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Separate Collected Versus Mechanical Segregated Organic Fractions in Terms of Fertilizers Suitability

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Abstract: Nowadays, municipal solid waste (MSW) management is one of the most critical issues. MSW may threaten the environment; however, the concerning high organic fraction content can be useful. This study aimed to compare the suitability of mechanically sorted organic fraction (OF) of MSW and source-segregated biowaste for biofertilizer usage. The compost and the effluents compositions were analyzed. Compost derived from biowaste can be applied to the soil, while, after processing OFMSW, the metal contents are too high. The exceeding limit values were noted, e.g., lead (over 80 mg/kg) and chrome (75 mg/kg). Effluents from biowaste treatment fulfill the national and UE fertilizers' requirements, considering the heavy metal contents, while effluents from OFMSW treatments exceed the limit values. The biggest exceedings were observed for nickel (over 3 mg/kg) and zinc (over 500 mg/kg). In general, the heavy metal contamination of byproducts from the OFMSW treatment was much higher. At the same time, the biogenic elements, e.g., nitrogen and phosphorus concentrations, were much lower than the biowaste treatment byproducts; however, even for them, the concentrations of the biogenic elements were too low to meet EU requirements. The compost and effluents derived from the biowaste treatment may be suitable for crop applications, considering the current national requirements.

Keywords: anaerobic digestion; compost; digestate; effluents; organic waste

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1. Introduction

Urbanization, rising living standards, and the expanding population affect the increment in the quantity of municipal solid waste (MSW) [1,2]. Yearly, the global generation of MSW is at the level of 2.01 billion tons [3], and its further increase is expected, even by 70% (to 3.4 billion tons) by 2050 [4]. Thus, MSW management remains a critical concern of the present and future, considering environmental protection and sustainability.

MSW can affect the environment by the emission of leachate, greenhouse gases, or odors. On the other hand, due to the organic fraction content (40–50%) [5], MSW can be valuable material. For the MSW treatment (mainly the organic fraction of municipal solid waste (OFMSW)), various methods have been applied to reduce landfilling, which is incompatible with current tendencies (e.g., circular economy, zero waste) [1]. For example, biological (anaerobic digestion [6] and composting [5]) and thermochemical (gasification [7] and hydrothermal [8]) treatments [9] have been used. Among the developed treatment pathways, anaerobic digestion (AD) has received more adherents worldwide [3,10]. The AD allows for energy recovery and organic matter decomposition. Thus, except for biogas generation improvement, biofertilizer production has to be still widely investigated, mainly in cooperation with existing facilities, which is limited.

There are around 18,000 biogas plants in Europe [11], using agriculture, food waste, and the OFMSW as feedstock. The OFMSW is generally an effect of the mechanical sorting of mixed solid waste. Source-segregated and collected separately from inhabitants, organic fractions can be defined as biowaste. In the analyzed area, it was a "door-to-door" system regarding rural and single-family housing, with the assumption of disposal in various standard bins in the case of multi-family housing. The OFMSW is generated in the mechanical sorting and separation process performed in mechanical–biological treatment (MBT) plants [12]. Source segregation fits the circular economy concept and is regarded as a landfilling problem solution [12]. Source-segregated biowaste provides higher recovery potential and treatment process performance compared to OFMSW [13]. Nevertheless, the biological treatment of OFMSW still has to be verified, mainly in full-scale, considering that also generated byproducts.

In full-scale AD plants, a wide variety of biowaste is used to produce biogas, i.e., biological household waste, food waste, OFMSW, sewage, and biowaste [6]. The two main byproducts: the digestate (semi-solid residue) and the effluents (together with liquid digestate) occur from AD and must be adequately managed. The digested residue might be used as a fertilizer and must, therefore, be hygienically safe [14]. The AD might also be followed by composting. Composting is a natural process conducted in aerobic conditions, leading to partial mineralization and biomass humification [15]. In Europe, nearly 95% of the produced digestate can be used as an organic fertilizer to replace chemically produced fertilizers [16]. Thus, it is crucial to ensure the quality of the fertilizers. Furthermore, the reviewed literature focused on the digestate from agricultural raw materials (manure, slurry, and energy crops); only a minor part concern with digestate derived from the urban feedstock, i.e., OFMSW. Therefore, the highlights of possible differences between digestate and effluents from OFMSW and biowaste are still missing.

