) concentrations were analyzed according to the Standard Methods for the Examination of Water and Wastewater [20]. Nitrogen was extracted by the Kjeldahl digestion method using Büchi Distillation Unit K-335 equipment followed by distillation. Total carbon was measured using a TOC analyzer (Analytik Jena Multi N/C 2100). All raw materials, compost, and biomass were analyzed for the presence of heavy metals using an ICP-OES spectrometer (Thermo Electron IRIS Intrepid II), after prior digestion of the samples with a mixture of concentrated hydrochloric acid and nitric acid (aqua regia) in a microwave digester system (ETHOS Easy, Milestone). Salmonella was detected according to the standard method [21]. Helminth eggs were monitored in compliance with [22]. Additionally, loss of organic matter (OM) was calculated based on the formula shown below [23], where X1 (% TS) and X2 (% TS) are the initial and final ash, respectively.

$$\text{OM loss } (\%) = 100 - 100\frac{[\text{X1}(100 - \text{X2})]}{[\text{X2}(100 - \text{X1})]}. \quad (1)$$

In order to estimate the effect of organic amendments on heavy metal immobilization in degraded soil from the zinc smelter area, the immobilization factor was calculated.

2.4. Statistical Analysis

The statistical analysis was carried out using STATISTICA software (STATISTICA 8.1 StatSoft, Inc., TIBCO Software, Palo Alto, CA, USA). The following statistical methods were used for data analysis: one-way ANOVA, factorial ANOVA, and post hoc Tukey honest significant difference (HSD) in cases where analyses showed statistically significant differences ($p < 0.05$).

3. Results and Discussion

3.1. Monitoring of the Composting Process

3.1.1. Evaluation of the Thermal Profiles of the Composting Process

One of the most useful parameters of composting process monitoring is temperature because its variation is very well correlated with organic matter biodegradation. Figure 3 shows the temperature changes in the bioreactors. The temperature increased sharply during 6 days of composting. The thermophilic phase at reactors R1 and R3 was shorter than it was at R2 and R4, and, moreover, a lower temperature was achieved (<55 °C). It could indicate that the exothermic process was stronger in R2 and R4 because of the digestate properties from the co-digestion processes of sewage sludge and fat rich waste. As shown in Table 3, the concentrations of palmitic acid (C16:0) and oleic acid (C18:1) were nearly three and more than four times higher in the digestate from the co-digestion process than in digestate from the municipal WWTP. This indicated that both the percentage of sewage sludge in the mixtures and the type of sludge affected the temperature development during the aerobic stabilization process. Similar results were found by Gea et al. [24] during the composting of sewage sludge with animal fat mixtures. It was found that because of the longer thermophilic phase, the co-composting process of fats and sludge can be successfully carried out to obtain a sanitized and stabilized product. Moreover, the authors recommended addition of fat-enriched wastes to feedstock with low energy content in order to fulfill the international requirements for compost sanitation.

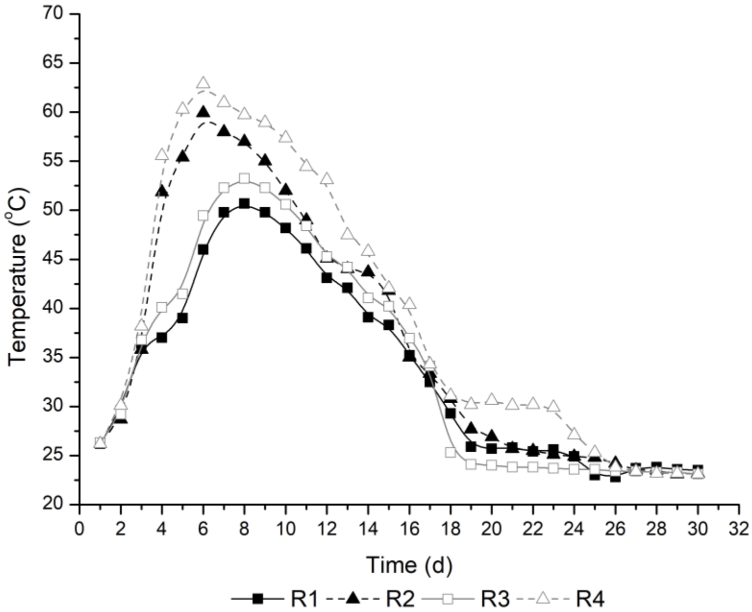

Figure 3. Thermal profile of the composting process in the bioreactors.

