

Towards a circular economy for stabilized residual from organic municipal solid waste processed at an MBT installation – the potential of SR recycling and recovery

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ABSTRACT

Stabilized residual (SR) will not lose its waste status as long as mechanical-biological treatment (MBT) installations deal with residual municipal solid waste. So far, SR has mainly been land-filled, but its recovery could be a new direction for its management. An efficient approach should consider the specific characteristics of SR that can be used for designing SR recycling. Thus, this study aimed to determine the efficiency of organic waste stabilization, detailed biodegradation kinetics and leachate quality. Moreover, the shares of size fractions and SR composition were determined after two-stage aerobic stabilization. Three variants were conducted in a full-scale MBT installation for 8 (SR8), 10 (SR10) and 12 (SR12) weeks with differing aeration intensities in the covered windrows (405–810 m³/h), and optional maturation in uncovered windrows (0–4 weeks). After 8 weeks, the organic waste had become stable. In SR12, the biodegradable waste content was 1.5-times lower and the share of the <10 mm size fraction was 1.3-times higher than in SR8. In the SRs, glass waste constituted over 40% of the 40–10 mm fraction; plastic waste was more than 50% of the >40 mm fraction. Valorization and recovery of valuable materials from specific size fractions of SR should be considered at MBT plants.

Keywords: Contamination ratio; Leachate; Aerobic stabilization; Municipal solid waste; Kinetics of biodegradation; Mechanical-biological treatment

1. Introduction

Mechanical-biological treatment (MBT) plants prepare residual municipal solid waste (rMSW) for landfilling. They process rMSW as well as selectively collected fractions of municipal solid waste. MBT includes mechanical pre-processing stages to sort out recyclable materials such as paper, metals and plastics, and a biological stage to reduce and stabilize the biodegradable organic matter (commonly called organic fraction of municipal solid waste (OFMSW))

under controlled anaerobic and/or aerobic conditions. Thus, a MBT plant combines a sorting facility with biological treatment, such as aerobic stabilization and/or anaerobic digestion. MBT is considered a pretreatment method for improving aerobic stabilization or anaerobic digestion of the biodegradable fraction of rMSW [1]. MBT plants use a wide range of different technologies, and defining what an average facility is can therefore be difficult. The main difference between plants is the method of biological treatment

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during the decomposition stage. MBT plants can be classified into two categories: plants that combine anaerobic and aerobic biological treatments, or anaerobic treatment plants.

Aerobic processes are more commonly used for stabilization of organic waste. Aerobic stabilization of the OFMSW mechanically separated from rMSW should reduce its volume, minimize its content of organic matter available to microorganisms, and reduce its biogas production potential and susceptibility to washing out or settling after it is landfilled. MBT can increase the useful life of a disposal site by reducing the amount of waste inflow [2].

Although stabilization process is not strictly regulated, the quality of the final product from MBT plant is regulated [3]. Therefore, process monitoring at full scale usually relies on indicators enabling indirect control, whereas the final product is evaluated in terms of maturity and biological stability. Assessments of biological stability have recently been classified in two categories, focusing on either the biotic response of the tested materials or on the physio-chemical characteristics of the organic matter [4]. As microbial (biotic) activity is directly associated with the content and bioavailability of organic matter, this method of assessment is therefore extensively applied. Microbial activity can be evaluated by measuring the rate or amount of oxygen uptake/consumption, the rate of carbon dioxide production, the increase in temperature due to aerobic respiration of biodegradable organic matter, or in an anaerobic environment, the amount of methane produced. Assessment of biological stability by determining the physio-chemical characteristics of the materials is based on the fact that these characteristics are affected by degradation or mineralization of biodegradable organic matter.

The stability of a waste is defined as the extent to which its readily biodegradable organic matter has decomposed. Thus, an analysis of the efficiency of MBT plants requires a reliable measure of the content of biodegradable organic matter in organic wastes. In biologically stable stabilized residual (SR), the availability to microorganisms of readily biodegradable organic matter is limited [5]. In other words, biological stability is the degree of mineralization achieved during aerobic or anaerobic biological processes. This is connected to the degree of degradation of biodegradable organic substances and to the biological activity of microorganisms [6]. Traditionally, organic matter is measured in terms of volatile solids content, and this measurement is also used to evaluate the stabilization of the SR. However, in the case of rMSW and SR, this leads to overestimation of the amount of readily biodegradable organic matter, as these wastes contain plastics and other organic non-biodegradable substances.