The reviewed literature indicates that AD has the best environmental and economic fulfillment amid organic waste various biological treatment options [9]. However, it should be mentioned that attention should be paid to process efficiency (biogas yield) and performance (stability), together with the possibility of reusing byproduct (digestate, compost, and effluents). Meanwhile, most of the currently published studies are focused only on the biogas yield. Furthermore, the literature is scarce on the overall AD analysis, considering the mentioned issues, especially in full-scale. Moreover, the comparison of separately collected biowaste and OFMSW should be performed to define source segregation benefits, which is more absorbing for people.

Annually, around 56×10^6 tons of digestate is generated in Europe; consequently, digestate management becomes a major concern for plant operators and policymakers [17]. Currently, regarding digestate, the effluents and compost requirements to usage as the fertilizer and end-of-waste criteria are defined by different countries and on different levels [17,18]. In the middle of 2019, the European Parliament released the regulation, which defines the CE marking rules [19]. The manufacturer indicates that the EU fertilizing product conforms with the applicable requirements set out in Union harmonization legislation, providing for its affixing. However, the rules will apply with some delay. For instance, due to Poland, the starting date is 16 July 2022. Thus, the comparison of current applied requirements with the future is crucial.

This study aimed to compare the suitability of OFMSW and separately collected biowaste for biofertilizer usage. The compost derived from both organic waste streams AD and the effluents compositions were analyzed. The research was performed on a full scale, using an operating plant. The source segregation fits with current trends and is considered to be the right path towards zero waste. This comparison complements the analysis of selective municipal waste collection benefits, considering anaerobic digestion and its byproduct usage possibility. Furthermore, the EU requirements should be the target for countries; thus, it is important to get to know the current status and have some time for improvements.

2. Materials and Methods

2.1. The Full-Scale Research

The research was performed at the MBT Plant (ZGO Gać), located in the Lower Silesia region (Oława, Poland). The plant processes around 65,000 tons of MSW per year and around 14,000 tons of separately collected biowaste (such as food waste, kitchen waste, and green waste). A simplified diagram of the biological treatment installation is presented in Figure 1.