3.1.2. Evolution of the Physico-Chemical and Microbiological Parameters during the Composting Process

The characteristics of raw mixtures and compost are given in Table 5 The pH values of the mixtures were below 6.0 while in the mature composts, they were nearly neutral (between 6.74 and 6.92). The moisture levels in the reactors at the beginning of the stabilization process were between 72.53 and 77.61%. A moisture content of 50–60% is generally considered as an optimum for composting; however, some authors believe that it should be kept at 70% [25]. It is well known that too low moisture (<30%) inhibits bacterial activity, while too much water content in the waste at the beginning of the stabilization process results in slow decomposition, nutrient leaching, and odor generation. During the composting process, the moisture decreases owing to evaporation as a result of heat generation during the microbial decomposition of organic matter as well as the mechanical aeration process. In the presented research, the moisture decreased to values between 58.77 and 65.86% in the final products.

Table 5. Chemical characteristics of mixtures and compost (averages with the same letters are not significantly statistically different; Tukey's test was conducted separately for raw mixture (indicated as mix) and compost (indicated as comp.).

MIX	Moisture (%)	pH	TN (mg/g)	P (%P_2O_5)	K (% K_2O)	C/N	Ash (% TS)	VS (%TS)	OM Loss (%)
R1 mix	74.19 ± 1.05 ab	5.90	20.91 ± 0.32 a	0.20	0.15	20.93 c	15.54 ± 1.74	84.46 ± 1.74 ab	52.44
R1 comp.	58.77 ± 0.14 b	6.92	30.33 ± 0.32 c	0.55	0.25	12.24 a	27.90 ± 1.25 bc	72.10 ± 1.25	
R2 mix	73.21 ± 2.87 ab	5.72	24.36 ± 0.48 b	0.25	0.17	19.07 b	12.29 ± 1.73	87.71 ± 1.73 bc	58.42
R2 comp.	65.86 ± 0.03 d	6.98	27.63 ± 0.16 b	0.64	0.29	13.40 b	25.21 ± 2.01 ab	74.79 ± 2.01	
R3 mix	77.61 ± 0.32 b	5.60	24.17 ± 0.32 b	0.21	0.17	18.25 a	11.20 ± 2.66	88.80 ± 2.66 c	55.38
R3 comp.	63.86 ± 0.24 c	6.74	25.71 ± 1.29 a	0.59	0.28	12.51 b	22.03 ± 1.94 a	77.97 ± 1.94	
R4 mix	72.53 ± 2.09 a	5.59	25.01 ± 0.16 b	0.35	0.18	19.53 b	15.07 ± 0.89	84.93 ± 0.89	60.59
R4 comp.	57.47 ± 0.41 a	6.79	29.03 ± 0.16 bc	0.70	0.34	13.79 b	31.05 ± 2.85 c	68.95 ± 2.85 a	

bdt—below detection threshold.

The initial C/N ratio between 25 and 30 is considered to be optimal for composting [26]; however, it is possible to carry out the process at lower C/N with good efficiency [27,28]. In this study, C/N ratios in feedstock were below the values recommended by [26]. A significant decrease in those parameters in the composts at levels of 42, 30, 26, and 29% for R1, R2, R3, and R4, respectively, was observed. The final C/N ratios of 12.24 (R1), 13.40 (R2), 12.51 (R3), and 13.79 (R4) seemed to indicate properly produced composts. The C/N ratio is also considered as a good parameter of compost maturity [29]; however, in the literature, the optimal value of that ratio has been reported in very wide range that depends on feedstock composition [30,31]. For instance, according to Moldes et al. [32], the stability and maturity of compost is achieved when the C/N ratio decreases below 17, whereas Bernai et al. [33] suggested a ratio below 12. Various values of the C/N ratio given by different authors suggest a cautious approach to this parameter as an indicator of compost maturity. In this study, the statistical analyses showed that the content of sewage sludge in the feedstock as well as its source had an impact on the C/N ratio in the final products (Table S1, Supplementary Materials).

Because of the mineralization of organic matter during the process, ash content increased in all mixtures by 44, 51, 49, and 52% for R1, R2, R3, and R4, respectively. Organic loss was higher for R3 and R4, which indicated that digestate from the co-digestion process contained a larger amount of the easily biodegradable compounds.

