detritus | Multidisciplinary Journal for Waste Resources & Residues

CISA

PILOT-SCALE VERMICOMPOSTING OF DEWATERED SEWAGE SLUDGE FROM MEDIUM-SIZED WASTEWATER TREATMENT PLANT (WWTP)

Petra Innemanová [1,2,*], Alena Grasserová [1,3] and Tomáš Cajthaml [1,3]

[1] Institute for Environmental Studies, Faculty of Science, Charles University, Benátská 2, 128 01 Prague 2, Czech Republic
[2] DEKONTA a.s., Dřetovice 109, 273 42 Stehelčeves, Czech Republic
[3] Institute of Microbiology Czech Academy of Sciences, Vídeňská 1083, 14220, Prague 4, Czech Republic

Article Info:
Received:
15 December 2021
Revised:
17 February 2022
Accepted:
9 March 2022
Available online:
31 March 2022

Keywords:
Sewage sludge
Vermicomposting
Organic micropollutants
PPCPs

ABSTRACT

The transformation of dewatered sewage sludge into vermicompost provides an advantageous solution in cases where the sludge is not too contaminated with inorganic pollutants, especially heavy metals. In addition to the conversion of the sludge to a product with a higher-added value, undesirable organic pollutants and micropollutants are partially eliminated. Anaerobically stabilized dewatered sewage sludge from a medium-sized Wastewater Treatment Plant (WWTP) was subjected to the vermicomposting process under field conditions. Straw was used as the bedding material in the form of two mixing ratios. The almost 1 year of the monitoring of the process focused on the hazardous substances present, the concentrations of which are regulated by legislation on the use of sludge on agricultural land. In addition, the contents of macro- and micro-nutrients such as N, P, K, Mo, Ca, Mg, and the wintering of the earthworm inocula were monitored. The potential of the vermicomposting process to reduce the content of emergent pollutants from the PPCP group was described with respect to 35 detected substances, including five endocrine disruptors. The study suggested that the bio-stabilization of dewatered sewage sludge using earthworms provides an effective technology for converting noxious wastewater treatment products into nutrient-rich bio-fertilizers.

1. INTRODUCTION

Sewage sludge contains nutrients and other substances that are able to positively contribute to the enhancement of the properties of soil and overall fertility (Latare et al., 2014; Shanta Mendis et al., 2020). Its reuse, where suitable, is encouraged by European Council Directive 91/271/EEC. Treated sludge in the Czech Republic must fulfil the quality criteria set for toxic metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn), adsorbable organic halogens (AOX), polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs) and the microbial pathogens *Salmonella sp.* and *Escherichia coli* (Ministry of the Environment of the Czech Republic, 2021). National legislation has incorporated the relevant regulations of the European Union, including Directive 86/278/EEC. Apart from those pollutants whose concentrations are regulated, a broad spectrum of so-called 'emerging' organic chemicals, including pharmaceuticals and other personal care products (PPCPs), may be transferred to residual solids during the treatment of wastewater. Thus, a reliable assessment is required of their significance and implications for the beneficial recycling of treated sewage sludge (Khakbaz et al., 2020).

Vermicomposting is a process via which earthworms act to convert organic materials (usually waste) into a humus-like material known as vermicompost. It comprises a bio-oxidative and stabilizing process for the conversion of organic material which, unlike classical composting, uses the interaction between the intensive activity of earthworms and microorganisms, and does not involve the thermophilic decomposition phase (Domínguez and Edwards, 2011; Champar Ngam et al., 2010). Vermicompost generally appears to be superior to conventionally-produced compost in terms of a number of important parameters including a higher content of available nutrients associated with the enhanced hydrolytic activity and microbial population size (Tognetti et al., 2005; Sinha et al., 2010).

Our study concerns the long-term field testing of sludge vermicomposting in two separate pits, each with a working volume of 3m^3. Straw was used as the bulking material in two mixing ratios. The research covered the testing phase of a pilot vermicomposter conducted for the purpose of

* Corresponding author:
Petra Innemanová
email: petra.innemanova@dekonta.cz

follow-up experiments focusing on the reprocessing and sanitation of sewage sludge. The aim was to ensure a sufficient inoculum density and to test the overwintering of the system under outdoor conditions. However, even during this start-up phase, all the parameters required to be monitored by Czech legislation, as well as the contents of macro- and micro-nutrients such as N, P, K, Mo, Ca and Mg were monitored, as was the development of the concentration of selected PPCP micropollutants.