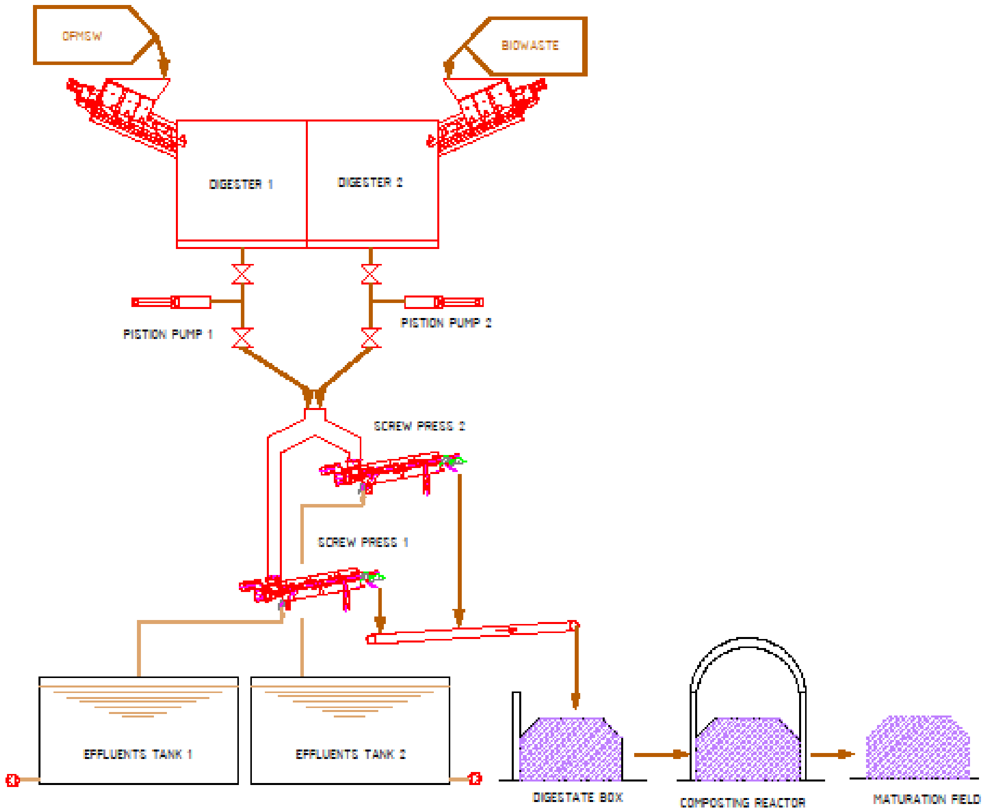

Figure 1. Simplified diagram of the biological treatment facility.

Both waste streams are processed via anaerobic digestion (AD) at the plant. The AD facility consists of two Kompogas® chambers, operating in thermophilic conditions (54 °C) [13]. After the fermentation, waste was removed from the chamber using a piston pump. Then, the digestate was dewatered using screw presses (TSP350, Thöni, Austria). Next, the effluents were collected in a storage tank (200 m^3) and characterized, considering fertilizer usage. Finally, the solid digestate was composted.

The composting process was performed in an enclosed reactor (pile size 21.5 m × 7.5 m × 2.0 m) with positive aeration (fresh air flow of 60.5 m^3/min) to ensure oxygen within the pore spaces inside the pile more than 5%. The temperature was measured by a stainless temperature probe (2 m long) to control the process. Proper porosity was ensured by adding 30% of structuring material. After three weeks, composting was continued on an open maturation field for eight weeks. Finally, the 20-mm grain size compost was generated using the trommel (MPB 18.47, Pronar, Narew, Poland).

2.2. Analytical Methods

The feedstock samples were collected over a month. First, the daily sample was prepared by collecting 10–15-kg samples at about 60 min. intervals. Then, the daily samples collected over a week were mixed and averaged to get one weekly sample of OFMSW and one weekly sample of biowaste of approx. 100 kg each. The determination of the composition, including 11 main material fractions: organic, wood, paper, plastics, glass, metals, textiles, multi-material, inert, hazardous, and others of a fine fraction, was verified. Finally, the average values based on the weekly samples were reported.

The chemical analyses were conducted on dried samples at 105 °C for 12 h. Three samples of each material were analyzed. Average values were reported.

The loss-on-ignition (LOI) test was used to determine organic matter (OM) in biofertilizers. The samples were subjected to dry combustion for six hours at a temperature of 550 °C. The total organic carbon (TOC) and nitrogen (N) contents were determined using a Vario Max CNS elemental analyser (Elementar Analysensysteme GmbH, Langenselbold, Germany). The amounts of metals in the sample were determined after the sample's calcination at 450 °C for six hours. The ash was dissolved in 5 mL of 6-mol × dm^3 HCl and diluted to a constant volume with distilled water [20]. The obtained extracts were analyzed to determine the amounts of potassium (K), zinc (Zn), copper (Cu), nickel (Ni), lead (Pb), and cadmium (Cd) using atomic absorption spectrophotometry in a Varian Spectra AA 220 FS apparatus (Varian Inc., Palo Alto, CA, USA). The total phosphorus (P) content was measured colorimetrically by the vanadium–molybdenum method [20].

Dry matter was measured gravimetrically after drying a 200-g sample for 24 h at 105 °C.