Because composts are organic fertilizers, their composition was compared with the regulatory requirements specified in the Polish regulations [34]. According to this regulation, organic fertilizers should meet the following requirements: organic matter content no less than 30%; total phosphorus (expressed as P_2O_5) no less than 0.2% (m/m); total nitrogen no less than 0.3% (m/m); total potassium (expressed as K_2O) no less than 0.2% (m/m). The organic matter and NPK contents in mixtures and final products are presented in Figure 4. With respect to the mentioned parameters, all composts fulfilled the assumed concentration.

The ordinance also specifies the permissible concentration of heavy metals (Cr, Cd, Pb, Ni and Hg) and the content of microbial contamination in fertilizers. The presence of heavy metals in fertilizers may cause negative environmental effects. This risk increases when waste such as sewage sludge is used for the production of fertilizers. The concentration of heavy metals in all composts did not exceed a permissible level (Figure 5). The content of Hg was below the detection limit in both mixtures and composts. However, it should be noted that the content of Cr was relatively high in all composts, and in the case of R3 it was close to the acceptable limit. This was due to the high concentration of this metal in the sewage sludge. Studies conducted by Kominko et al. [9] on sewage sludge from the same WWTP also showed a high concentration of this metal (over 300 mg/kg TS). The heavy metals content in digestate is crucial for its use as a feedstock for the production of fertilizers or soil improvers.

If their content is lower than the legally required thresholds, biosolids can be directly used in agricultural land and reclamation sites (e.g., mining sites). However, this is not possible with most large WWTPs. Thus, co-composting of biosolids from this type of WWTP with biodegradable waste over the limit is a very rational method of resource recovery from the CE point of view. This is because it allows for use of the fertilization potential of sludge and, at the same time, reduces the concentration of heavy metals by diluting them by adding other substrates.

One of the main environmental problems associated with land application of composted sewage sludge and the organic fraction of municipal solid waste is the presence of microbiological contamination. Moreover, sewage sludge is a reservoir of antibiotic-resistant bacteria (ARB), and a further proliferation of antibiotic-resistant genes (ARGs) into the soil after fertilization is possible [35]. According to the Polish regulations, fertilizers cannot contain *Salmonella* (in 100 g) and eggs of *Ascaris lumbricoides*, *Trichocephalus trichiurus* and *Toxocara* sp. (in kg TS). In this study, *Salmonella* sp. was not detected in any final products. On the other hand, Helminth eggs were detected in R1 and R3 composts in the amounts of 2 eggs/kgTS and 3 eggs/kgTS, respectively. The results of the study showed that the inactivation of Helminth eggs was possible only if the temperature of the compost exceeded 55 °C for at least 5 days. For mixtures R1 and R3, an additional post-treatment method (e.g., liming) should be used to remove hazardous microorganisms.