2. MATERIAL AND METHODS

2.1 Material and the design of the field experiment

The dewatered anaerobically stabilized sewage sludge with an initial dry matter content (DMC) of 24.9 ± 0.7% was taken from WWTPs of a 33 thousand population-equivalent (p.e.) located in South Bohemia. The straw was supplied by a local farmer. The earthworms (*Eisenia andrei*) were supplied by the FLORIUM s.r.o. vermicomposting plant.

The pilot-scale vermicomposting experiment is being conducted in segments A and B of a field vermicomposter (see Figure 1). The working volume of each segment (A and B) is 3 m^3. The working volume of the backup segment (C) is 3.5 m^3; this part of the vermicomposter serves as the earthworm inoculum for subsequent experiments. The drainage system of the field vermicomposter allows for the leachate sampling of each segment. The excess leachate is collected in an underground tank with a volume of 1 m^3 and subsequently disposed of at the nearest WWTP. This experiment does not include the monitoring of the leachate (Figure 2).

A perforated drainage pipe made of polyvinyl chloride was positioned at the bottom of each segment and covered with a layer of straw (36 kg for each of segment A and B). After separating this drainage layer with a geotextile material, each of the segments was filled with the test material according to the following arrangements:

Segment A: 4 layers of straw (40 kg in total) and 3 layers of dewatered sewage sludge (608 kg in total, representing 159 kg of dry matter). Straw formed the bottom and upper layers. The weight ratio of the straw to the dry sludge was 1:4.

FIGURE 2: Field experiment.

Segment B: 3 layers of straw (30 kg in total) and 2 layers of dewatered sewage sludge (the same amounts as in segment A). Straw formed the bottom and upper layers. The weight ratio of the straw to the dry sludge was 1:5.3.

After filling the vermicomposter with a substrate, two perforated polypropylene boxes containing the earthworm hybrid *Eisenia andrei* were placed in each segment. The total weight of the earthworm inoculum was 7 kg for each segment.

The layers of straw created air pockets that improved the level of comfort for the earthworms. Sludge samples

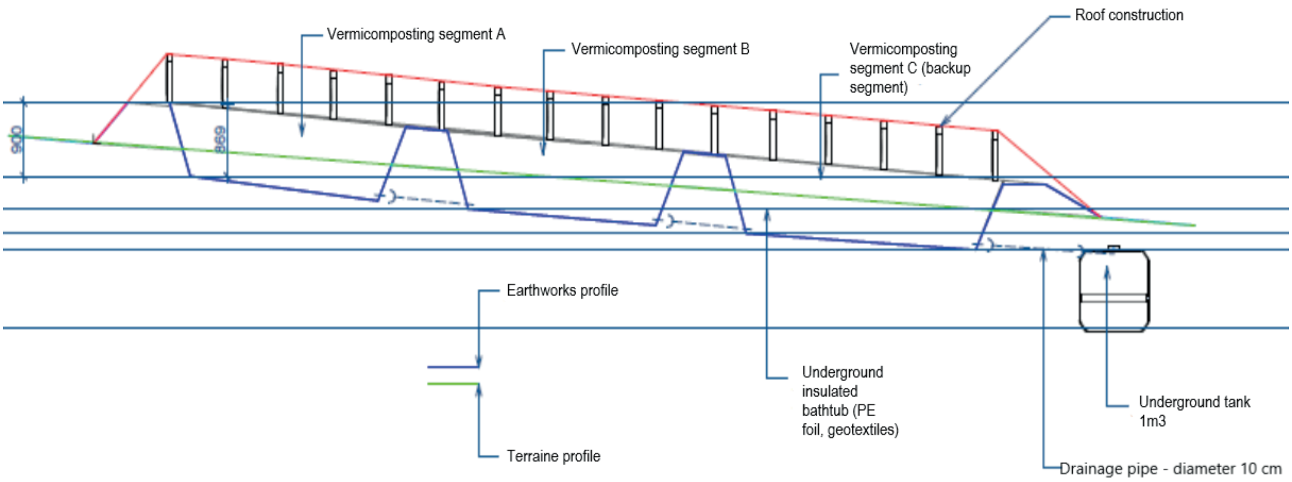

FIGURE 1: Pilot-scale vermicomposter scheme (if not directly specified, the dimensions are given in cm).

for subsequent analysis purposes were taken from the layers without straw.

The vermicomposting process commenced on 4 June 2020 and is ongoing. Both segments were sprinkled twice with the same amount of water during the dry summer of 2020. Otherwise, a perforated cover was sufficient to provide the necessary irrigation.

In November 2020, compact piles were formed from the vermicompost layers of the two segments, in the lower one-third of the segment in both cases. This arrangement allowed the earthworms to overwinter comfortably via the creation of non-freezing zones. In addition, this form of vermicompost will serve as the inoculum for the next batch of sludge in the so-called wedge system (currently in progress).