The pH value was determined in polyethylene bottles (1000 mL) filled with 400 mL of deionized water. Samples were added up to a volume of 600 mL and extracted for one hour. Immediately after extraction, the pH was determined in the substrate water suspension (Hach HQ40d, Düsseldorf, Germany).

3. Results and Discussion

The AD input materials characteristics are presented in Table 1. The fraction contents were similar to the results obtained in our previous study [13]. It was noticed that the organic content was higher in biowaste (67.2%) compared to OFMSW (46.3%), while the wood quantity was at a similar level (7.4 and 6.2%, respectively). The fine fraction content was about 13% higher in OFMSW, which can be explained by the coal ashes typical of Poland. Furthermore, the presence of paper, plastics, glass, inert, and other fractions may indicate insufficient sources of segregation.

Table 1. The composition of the mechanically sorted organic fraction of municipal solid waste (OFMSW) and separately collected biowaste.

Fraction	OFMSW	Biowaste
	Mass Share	Mass Share
Organic (incl. green waste) (%)	46.3 ± 2.3	67.2 ± 6.1
Wood (%)	6.2 ± 0.7	7.4 ± 0.8
Paper (%)	3.1 ± 0.3	2.9 ± 0.5
Plastics (%)	3.3 ± 0.5	1.2 ± 0.3
Glass (%)	4.6 ± 0.9	1.0 ± 0.3
Inert waste (%)	3.9 ± 1.0	1.5 ± 0.6
Textiles (%)	0.2 ± 0.1	0.1 ± 0.1
Metals (%)	0.1 ± 0.1	0.1 ± 0.1
Hazardous (%)	0.1 ± 0.1	0.1 ± 0.1
Tetra Pak (%)	0.5 ± 0.1	0.3 ± 0.1
Others (%)	0.9 ± 0.2	0.5 ± 0.1
Fine fraction 0–15 mm (%)	30.8 ± 3.9	17.7 ± 2.7

The comparison of the produced compost originated from OFMSW and biowaste and organic fertilizers requirements is presented in Table 2. The liquid fraction (effluents) was analyzed as the liquid fertilizer (Table 3).

Table 2. Characterization of the composts from digestate derived from the organic fraction of the municipal solid waste (ms-compost) and source-segregated biowaste (ss-compost).

Parameter	ms-Compost	ss-Compost	Polish Required Levels [21]	EU Required Levels [19]	German Required Levels [22]	Czech Required Levels [22]	Dutch Required Levels [22]	Greek Required Levels [22]
Metal contents								
Cadmium (Cd) (mg/kg $_{dry\ matter}$)	<1.0	<1.0	Max. 5	Max. 1.5	Max. 1.5	Max. 2	Max. 1	Max. 3
Chrome (Cr) (mg/kg $_{dry\ matter}$)	175 ± 6.6	23.5 ± 0.01	Max. 100	Max. 100 *	Max. 100	Max. 100	Max. 50	Max. 250
Mercury (Hg) (mg/kg $_{dry\ matter}$)	<0.3	<0.3	Max. 2	Max. 1	Max. 1	Max. 1	Max. 0.3	Max. 2.5
Nickel (Ni) (mg/kg $_{dry\ matter}$)	60.4 ± 2.1	18.1 ± 0.8	Max. 60	Max. 50	Max. 50	Max. 50	Max. 20	Max. 100
Lead (Pb) (mg/kg $_{dry\ matter}$)	221 ± 10.1	111 ± 10.1	Max. 140	Max. 120	Max. 150	Max. 100	Max. 100	Max. 300
Non-metal contents								
Organic matter (% $_{dry\ matter}$)	28.2 ± 4.0	31.6 ± 3.9	Min. 30					
Phosphorus (P_2O_5) (% $_{dry\ matter}$)	0.21 ± 0.2	0.48 ± 0.2	Min. 0.2	Min.1.0 **				
Potassium (K_2O) (% $_{dry\ matter}$)	0.31 ± 0.06	0.94 ± 0.06	Min. 0.5	Min. 1.0 **				
Total nitrogen (% $_{dry\ matter}$)	0.6 ± 0.1	1.06 ± 0.1	Min. 0.3	Min.1.0 **				
pH value (-)	7.8 ± 0.1	7.8 ± 0.1	-					
Water content (%)	33.5 ± 4.8	34.5 ± 6.0	-					

* Hexavalent chromium (Cr VI) must not exceed 2-mg/kg dry matter. ** The sum of each must be at least 3% for compound fertilizer.