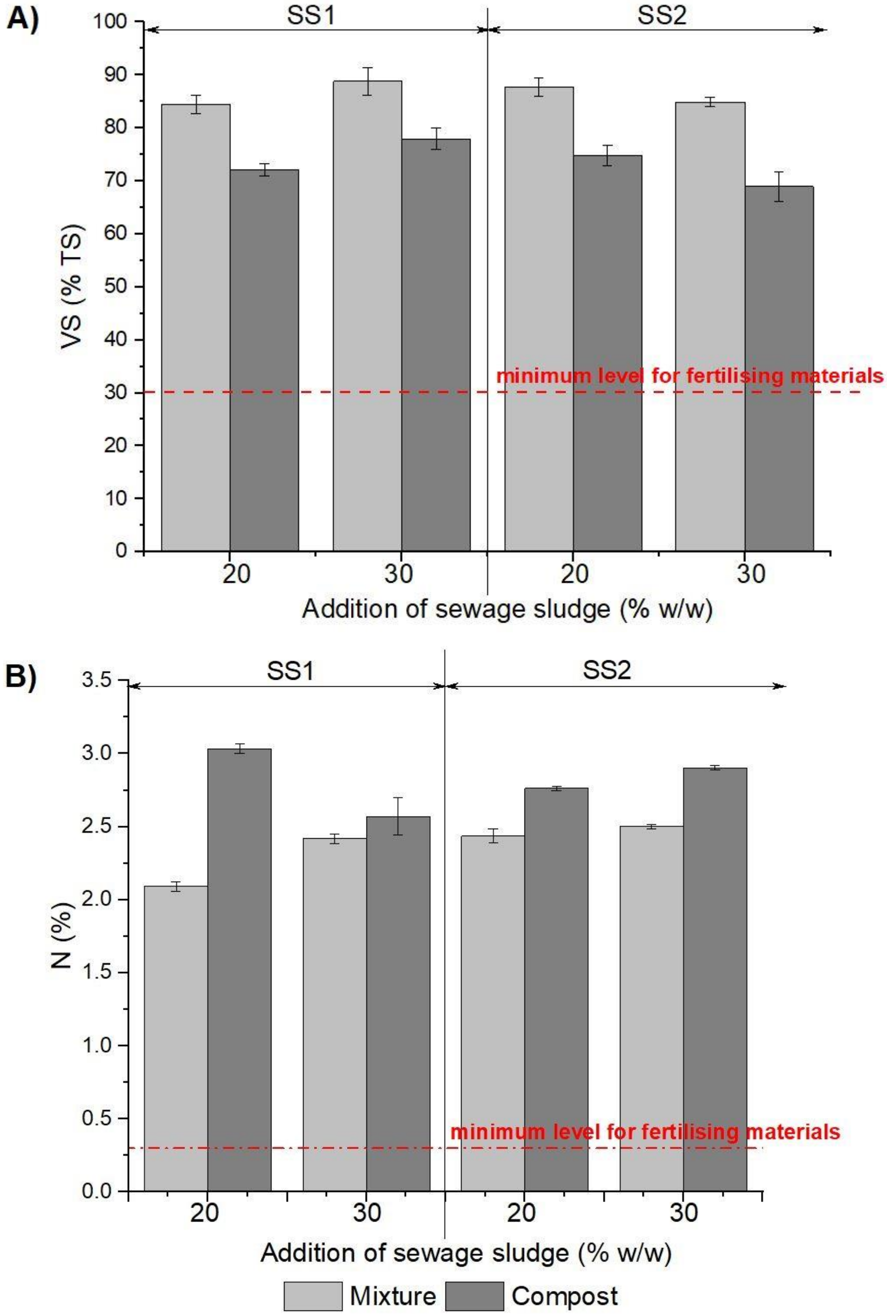

Figure 4. *Cont*.