2.2 Sample analysis

The earthworm biomass was determined on the basis of the manual counting of individual worms (adults and juveniles) in a 1 l sample of vermicompost. 5 parallel samples were taken from the two segments A and B. The dry matter content (DMC) was measured gravimetrically after the drying of the samples at 120^{0}C. DMC was expressed as a percentage of the dry weight of the respective sample.

E. coli was determined according to the Czech ČSN EN ISO 9308-1 national standard. The *Salmonella sp.* was determined according to ČSN EN ISO 6579.

The determination of heavy metals, the Ca, Mg, K, P and N contents, the pH, the DMC and the content of TOC, PCBs (the sum of 7 congeners 28+52+101+118+138+153+180), PAHs (the sum of anthracene, benzo(a) anthracene, benzo(b) fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, benzo(ghi)perylene, phenanthrene, fluoranthene, chrysene, indeno(1,2,3-cd)-pyrene, naphthalene and pyrene) and AOX was conducted by an accredited analytical laboratory (Dekonta, a.s., Ústí nad Labem, Czech Republic). All the measurements were taken in triplicate.

The samples intended for the PPCP and endocrine disruptor analysis using LC-MS/MS were freeze-dried and homogenized. Each sample (weights of 1-2 g) was then transferred to an extraction cell and positioned in an Accelerated solvent extractor (ASE, Dionex). The extraction method was as follows: the preheating of the methanol solvent and the cell to 80°C with a pressure of 1500 psi; 3 extraction cycles and 5-minute static periods between the cycles. The extracts were then evaporated to 5 mL and centrifuged (6000g, 10 min), whereupon the supernatants were transferred to 2mL vials for subsequent analysis purposes. The extracts were analyzed using the LC system (Agilent 1260 Infinity) coupled with a triple quadrupole mass detector (Agilent 6470 LC/TQ). Separation was performed using a Poroshell 120 EC-C18 column (2.7 µm, 3 mm x 100 mm, Agilent) equipped with a Poroshell 120 EC-C18 precolumn (2.7 µm, 3 mm x 5 mm, Agilent); both were heated to 40°C. The mobile phase consisted of phase A (0.5mM ammonium fluoride in MQ water + 0.01% formic acid, LC-MS grade) and phase B (100% methanol, LC-MS grade). The gradient elution program was as follows (time [min], % phase B): 0, 5; 4, 50; 6, 50; 18, 100; 21, 100; 22, 5 and 23, 5. The mobile phase flow was 0.4 mL/min; one run lasted 23.50 min and the injection volume was 2 µL. In order to suppress the matrix effect, the samples were measured with automatic standard additions of 1, 5 and 25 ng/mL. The mass spectrometric parameters were optimized using MassHunter Workstation Optimizer and Source Optimizer (both Version 10.0, SR1, Agilent).

The output values of the monitored chemical parameters represented the results of the field sampling after 9 months (which included the winter season). With respect to the microbiological parameters, the sanitation efficiency of the process was evaluated after approximately 5 and 11 months of the duration of the process.

3. RESULTS AND DISCUSSON

3.1 Dry matter content and earthworm biomass

The dry matter contents of segments A and B after 11 months of processing were 28.6 ± 0.4% and 26.8 ± 0.9%, respectively. The small (but statistically significant difference, $p < 0.01$) did not lead to a differing worm density, i.e. 54.8 ± 15.2 individuals per liter in segment A and 46.2 ± 20.2 individuals per liter in segment B (mean and standard deviation of 5 measurements) 11 months after the start of the experiment. Nevertheless, the observed average weight of the adults of 0.86 ± 0.27 g in segment B was significantly higher than the value of 0.47 ± 0.18 g determined for segment A ($p < 0.01$, mean and standard deviation of 30 measurements). The slight difference in the moisture contents of segments A and B was the most likely reason for the observed differences in the body weights of the earthworms. Similar observations were described in a study by Domínguez and Edwards (1997), which described that beneath an 85% moisture level, higher moisture conditions clearly facilitated growth as measured by an increase in the individual biomass of *Eisenia andrei*.