Global indicators of the biological stability of SR are its content of total organic carbon ($\text{TOC} \leq 18\%$), its calorific value ($H_0 \leq 6,000 \text{ kJ/kg DM}$) and the concentration of TOC in the eluate ($\text{TOC} < 250 \text{ mg TOC/L}$) [7]. For leachate formed during biological stabilization, the standard method for determining the amount of readily biodegradable organic matter is the biochemical oxygen demand (BOD_5). Measurements of the BOD_5/COD (chemical oxygen demand) ratio in leachate have been proposed as an indicator of stability by Cossu et al. [8], who maintain that this ratio is a more useful index than respirometric indexes and biogas

productivity measured directly in SR samples. However, although measurements of the BOD_5/COD ratio can be used to evaluate the biological stability of organic samples, respirometric techniques are also recognized to be highly effective [9,10] and suitable for monitoring the process of organic matter biodegradation [11–13]. Microorganism respiration tests are used to predict the biological stability of heterogeneous solid waste and the share of the readily biodegradable fraction in rMSW and SR [14]. One of the most common procedure for measuring stability under anaerobic conditions is the GB21 anaerobic test [15], which was designed to measure biogas production over 21 d after completion of the lag period; a GB21 value $\leq 20 \text{ NL/kg DM}$ is desirable [16].

Another example is the dynamic respiration rate (DRI) test introduced by Adani et al. [14,17]. However, the reference is the aerobic respiration test (AT4), which is conducted over 4 d of aerobic incubation. An AT4 value $\leq 10 \text{ g O}_2/\text{kg DM}$ indicates that the organic material is stable. These indices have proven to be very useful for monitoring the performance of a wide variety of full-scale waste treatment facilities [11,12,18,19] and for predicting the stability of final products, such as SR. In the European Union, the required AT4 value in the final product depends on local standards: for example, in Germany, it should be $5 \text{ mg O}_2/\text{g DM}$; in Austria, $7 \text{ mg O}_2/\text{g DM}$; and in Poland, $10 \text{ mg O}_2/\text{g DM}$. If aerobic stabilization of the OFMSW is carried out in two stages with the use of closed reactors and a composted aerated pile, at the end of the first so-called hot phase, the material should have an AT4 value of $20 \text{ mg O}_2/\text{g DM}$ [20].

An indicator of the effectiveness of the biological part of a MBT installation is the biological stability of the SR. Biological stability is increased by decreasing the content of readily biodegradable organic matter. Moreover, as a result, the concentration of organic compounds in the leachate generated during aerobic stabilization of SR is 90% lower than that in the leachate generated in landfills with unstabilized waste. The SR from MBT plants occupies up to 70% less volume than unstabilized rMSW [21]. The SR can be used for intermediate layers, coverings or reclamation layers for landfills, and not only as waste for landfilling.

It is not expected that the SR will lose its waste status, because the main goal of a MBT installation is not to produce compost that can be used as fertilizer, but rather to minimize greenhouse gas emissions from the waste [22]. Following the changes in the framework around the management of waste and its use for energy, strategic and operational decisions with respect to investments in new treatment facilities, are indeed necessary [23]. Although several decision tools have been proposed [24], an efficient approach should consider the specific characteristics of waste. Whether stabilized organic residues are recovered or landfilled, the assessment of the biological process efficacy is fundamental.

Despite many years of operation of MBT installations, one of the technological problems in the treatment of rMSW is the biological stability of the SR. The effectiveness of biological treatment of different kinds of organic waste has been extensively studied. However, to date, only several attempts have been made to determine the kinetics of biostabilization of organic matter in OFMSW. Moreover, in the

context of a circular economy, it would be worth knowing the detailed composition of the SR, of which studies are scarce. Knowledge of SR composition may be used as a decision tool for designing SR recycling. Thus, in view of the above, the aim of this study was not only to determine the stabilization efficiency of the <80 mm organic fraction mechanically separated from rMSW, but also to determine the detailed kinetics of biodegradation and the quality of leachate produced during the process. Moreover, the share of the size fractions and the composition of the SR was determined during 2-stage aerobic stabilization. The experiment was conducted under the operational conditions of the MBT installation.