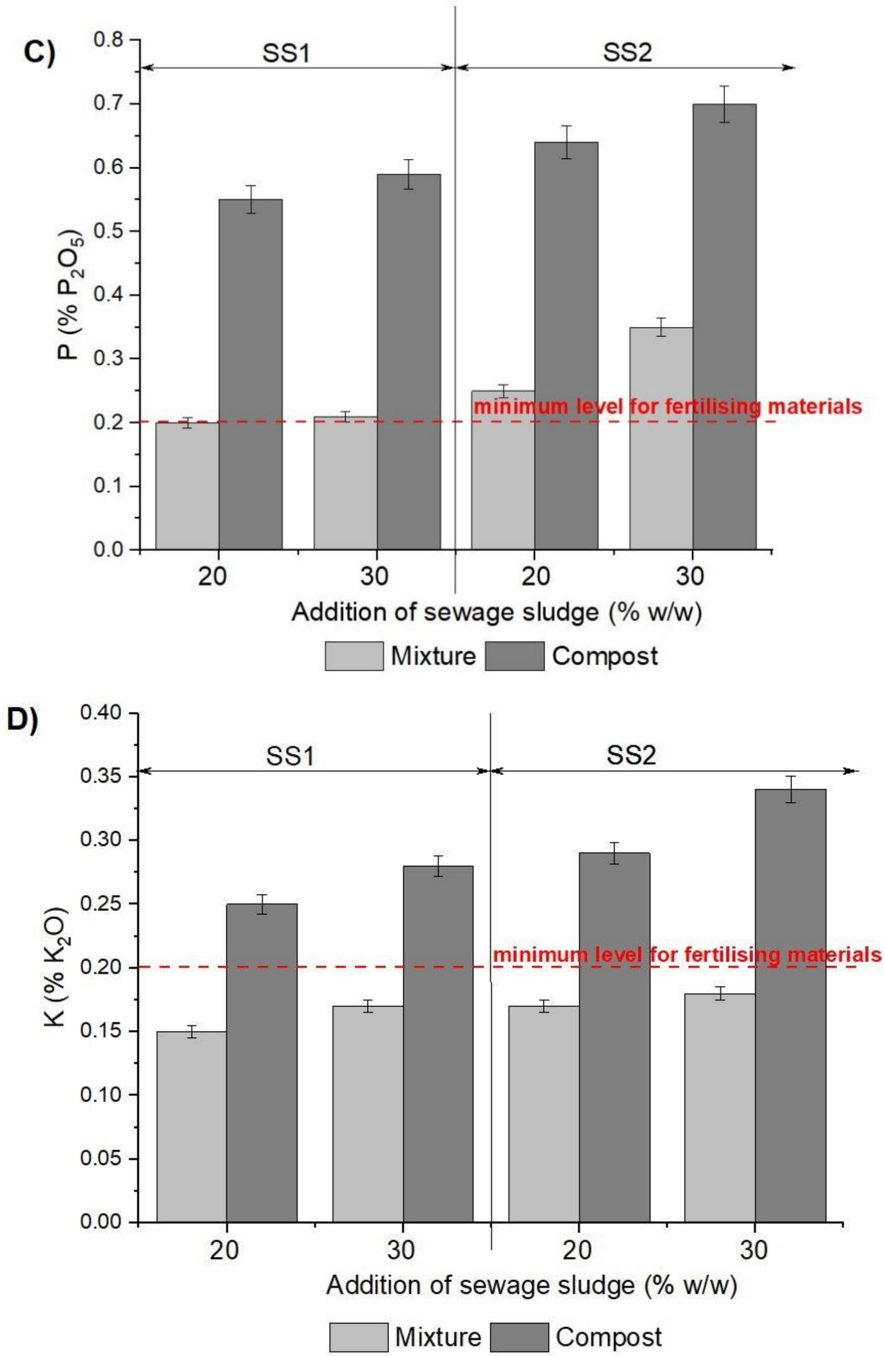

Figure 4. Comparison of organic matter and NPK in mixtures and compost with Polish Regulations requirements in red, where: (**A**) content of volatile solids (%) in the mixture and the compost; (**B**) nitrogen concentration (%) in the initial composting mixtures and final composts; (**C**) phosphorus concentration (%) in the feedstock and final composts; (**D**) the concentration of potassium (%) in the mixture and the compost.