3.2 Chemical and microbiological parameters

Adequate sanitation had not been achieved after 5 months of the process. *Salmonella sp.* was not detected in the sludge used in the experiment but concerning the *E. coli* parameter, the required limits were met after approximately 11 months of the duration of the experiment (see Table 1), thus indicating that sludge sanitation is possible in the absence of a pre-composting step with the thermal phase of the process; however, it requires a longer time period. These results are at variance with trends reported in the literature. For example, Procházková et al. (2018) observed a decrease in *E. coli* to an undetectable level after 8 weeks of the vermicomposting of apple pomace waste with an artificial bacterial load. In addition, a study by Parseh et al. (2021) described the extensive ability of *E. fetida* to reduce pathogens within 8 weeks in dewatered sludge without the need for an increase in temperature. However, the results of these studies are difficult to compare since they are usually recorded under optimal laboratory conditions. It is necessary to take into account that a longer period of time is required for complete sanitation under real conditions. This is due not only to temperature and moisture fluctuations; it was observed during the experiment that due to the inhomogeneity of the mixture, random layers without

TABLE 1: Concentrations of *E. coli* in segments A and B at the commencement and after 140 and 340 days of the process.

	E. coli in parallel samples (CFU/g)					Czech legislation limit
Input	7.8×10^4	9.2×10^4	1×10^5	2.2×10^5	2.8×10^5	Max. 10^3CFU/g for 4 samples and 5×10^3CFU/g for one sample from 5 parallel samples
A (day 140)	3.1×10^4	3.5×10^4	3.5×10^4	3.6×10^4	4.2×10^4	
B (day 140)	2×10^4	2.5×10^4	2.9×10^4	3.4×10^4	3.5×10^4	
A (day 340)	Negative	Negative	Negative	Negative	Negative	
B (day 340)	Negative	Negative	Negative	4×10^2	2.4×10^3	

the presence of earthworm settlements occurred over relatively longer time period.

As can be seen in Table 2, the treated sludge complied with the limits for hazardous substances set by Czech legislation (Ministry of the environment of the Czech Republic, 2021) for the application of treated sludge to agricultural land even before the start of the vermicomposting process. The relative stabile concentration at the most of monitored heavy metals can be explained by the combination of two conflicting phenomena: the concentration through the decomposition of the organic matter and elimination due to ingestion by the earthworms and following bioaccumulation. The predominant effect of bioaccumulation may provide an explanation for the decrease in the content of Cu and As. According to Rorat et al. (2017), *Eisenia andrei* accumulated heavy metals as follows: Cd>Cu>Zn>Ni>Cr>Pb. Kilpi-Koski et al. (2019) observed a high bioaccumulation factor (BAF) for As, but a low BAF for Cu. Moreover, other studies have provided differing information on heavy metal bioaccumulation factors (Suleiman et al., 2017; Wang et al., 2018), and further research is required in this regard. In any case, bioaccumulation cannot be considered to provide a tool for the removal of heavy metals from vermicomposted material since the continuous earthworm mortality and their subsequent decomposition during a full-scale application leads to the re-supply of accumulated metals back into the final vermicompost. Therefore, only the initial concentration of heavy metals in the sludge is a key factor in the design of the appropriate technology. The limits set for selected organic substances from the persistent organic pollutants (POPs) category were fulfilled. The AOX concentration dropped to below the detection limit for both treatments. Some studies (for example Khakbaz et al., 2020) have used sludge parameter extractable organic halogens (EOX) for the quantification of organic halogens in sewage because of the suitability of this parameter to characterize complex two-phase matrices as a sludge (Rizzardini and Goi, 2014). Our study followed the requirements of the Ministry of the environment of the Czech Republic (2021) according to which, in addition to the AOX, the monitoring of PCBs (the sum of 7 congeners: 28+52+101+118+138+153+180) and PAHs (the sum of anthracene, benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, benzo(ghi)perylene, phenanthrene, fluoranthene, chrysene, indeno(1,2,3-cd)-pyrene, naphthalene and pyrene) is mandatory. While PCBs were under the detection limit even in the initial samples, there was no tendency for the sum of 7 selected PAHs to decrease from the initial value of 2.8 ± 1.1 ppm. The opposite tendency, i. e. concentration over time, indicates the presence of highly-persistent substances. The bioavailability of PAHs has been found to be strongly related to the number of their aromatic rings, their molecular weight and their structure (Amir et al., 2005). In this specific case, more persistent PAH representatives were probably present in the sludge while, for example, a study by Rorat et al. (2017) reported that of the PAHs regulated, indeno(1,2,3-c,d)-pyrene was not detected and the most efficient rate of removal was recorded for the two- and three-ring substances naphtalene and phenanthrene. When designing the appropriate technology, it is, therefore, necessary to take into account the relative concentrations of individual PAHs in the sum of those that are subject to regulation.