Table 3. The effluents' characterization from the anaerobic digestion of the organic fraction of municipal solid waste (ms-effluents) and source-segregated biowaste (ss-effluents).

Parameter	ms-Effluents	ss-Effluents	Polish Required Levels [21]	EU Required Levels [19]	German Required Levels [22]	Czech Required Levels [22]	Swedish Required Levels [22]	Greek Required Levels [22]
Metal contents								
Cadmium (Cd) (mg/kg $_{\text{dry matter}}$)	2.02 ± 0.41	0.73 ± 0.15	Max. 5	Max. 1.5	Max. 2	Max. 2	Max. 1	Max. 3
Chrome (Cr) (mg/kg $_{\text{dry matter}}$)	84.6 ± 21.2	20.9 ± 5.3	Max. 100	Max. 100 *	Max. 100	Max. 100	Max. 100	Max. 250
Cooper (Cu) (mg/kg $_{\text{dry matter}}$)	251 ± 51	59.4 ± 11.9	-	Max. 300	Max. 100	Max. 150	Max. 600	Max. 400
Lead (Pb) (mg/kg $_{\text{dry matter}}$)	138 ± 28	44.4 ± 8.9	Max. 140	Max. 120	Max. 150	Max. 100	Max. 100	Max. 300
Mercury (Hg) (mg/kg $_{\text{dry matter}}$)	1.0 ± 0.3	0.26 ± 0.08	Max. 2	Max. 1	Max. 1	Max. 1	Max. 1	Max. 3
Nickel (Ni) (mg/kg $_{\text{dry matter}}$)	63.7 ± 12.8	18.1 ± 3.7	Max. 60	Max. 50	Max. 50	Max. 50	Max. 50	Max. 100
Zinc (Zn) (mg/kg $_{\text{dry matter}}$)	1328 ± 332	449 ± 113	-	Max. 800	Max. 400	Max. 600	Max. 800	Max. 1200
Nonmetal contents								
Organic matter (% $_{\text{dry matter}}$)	34.0 ± 8.5	43.4 ± 10.9	Min. 30	-				
Phosphorus (P_2O_5) (% $_{\text{dry matter}}$)	0.77 ± 0.07	0.64 ± 0.06	Min. 0.2	Min. 1				
Total organic carbon (TOC) (% $_{\text{dry matter}}$)	18.7 ± 5.7	28.3 ± 8.5	-	Min. 5				
Total nitrogen (% $_{\text{dry matter}}$)	2.73 ± 0.41	5.74 ± 0.86	Min. 0.3	Min. 1				
Dry matter (%)	21.6 ± 4.4	13.6 ± 2.8	-	-				

* Hexavalent chromium (Cr VI) must not exceed 2-mg/kg $_{\text{dry matter}}$.

The quality of the soil improvers, determined by several indicators, is crucial for the potential usage of waste treatment residues. The amendments must contain the organic matter (OM) appropriate content to enrich the soil [23]. The OM of ss-compost reached about 31.5% of dry matter (DM) and was 3.5% higher than the ms-compost and fulfilled the required levels (Table 2). The obtained values were similar to those reported by Teglia et al. 2011 for the post-composted digestate of organic waste (kitchen waste (15%), garden waste (75%), paper, and cardboard (10%), where a 38.6% OM content was established [23]. Regarding the liquid residues examined in this study, the OM was higher than for solid ones. The ms-effluents were characterized by a 34% OM content, followed by 43.4% for the ss-effluents. However, it was still a lower value than reported by Teglia et al. for wastewater treatment sludges [23]. Depending on the proportion of the primary (33% and 60%) and activated (65% and 40%) sludges, the OM content reached 56.7% and 59.9%, respectively [23].