2. Materials and methods

2.1. Aerobic stabilization technology

The <80 mm organic fraction mechanically separated from rMSW on a two-section sieve was aerobically stabilized in a two-stage full-scale system at an MBT plant. In stage I, the process was carried out in reinforced concrete modules. The weight of the material in the module ranged from 300 to 400 tons, and the average density ranged from 0.65 to 0.80 Mg/m³. Reinforced concrete modules were equipped with aeration and irrigation systems. Air was supplied by fans with a capacity of 27 m³/min. To maintain the adjusted humidity at ca. 50% in the modules, the material was sprinkled with water.

After 4 weeks of stabilization in the modules, stage II began, in which the <80 mm organic fraction was stabilized in windrows (2.0 m high, 8.0 m wide, 30.0 m long) covered with a membrane for 4 weeks. As above, the capacity of the fans used for aeration was 27 m³/min; however, the intervals of aeration and break differed depending on the technological variant being tested (Table 1).

After 4 weeks of stabilization in the covered windrows, the material in two of the three variants was transported to the final maturation site: uncovered windrows (1.5–2.0 m high, 3.0 m wide, 15.0 m long). Further maturation in these windrows ranged from 2 to 4 weeks. Thus, the total time of stabilization of the <80 mm organic fraction lasted for 8, 10 or 12 weeks, and these experimental variants are hereafter designated SR8, SR10 and SR12, respectively. Thus, in the case of SR8, stabilization was completed after 8 weeks and took place only in the modules and covered windrows, whereas SR10 and SR12 additionally included maturation in uncovered windrows for 2–4 weeks, respectively. Each technological variant was done in duplicate. The average values of the parameters are given.

In the modules and the covered windrows, the temperature was monitored at depths of 0.5 and 1.5 m. The water content was monitored in both the modules and the covered windrows. The leachate formed during aerobic stabilization, was collected in tanks and treated together with municipal wastewater.

2.2. Composition and particle size distribution of <80 mm fraction and SR

The <80 mm fraction and the SR from each technological variant were sampled for analyses. Immediately after separating rMSW on the sieve, the <80 mm fraction was

randomly sampled in various places to obtain a representative sample (about 240 kg) of the entire mass (many tons) of this fraction. The samples of the SR were taken from different places in the windrows. The final weight of these samples was about 240 kg.

A cross-sectional technique was used for sample preparation. The samples were divided into four parts and then two parts were discarded. The other two parts constituted the sample for analysis. Samples of the <80 mm fraction and the SR were taken in three replicates at each sampling time.

The samples of the <80 mm fraction and SR were separated on the sieves into the following particle size fractions: >60 mm, 60–40 mm, 40–10 mm, <10 mm. The percent composition of these fractions was calculated on a fresh-weight basis. The composition of the size fractions, except the <10 mm one, were analyzed in accordance with the Polish Standard (PN-Z-15006:1993P) with the introduction of these divisions: biodegradable waste (paper and cardboard, vegetable waste, other organic waste, food animal waste, and textile waste), glass waste (packaging and technical glass), metal waste (ferrous, non-ferrous, and aluminium foil, as well as mineral waste, electronic and multi-material waste), plastic waste (PET, PS, PP, HD-PE, films and others), and other waste (including polystyrene foam and diapers).

2.3. Analyses of the <80 mm fraction, SR, and leachate

In the fresh mass of the <80 mm fraction and the SR, the humidity and dry matter (DM) content were determined. In dry solid samples, the content of total carbon (TC) and of organic matter (OM) as loss on ignition were determined (Shimadzu Liquid TOC-VCSN carbon analyser). For TC content analyses, the samples were milled in Retsch SM100 mill to a diameter of 0.5 mm. In the leachate, the TOC content was determined (Shimadzu Liquid TOC-VCSN carbon analyser), as well as the COD, by the dichromate method, and the concentrations of ammonium and total nitrogen (TKN), by distillation with titration. Chemical analyses of the <80 mm fraction, the SR, and the leachate were performed according to APHA [25].