In addition to hazardous substances, the monitoring of which is required by legislation, the content of selected biogenic elements was also monitored. As can be seen from Table 2, an obvious increase was observed especially in the case of phosphorus. An elevated level was also observed in potassium concentrations. Conversely, the total nitrogen content dropped and, at the same time, a marked shift was observed in the ratio of the NH^{4+}/NO^{3-} form of nitrogen. It decreased by 4 orders of magnitude from the original value of approximately 10^4. The levels of calcium and magnesium remained at similar levels for 9 months. These trends have also been observed under laboratory conditions (Zhang et al., 2020) and even without sludge blending (Khwairakpam and Bhargawa, 2009), which indicates that sewage sludge can be recycled as a good quality fertilizer. The observed loss of organic carbon can be attributed to the loss of organic matter from feed mixtures as carbon dioxide through earthworms and microbial respiration (Garg et al., 2008). The pH dropped from the original 7.6 ± 0.1 to 5.2 ± 0.3 and 5.4 ± 0,1 which is consistent with the results of other authors (Gupta and Garg, 2008; Bhat et al., 2016). A gradual return to neutral values was observed after longer processing times (data not shown).

3.3 Development of the micropollutant concentration

Although samples were taken for analysis from the sludge layer, it cannot be ruled out that the action of the earthworms and mechanical manipulation did not result in the mixing of the substrates and, thus, a reduction in the content of the monitored substances via dilution. On the other hand, during the vermicomposting process, the mass of the mixture generally declines due to the partial mineralization of the organic matter (Suleiman at al., 2017). Thus, recalcitrant substances may become concentrated as a result. The calculation of the actual loss of pollutants is subsequently complicated. Similar laboratory studies have applied an internal standard for the recalculation of the ef-

TABLE 2: Concentration of hazardous substances, nutrients and TOC in segments A and B at the commencement and after 9 months of the process (mean and standard deviation of 3 paralel samples).

Hazardous substances (mg/kg)	Input	A – output	B- output	Czech legislation limit
As	8.0 ± 0.2	5.2 ± 1.1	6.1 ± 0.6	30
Cd	1.3 ± 0.03	1.2 ± 0.1	1.2 ± 0.1	5
Cr	42.8 ± 4.2	42.7 ± 8.2	40.9.0 ± 0.7	200
Cu	249.0 ± 11.0	201.0 ± 21.0	202.0 ± 16	500
Hg	1.7 ± 0.5	1.3 ±0.4	1.2 ±0.1	4
Ni	29.5 ± 1.9	28.5 ± 2.8	31.1 ± 5.4	100
Pb	37.6 ± 2.6	34.6 ± 4.5	34.4 ± 2.8	200
Zn	804.0 ± 45.0	754.0 ± 80.0	714.0 ± 98.0	2500
Mo	6.0 ± 0.65	5.0 ± 0.65	4.7 ± 0.6	
AOX	96.0 ± 57.0	n.d.	n.d.	500
PCB	n.d.	n.d.	n.d.	0.6
PAH	2.8 ± 1.1	3.5 ± 0.4	6.8 ± 1.4	10
P	(26.0 ± 0.5) x10^3	(39.3 ± 4.1) x10^3	(39.4 ± 4.7) x10^3	
K	(2.7 ± 0.4) x 10^3	(4.5 ± 0.3) x10^3	(3.9 ± 0.2) x10^3	
N_{total}	(8.2 ± 2.5) x10^3	(3.7 ± 0.8) x10^3	(3.9 ± 0.3) x10^3	
Ca	(23.8 ± 0.4) x10^3	(22.6 ± 1.7) x10^3	(19.5 ± 4.6) x10^3	
Mg	(5.0 ± 0.2) x10^3	(5.0 ± 0.4) x10^3	(4.8 ± 0.7) x10^3	
TOC	(308 ± 44) x10^3	(227 ± 14) x 10^3	(235 ± 10) x10^3	

n.d.: not detected

ficacy. For example, Covino et al. (2016) used a selected heavy metal, which was present in only one part of the composting mixture (wooden chips). The removal efficiency of micropollutants and hazardous substances indicated as a percentage of reduction on the basis of the initial and final concentrations without the calculation of the actual loss may thus be misleading. The declared loss of monitored substances should be considered as a combination of the processes described above. However, with regard to the subsequent applicability of the sludge, we were primarily interested in the final quality of the product. For our purposes, the final removal of micropollutants might be referred to provisionally as the "operating removal efficiency".

The initial concentrations of the monitored pharmaceuticals ranged from 0.5 ± 0.1 ppb (Sulfamethazine) to 8.0 ± 0.4 ppm (Telmisartan). The initial and output concentrations of 35 substances detected from the PPCP group are summarized in Table 3.