The digestion residues characterize different DM, which is related to the feedstock and post-treatment process. Stürmer et al. (2020) analyzed over 560 test results of Austrian digestates, mainly agricultural. The reported DM content was, on average, 8.18% [18], which was similar to French digestate characteristics [24] but lower when compared to an Italian study (12.7% for agricultural waste) [17]. The effluents examined in this study were characterized by 21.6% and 13.6% of DM for ms- and ss-effluents, respectively (Table 3). The reason for this might be higher mineral and fine fraction contents in the mechanical sorted organic fraction of municipal solid waste [13]. The DM content affects the stickiness and viscosity. It was found that the DM content around 20% appeared too high to be easily used directly [23]. The moisture can affect higher transport costs, storage difficulties, and distribution problems. Thus, the liquid residues should be directly spread on soils in a local area. When intended for transport, distribution should be solid amendments. In the case of examined composts, the moisture was at the level of around 34% (Table 2), which proved sufficient for commercialization.

The ss-effluents were characterized by around 28% of the organic carbon (OC) content, while the ms-effluents reached almost 19% (Table 3). Stürmer et al. (2020) showed a 41.6% average OC content [18], while Möller et al. (2012) reported a carbon content of 28–47% in the literature research [25]. Furthermore, it was stated that an OC share of 80–95% of AD feedstock resulted in a 22.4–44.6% OC content in the digestate. Based on that, it can be assumed that, in OFMSW, the organic carbon share was much lower and might be affected by the mineral fractions content.

The balance between carbon and nitrogen and phosphorus and potassium is essential to state the agronomic use of an organic product [26]; therefore, their contents are under requirements. For instance, the total nitrogen (TN), phosphorus (P), and potassium (K) contents are under French regulations of 3% of the fresh matter [23]. According to the German requirements, fertilizers must have at least 0.5%, 0.3%, and 0.5% DM of TN, P, and K, respectively [23]. The Polish requirements are minimal at 0.3%, 0.2%, and 0.3%, respectively (Tables 2 and 3). The EU Regulations [19] established a minimal content of their sums at 1% for compound fertilizers. The ms-compost did not fulfill even the Polish requirements (Table 2). The ss-compost achieved national expectations. However, the EU regulations were met only regarding TN (1.06% of the DM), yet the total content of the TN, P, and K was only 2.48% of the DM (Table 2). In the case of ms-effluents, the TN content was at the level of 2.7% of DM, which met even the EU requirements for single-component fertilizers (2%). The ss-effluents contained double TN loads (5.74%) (Table 3). The EU Regulations [19] also foresee limits for copper and zinc as micronutrients (Table 3). Their concentrations in soil might be crucial if they are nutrients or toxic. Excess copper undermines plant growth [27]. The zinc limit was exceeded in the ms-effluents by over 65% (Table 2).

The heavy metals contents in fertilizers must be maintained on a low level that guarantees the safe production of food and animal feed in cultivated crops [28]. Due to OFMSW heterogeneous characteristics, it is difficult to generalize heavy metal contaminations [18].

The AD and post-composting processes ensure homogeneity of the materials. Furthermore, heavy metal availability and solubility decrease due to the precipitation processes [25]. Nevertheless, the amount of metal remains constant compared to the input [18]. Since the heavy metal loads affect environmental contamination, value limits are set. The ss-compost fulfills the national and EU requirements (Table 2), while in the ms-compost, the contents of chrome (175 mg/kg), nickel (60.4 mg/kg), and lead (221 mg/kg) were higher than the limits (Table 2). The ss-compost contamination of heavy metals was similar to the Italian composts examined by Beggio et al. [17] and Austrian [18]. Regarding ms-effluents, the acceptable amount of nickel (63.7 mg/kg) was exceeded, while the lead content (138 g/kg) was at the threshold limit values (Table 3).