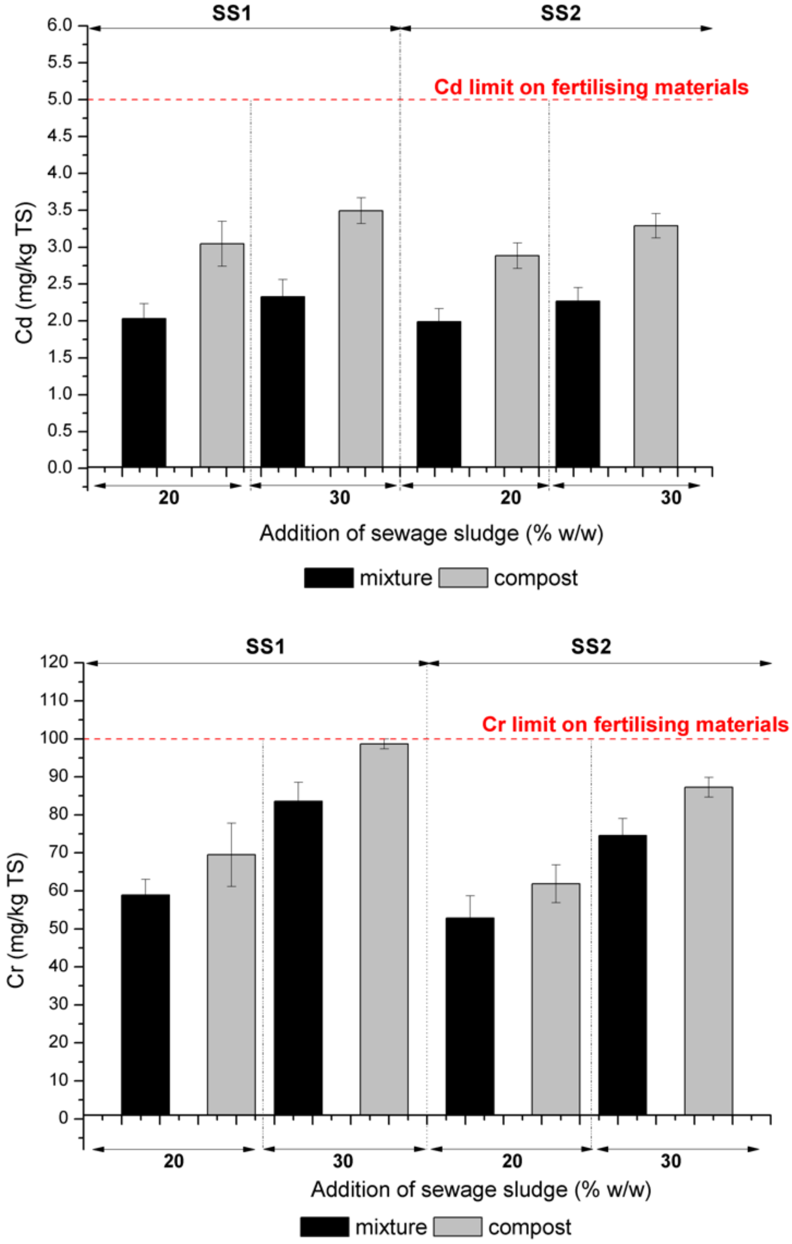

Figure 5. *Cont*.

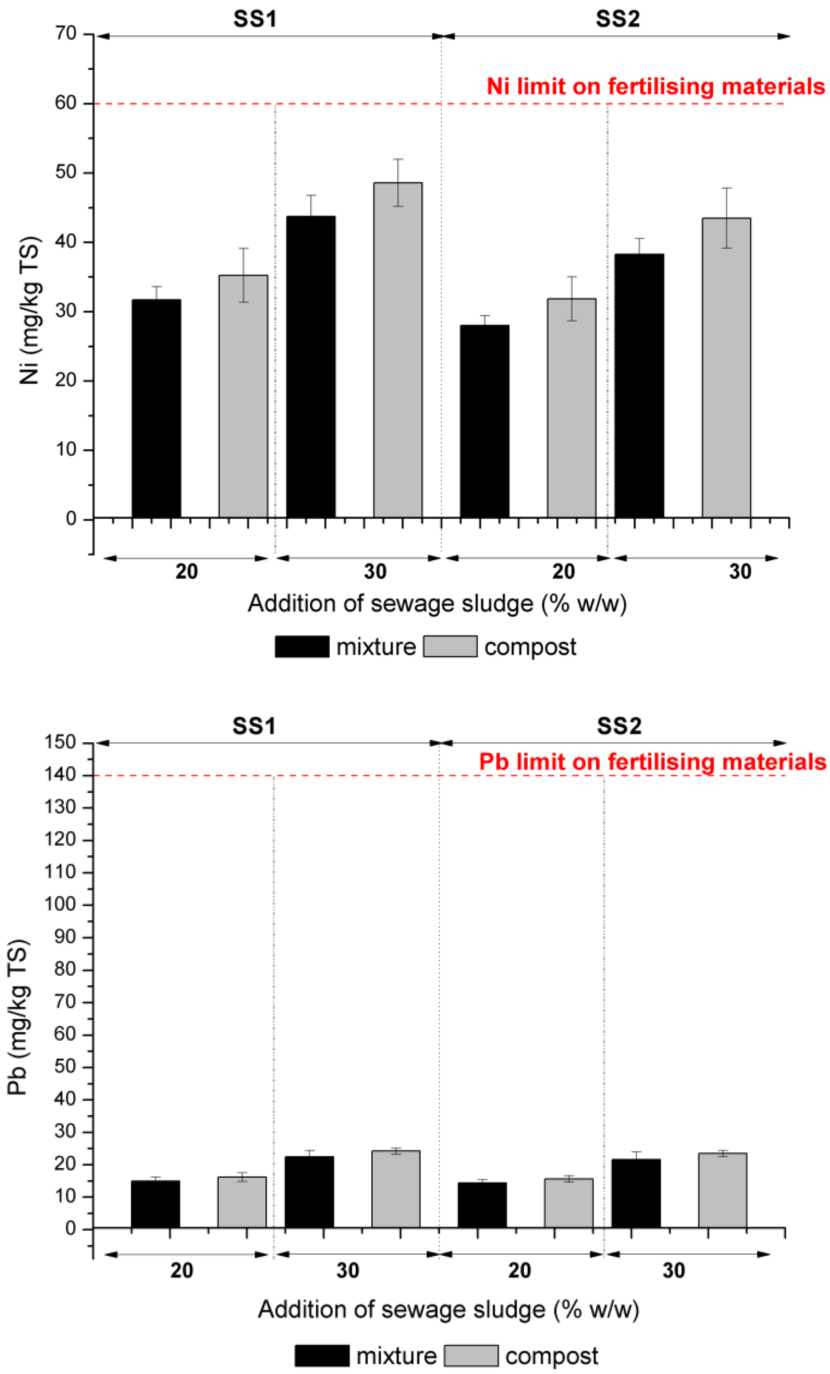

Figure 5. Comparison of total heavy metals content in mixtures and compost with Polish Regulations requirements in red.