The operating removal efficiency of the vermicomposting process differed between 0% and 100%, with the highest values (above 90%) determined for Acesulfame, Equilin, Equol, Furosemide, Hydrochlorothiazide, Ibuprofen, Saccharine and Sulfamethazine and endocrine disruptor 17beta-estradiol. With respect to this case study, 28.7% (segment A) and 29.2% (segment B) of the most abundant micropollutant, Telmisartan, were removed. The only increased level after 9 months of processing was observed for Bisphenol S, which was probably related to the composter insulation material used. The total operating removal efficiency of all the detected micropollutants was 35.3% and 34%. To date, only a small number of similar studies have been published, a review of which has recently been provided by Chowdhury et al. (2022). The cited studies differ in terms of the specific observed substances included in the groups of pharmaceuticals and PPCPs and are, therefore, difficult to compare. It is clear that further research is essential in the field, especially concerning the overall effects on the environment, e. g. endocrine disruptivity and ecotoxicity.

4. CONCLUSIONS

During the first year of the operation of the field vermicomposter, the earthworm inoculum in the mixture of sewage sludge and straw multiplied to a sufficient extent and the culture overwintered successfully, even though frosts reached temperatures of below -20°C in the winter of 2020/2021.

The different mixing ratio of the sludge/straw exerted a slight effect on the output dry matter content, which led to a minimal difference in the density of the earthworm populations and a significant difference in the biomass of the *Eisenia andrei*. No significant difference was observed between segments A and B with respect to the monitored parameters.

The sludge used in the experiment met the respective legislative requirements for agricultural land application in terms of the content of heavy metals and that of the monitored organic substances and *Salmonella sp.*, the content of which met legislative requirements even at the outset of the process. The *E. coli* content met the criteria in the 11th month.

TABLE 3: Concentration of selected PPCPs in segments A and B at the commencement and after 9 months of the process, mean and standard deviation of 18 input samples and 6 output samples from each of segment A and B; the variance associated with the compound content via the analysis of variance (ANOVA) and its significance, *p <0.05; **p <0.01.

Pollutant	Input (ng/g)	Segment A (ng/g)	Segment B (ng/g)
Acesulfame	47.5 ± 9.0	4.1 ± 1**	3.9 ± 0.7**
Acetaminophen (Paracetamol)	10.8 ± 2.2	4.8 ± 1.5**	3.9 ± 0.4**
Amitriptyline	64.4 ± 11.5	52.2 ± 11.6	51.7 ± 7.3*
Atorvastatin	13.1 ± 4.2	10.3 ± 4	13.5 ± 5
Azithromycin	41.4 ± 11.7	59.8 ± 18.1	45.7 ± 25.4
Bisphenol A	615.5 ± 63.4	93.4 ± 23.6**	158.5 ± 24.6**
Bisphenol F	29.6 ± 4.3	21.5 ± 8.4**	17.8 ± 2.2**
Bisphenol S	27.3 ± 2.6	95.0 ± 31.5*	45.6 ± 29.1
Caffeine	50.0 ± 4.0	40.8 ± 5.2**	42.9 ± 2.3**
Carbamazepine	132.5 ± 38.4	75.8 ± 11.4**	87.9 ± 12.3*
Carbamazepine 10,11-epoxide	4.9 ± 0.4	3.2 ± 0.6**	3.7 ± 0.6**
Cetirizine	152.8 ± 9.6	84 ± 15.7**	91.5 ± 12.5**
Citalopram	421.1 ± 32.1	320.1 ± 62.8**	287.3 ± 61.8**
Daidzein	7.4 ± 1.1	2.6 ± 0.2**	2.5 ± 0.1**
Equilin	1.2 ± 1.4	n.d.	n.d.
Equol	39.7 ± 8.6	2.6 ± 0.8**	4.9 ± 4.2**
Estrone	3.5 ± 2.7	0.4 ± 1.0*	0.9 ± 1.3
Fluoconazole	1.3 ± 0.2	1.0 ± 0.2**	1.1 ± 0.1*
Furosemide	19.2 ± 2.8	n.d.**	n.d.**
Gabapentin	38.5 ± 9.8	7.0 ± 2.8**	9.8 ± 1.9**
Genistein	3.5 ± 2.7	2 ± 0.4	2.0 ± 0.2
Hydrochlorothiazide	2.6 ± 0.5	n.d.**	n.d.**
Ibuprofen	129.7 ± 79.2	7.7 ± 7.2**	n.d.**
Lamotrigine	94.7 ± 12.6	21.4 ± 7.8**	27.6 ± 5.6**
Metoprolol	135.8 ± 8.2	45.2 ± 7.5**	48.0 ± 13.1**
Mirtazapine	74.2 ± 5.7	33.8 ± 10.2**	36.3 ± 5**
Saccharine	28.4 ± 13.2	n.d.**	n.d.**
Sulfamethazine	0.5 ± 0.1	n.d.**	n.d.**
Sulfanilamide	9.4 ± 3.1	2.2 ± 0.4**	2.9 ± 0.5**
Sulfapyridine	8.1 ± 1.9	1.9 ± 0.2**	2.6 ± 0.8**
Telmisartan	(8.0 ± 0.4) x10^3	(5.7 ± 0.8) x10^3 **	(5.7 ± 0.8) x10^3 **
Tramadol	58.4 ± 4.3	28.8 ± 4.3**	31.3 ± 5.9**
Trimethoprim	10.2 ± 1.6	1.6 ± 0.1**	1.3 ± 0.2**
Venlafaxine	128.6 ± 9.6	91.2 ± 15.1**	90.5 ± 11.3**
17beta-estradiol	24.8 ± 20	n.d.**	n.d.**