The discrepancies in limits can be noticed in the local requirements (Tables 2 and 3). As for liquid biofertilizers, the Swedish Cd maximum contamination was established at 1, while the Greek at 3 and Czech at 2-mg/kg $_{\text{dry matter}}$. In contrast, the Cu content was at the maximum levels of 600, 400, and 159-mg/kg $_{\text{dry matter}}$, respectively (Table 3). Additionally, in composts, the heavy metal limits in various standards from across Europe can be found, e.g., the Greek Cr maximum contamination was established at 250, while the Czech at 100 and the Dutch at 50-mg/kg $_{\text{dry matter}}$ (Table 2). However, compared to the local requirements, the European ones are on a higher level (Tables 2 and 3). Thus, it can be stated that they indicate target values that the EU Members should strive to achieve. The reason for the difficulty of meeting them might be the source segregation quality. The heavy metal contents might also affect the coal ashes contents or the waste origin from the urban area.

Another critical issue is the hygienic parameters. Every soil amendment cannot contain pathogens, toxins that threaten the safety of crops, animals, and humans; thus, legal requirements are implemented. Due to fertilizers containing animal byproducts, including food waste, Regulation (EU) 142/2011 necessitates the absence of *Salmonella* in 25 g of a sample and the number of colony-forming units (CFU) less than 1000 of *Enterobacteriaceae* or *Enterococci*. These requirements were applied in the EU regulation of fertilizers. The AD in thermophilic conditions ensures the proper sanitization of OFMSW [14].

It is important to produce good-quality organic fertilizers, because, in the long term, the usage of inorganic fertilizers causes water pollution and soil structure degradation [29,30]. In contrast, organic fertilizers might improve them [31]. Cavagnaro [32] confirmed the improvement in the effectiveness of essential nutrients for improving plant growth. Thus, it can be stated that waste biological treatment can bring environmental gains. AD brings more benefits than single composting, mainly due to the possibility of energy recovery from waste [33], despite the digestate and its proper sanitization [14]. Some researchers have confirmed the soil amendment effect of a digestate [17,34]. Contrariwise, some researchers reported negative impacts of applying a digestate. The soil toxicity might appear due to uneven distribution, uncontrolled nitrogen application, or inadequate quality assessment, including sanitization [35,36]. Thus, the production of good-quality fertilizers requires the careful control of all aspects of the process, from feedstock to field. Considering the potential negative effects of using a digestate from agricultural waste, providing a safety assurance for the digestate is essential in the organic fraction of municipal waste. Hence, the thermophilic aerobic digestate treatment should ensure the sanitization of OFMSW [14], and as a second step, the aerobic digestate treatment should provide higher-quality compost.

4. Conclusions

Based on the compost examination, ss-compost fulfills the local fertilizers' requirements, while the ms-compost metal contents are too high. The nitrogen and phosphorus contents are even two times higher in ss-compost than in ms-compost, while the potassium concentration is even three times higher. Regarding the metals, the biggest exceeding limit values were noted for lead (over 80 mg/kg) and chrome (75 mg/kg). The heavy metal contamination of the ms-compost was much higher and followed by a lower concentration of nutrients.

Based on the effluents examination, ss-effluents fulfilled the fertilizers' requirements, while, regarding ms-effluents, the limit values were exceeded. The nitrogen content was even two times higher in ss-effluents than in ms-effluents. Regarding metals, the biggest exceeding limit values were noted for nickel (over 3 mg/kg) and zinc (over 500 mg/kg). In general, the heavy metal contamination of ms-effluents was much higher. Therefore, the European requirements should be the goal for European countries to produce high-quality and safe biofertilizers.

One of the more significant findings of this study was that compost and effluents derived from separately collected biowaste AD are appropriate for biofertilizer generation and usage, while the OFMSW suitability is limited. However, to meet the EU requirements, the source segregation quality should be improved and environmental pollution reduced.

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