3.2. The Impact of Composts on Remediation Process

In terms of biomass yield, it was found that all used composts caused a significant increase in fescue biomass (Figure 6). Moreover, with R4 compost application a much higher biomass generation was achieved, compared to R1, R2, and R3 compost application for both types of soil. In the control sample (cont M), very poor plant growth was observed, which was associated with very high contamination of soil from the zinc smelter area by heavy metals. Two main mechanisms were most likely responsible for this effect: first, the low nutrient content compared to the soils treated with composts and, second, the toxic effect of heavy metals [36]. The obtained plant cover stabilized heavy metals in the ground and prevented heavy metals from spreading as a result of secondary emissions from weathering [37]. Applied composts introduced macronutrients as well as organic matter into the soil, and thus enabled proper growth of plants. Moreover, the compost had biosorbent functions and absorbed heavy metals [38]. This function is linked with the presence of humus and inorganic compounds with a number of functional groups as well as microorganisms [26,39]. The higher growth of biomass with compost addition was also observed for soil B, where composts enriched the degraded soil in macronutrients and organic matter. The factorial analysis showed that the highest impacts on biomass growth came from the type of sewage sludge and the addition ratio (Table S2, Supplementary Materials). The highest yield was achieved for compost produced from mixture R4 (30% sewage sludge from the co-digestion process). As compared with control samples, it was almost 5-fold and 3-fold higher for soil M and soil B, respectively.

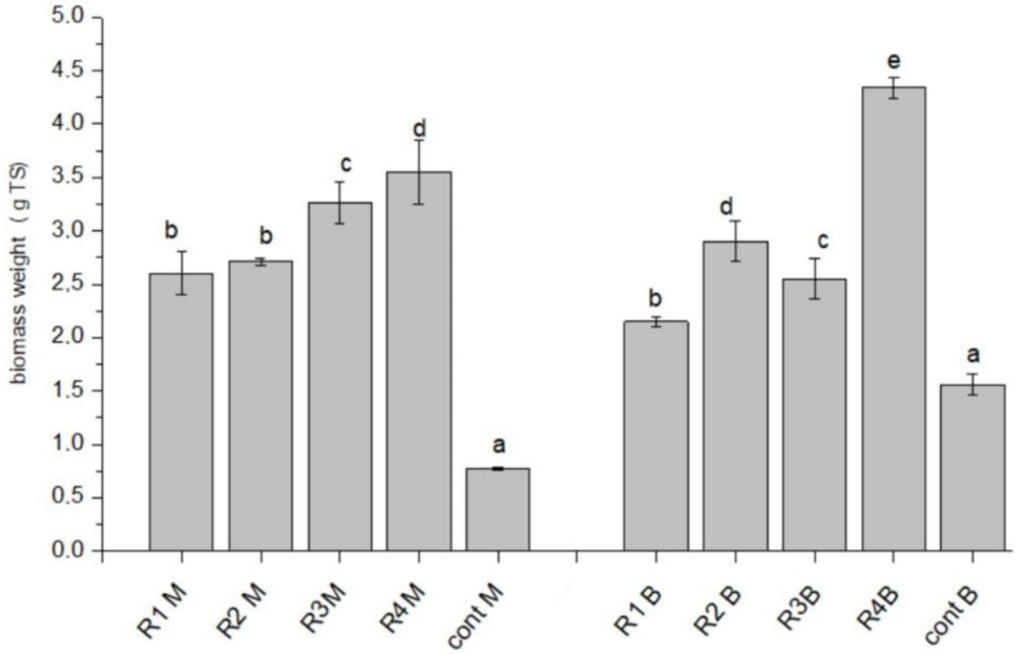

Figure 6. Fescue biomass M soil from the zinc smelter area. B soil from the lignite mine dumping site; bars with different letters are statistically different (Tukey's test).

In order to investigate the effect of organic amendments on heavy metal immobilization in degraded soil from the zinc smelter area, the immobilization factor was calculated (Figure 7). It was considered that IF < 1 indicated a favorable effect of fertilization on heavy metals immobilization in the soil, while IF > 1 proved the effect of contributing to the immobilization of heavy metals. For cadmium, IF was similar for all pots and did not exceed the value of 0.2 except for the control sample. For Pb and Zn, immobilization factors increased after compost addition. In the case of lead, the IF value was the highest (>3) for soils where composts with 30% addition of sewage sludge were applied (R3, R4), while for Zn immobilization factors were higher (>2.5) in soils fertilized with composts R1 and R2.