n.d.: not detected

The degradation potential of selected micropollutants from the PPCP group differed. A total of 35.3% degradation of the monitored substances was observed in segment A and 34% in segment B.

Vermicomposting led to a significant decrease in the concentration of the 4 detected endocrine disruptors (Bisphenol A, Bisphenol F, Estrone and 17beta-estradiol). Conversely, an increase was observed in the content of Bisphenol S, which was probably due to the film material that was used for the insulation of the vermicomposter.

Thus, vermicomposting appears to be a useful method for processing sewage sludge from at least smaller WWTPs. It is recommended that the further potential of this process be explored in subsequent research.

AKNOWLEDGEMENTS

The "Use of Vermicomposting to Eliminate Micropollutants for the Safe Application of Sewage Sludge on Agricultural Land" project (No. QK1910095) was financially supported by the Ministry of Agriculture of the Czech Republic as part of the "ZEMĚ" program.

REFERENCES

Amir, S., Hafidi, M., Merlina, G., Hamdi, H., Revel, J.C. 2005. Fate of polycyclic aromatic hydrocarbons during composting of lagooning sewage sludge. Chemosphere 58(4). 449-458. doi.org/10.1016/j.chemosphere.2004.09.039

Bhat, S. A., Singh, J., Vig, A.P. 2016. Effect on growth of earthworm and chemical parameters during vermicomposting of pressumd sludge mixed with cattle dung mixture. Procedia Environmental Sciences 35. 425-434. doi.org/10.1016/j.proenv.2016.07.025

Chowdhury, S.D., Surampalli, R.Y., Bhunia, P. 2022. Potential of the constructed wetlands and the earthworm-based treatment technologies to remove the emerging contaminants: A review. J hazard Toxic radioact Waste 26(2). 04021066. doi.10.1061/(ASCE)HZ.2153-5515.0000668

Covino, S., Fabianová, T., Křesinová, Z., Čvančarová, M., Burianová, E., Filipová, A., Voříšková, J., Baldrian, P., Cajthaml, T. 2016. Polycyclic aromatic hydrocarbons degradation and microbial community shifts during co-composting of creosote-treated wood. J Hazard Mater. 301(15). 17-26. doi.org/10.1016/j.jhazmat.2015.08.023

Domínguez, J., Edwards, C., A. 1997. Effects of stocking rate and moisture content on the growth and maturation of *Eisenia andrei* (Oligochaeta) in pig manure. Soil Biol Biochem. 29(3/4). 743-746. doi.org/10.1016/S0038-0717(96)00276-3

Domínguez, J., Edwards, C., A. 2011. Relationships between composting and vermicomposting. In: Vermiculture Technology (Eds Edwards C.A., Arancon N.Q., Sherman R.), Boca Raton: CRC Press, Taylor & Francis Group, 11-25.

Garg, V. K., Gupta, R., Yadav, A. 2008. Potential of vermicomposting technology in solid waste management. In: Pandey A et al (ed) Current developments in solid state fermentation. Asia-Tech. Publishers Inc. New Delhi. 468-511. doi.org/10.1007/978-0-387-75213-6_20

Gupta, R., Garg, V.K. 2008. Stabilization of primary sewage sludge during vermicomposting. J Hazard Mater. 153(3). 1023-1030. doi.org/10.1016/j.jhazmat.2007.09.055

Champar-Ngam, N., Iwai, C.B., Ta-oun, M. 2010. Vermicompost: tool for agro-industrial waste management and sustainable agriculture. IJERD. 1-2. 38-43

Khakbaz, A., De Nobili, M., Mainardis, M., Contin, M., Aneggi, E., Mattiussi, M., Cabras, I., Busut M., Goi, D. 2020. Monitoring of heavy metals, EOX and LAS in sewage sludge for agricultural use: a case study. Detritus Journal, 12-2020.160-168. doi.org/10.31025/2611-4135/2020.13993

Khwairakpam, M., Bhargava, R. 2009. Vermitechnology for sewage sludge recycling. J Hazard Mater 161. 948-954. doi.org/10.1016/j.jhazmat.2008.04.088

Kilpi-Koski, J., Penttinen, OP., Väisänen, A.O., van Gestel, C.A.M. 2019. An uptake and elimination kinetics approach to assess the bioavailability of chromium, copper, and arsenic to earthworms (*Eisenia andrei*) in contaminated field soils. Environ Sci Pollut Res 26. 15095–15104. doi.org/10.1007/s11356-019-04908-6

Latare, A.M., Kumar, O., Singh, S.K., Gupta, A. 2014. Direct and residual effect of sewage sludge on yield, heavy metals content and soil fertility under rice-wheat system. Ecol. Eng. 69. 17-24. doi.org/10.1016/j.ecoleng.2014.03.066

Ministry of the environment of the Czech Republic. 2021. Vyhláška č. 273/2021 Sb., vyhláška o podrobnostech nakládání s odpady. In: Sbírka zákonů ČR, volume 2021, Number 273. https://www.zakonyprolidi.cz/cs/2021-273

Parseh, I., Mousavi, K., Badieenejad, A., Golbini Mofrad, M.M., Hashemi, M., Azadbakht, O., Karimi, H. 2021. Microbial and composition changes during vermicomposting process resulting from decomposable domestic waste, cow manure and dewatered sludge. Int J Env Health Eng 10:3. doi.10.4103/ijehe.ijehe_56_20

Procházková, P., Hanč, A., Dvořák, J., Roubalová, R., Drešlová, M., Částková, T., Šustr, V., Škanta, F., Navarro Pacheco, N.I., Bilej, M. 2018. Contribution of *Eisenia andrei* earthworms in pathogen reduction during vermicomposting. Environ Sci Pollut R 25. 26267-26278

Rizzardini, C.B., Goi, D. 2014. Sustainability of domestic sewage sludge disposal. Sustainability 2014. 6(5). 2424-2434. doi.org/10.3390/su6052424

Rorat, A., Wloka, D., Grobelak, A., Grosser, A.S., Milczarek, M., Jelonek, P., Vandenbulcke, F., Kacprzak, M. 2017. Vermiremediation of polycyclic aromatic hydrocarbons and heavy metals in sewage sludge composting process. J Environ Manage 187. 347-353. doi.org/10.1016/j.jenvman.2016.10.062

Sinha, R.K., Herat, S., Bharambe, G., Brahambhatt, A. 2010. Vermistabilization of sewage sludge (biosolids) by earthworms: converting a potential biohazard destined for landfill disposal into a pathogen-free, nutritive and safe biofertilizer for farms. Waste Manage Res 2010:28. 872-881

Shanta Mendis, A. S., Dunuweera, S.P., Walpolage, S. & Gamini Rajapakse, R. M. (2020). Conversion of biological treatment plant sludge to organic fertilizer for applications in organic farming. Detritus Journal, 9-2020. 83-93. doi.org/10.31025/2611-4135/2020.13899

Suleiman, H., Rorat, A., Grobelak, A., Grosser, A., Milczarek, M., Plytycz, B., Kacprzak, M., Vandebulcke, F. 2017. Determination of the performance of vermicomposting process applied to sewage sludge by monitoring of the compost quality and immune responses in three earthworm species: *Eisenia fetida*, *Eisenia andrei* and *Dendrobaena veneta*. Bioresource Technol 241. 103-112. doi.org/10.1016/j.biortech.2017.05.104

Tognetti, C., Laos, F., Mazzarino, M.J., Hernández, M.T. 2005. Composting vs. Vermicomposting: A Comparison of End Product Quality, Compost Sci Util, 13:1. 6-13. doi: 10.1080/1065657X.2005.10702212

Wang, K., Qiao, Y., Zhang, H., Yue, S., Li, H., Ji, X., Liu, L. 2018. Bioaccumulation of heavy metals in earthworms from firld contaminated soil in a subtropical aera of China. Ecotox Environ Safe 148. 876-883. doi.org/10.1016/j.ecoenv.2017.11.058

Zhang, H., Li, J., Zhang, Y., Huang, K. 2020. Quality of vermicompost and microbial community deversity affected by the contrasting temperature during vermicomposting of dewatered sludge. Int J Environ Res Public Health 17(5). 1748. doi.org/10.3390/ijerph17051748