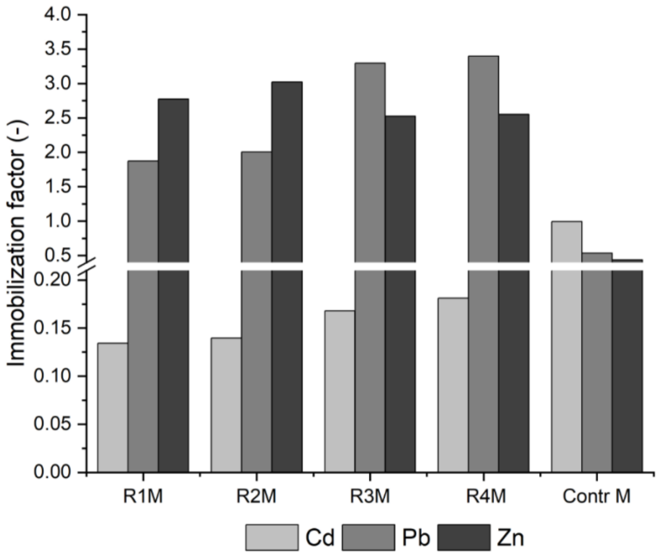

Figure 7. Immobilization factors of heavy metals in soil from the zinc smelter area.

4. Conclusions

The results presented in the paper showed that joint composting of sewage sludge with other biodegradable waste allowed for obtaining a good quality product that can be used in the bioremediation of degraded areas. It is especially important when using sludge from large WWTP plants, which cannot be used on land owing to excessive concentrations of heavy metals. The use of digestate for the production of composts allows the reuse of sewage sludge and the implementation of the circular bioeconomy idea in wastewater treatment plants and the entire waste sector.

The novelty of the presented research was a comparison of composting process efficiency between using sewage sludge from the co-digestion process and using digestate from WWTP as co-substrates in the feedstock. This is important because implementation of co-digestion will be useful to achieving energy self-sufficiency in WWTPs. The addition of co-substrates into the digester will allow increasing biogas production and will also have an impact on the digestate quality. Therefore, it is crucial to investigate the effect of this digestate on its stabilization under aerobic conditions. The added value of the research was a demonstration of the better composting efficiency of the digestate over the co-digestion process.

The following conclusions can be drawn from the study:

1. A higher temperature in the thermophilic phase (which resulted in complete hygienization of the composts) and a higher OM loss ratio (at the level of 60%) were obtained during composting of feedstock with SS2 addition;
2. All obtained composts met the requirements set out in Polish law, taking into account the fertilizing properties and the concentration of heavy metals;
3. The composts produced with the digestate from the WWTP did not meet legal requirements because of the high content of Helminth eggs, which was probably linked to the lower temperature in the thermophilic phase during the process;
4. All composts used for remediation caused a significant increase in fescue biomass. The highest yield was achieved for compost produced from the mixture with the addition of 30% sewage sludge from the co-digestion process. As compared with control samples, it was almost 5-fold and 3-fold higher for soil from the zinc smelter area and soil from the lignite mine dumping site, respectively.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14216953/s1, Table S1: Results of the factorial ANOVA (F, and p-values) applied to C/N ratio in composts ($p \leq 0.05$), Table S2: Results of factorial ANOVA for biomass yield.

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Abbreviations

AD	anaerobic digestion
ARB	antibiotic resistance bacteria
ARGs	antibiotic resistance genes
BA	bulking agent
bdt	below detection threshold
C16:0	palmitic acid
C18:1	oleic acid
CE	circular economy
cont B	control sample for samples collected from brown coal post-mining area
cont M	control sample for samples collected from the zinc smelter
EPA	Environmental Protection Agency
G	grass
GTS	grease trap sludge
LCFAs	long chain fatty acids
OFMSW	organic fraction of municipal waste
OM	organic matter
SS	sewage sludge
SS1	sewage sludge from a municipal
WWTP	dewatered digestate from anaerobic digester
SS2	sewage sludge from a co-digestion process -dewatered digestate from laboratory reactor
TC	total carbon
TN	total nitrogen
TS	total solids
VS	volatile solids
WWTP	wastewater treatment plant

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