The aerobic respiration test (AT₄) was performed with samples of the fresh mass of the <80 mm fraction and the SR. The AT₄ was carried out during 4 d under aerobic conditions by measuring the oxygen consumed for degradation of readily biodegradable organic matter using a manometric Oxi-Top Control set (German Standard AbfAbIV, Anhang 4) [26]. AT₄ values were determined in triplicate for each sample.

2.4. Kinetic parameters and statistical analyses

The kinetics of changes in the AT₄ values, and the OM and TC content proceeded according to 1st order kinetics during aerobic stabilization. Linear regression was used to determine the relationships between (1) the values of AT₄ and OM content, (2) the TC and OM content, and (3) the values of AT₄ and TC content. The fit of the models was assessed with the coefficient of determination (R^2). For all calculations, STATISTICA 13.3 (StatSoft, Tulsa, USA) was used. A result was considered significant at $p < 0.05$.

3. Results and discussion

3.1. Characteristic of the <80 mm fraction subjected to aerobic stabilization

In the present study, the <80 mm fraction mechanically separated from rMSW at the MBT installation was subjected to aerobic stabilization. This fraction is generally considered to be rich in organic materials and to require biological treatment. Despite that fact that the <80 mm fraction was divided into four particle size fractions (>60 mm, 60–40 mm, 40–10 mm, <10 mm), it was only possible to analyze the composition of the three largest size fractions. The analysis of the composition of the <80 mm fraction revealed that biodegradable materials predominated, constituting from 55% to more than 60% of each of these three size fractions. Food waste content made up the largest share of biodegradable materials, and the remaining part was paper and textiles (Table 2; <80 mm fraction). The share of glass waste was highest in the 40–10 mm fraction (26%). Finally, the content of metal waste in the size fractions ranged from 1.2% to 4.95% (Fig. 1a).

On average, biodegradable waste constituted 51.5% of the <80 mm fraction, excluding the <10 mm fraction, in which separation of the particular components of waste was not possible. However, other researchers have indicated that the smallest size fractions of rMSW contain organic matter. For example, Jędrzak et al. [27] indicated that organic matter constituted $29.8\% \pm 7.1\%$ DM of the <10 mm fraction from MSW. Bernat et al. [28] found that, in the fine size fraction of 0–20 mm from MSW, the organic matter content was 31.4% DM. This means that the content of biodegradable waste in the <80 mm fraction would be higher if all of its constituent particle size fractions were taken into consideration.

Residual municipal solid waste (rMSW) is a very heterogeneous material, which affects the composition of the separated waste fractions. Edjabou [29] et al. found that rMSW contained 41%–45% of food waste, which comprised vegetable (31%–37%) and animal-derived food wastes (7%–10%). Those authors showed that the remaining fractions were composed of materials such as paper, board, etc., constituting 26% of the rMSW.

Cesaro et al. [30] found that biodegradable material constituted the main part of the mechanically sorted organic fraction of MSW (MS-OFMSW), accounting for 67% of the total weight. Despite this considerable content of organic materials, they also found impurities, mainly plastics (19%), paper (8%), inerts (5%), and metals (1%).

Montejo et al. [31] studied the composition of OFMSW from 10 different MBT plants and determined that on average the input contained up to $63.2\% \pm 5.5\%$ of organic matter; $9.4\% \pm 5.5\%$ of paper and cardboard; $9.3\% \pm 1.7\%$ of plastics, and $10.5\% \pm 3.2\%$ of glass. It is hard to say, if the organic matter means the loss after ignition or biodegradable waste as a component. They also found metals, textiles, wood, other non-combustible materials and batteries in the feedstock for stabilization. Ball et al. [32] estimated the share of the biodegradable fraction in municipal waste to be 65%. Finally, Jędrzak and Suchowska-Kisielewicz [33] found that the average share of organic compounds in OFMSW intended for biological

Table 1

Operational parameters of the aerobic stabilization of the <80 mm organic fraction in two-stage system (modules (stage I), covered windrows-uncovered windrows (stage II))

Variant of stabilization	SR8	SR10	SR12
Total time aerobic stabilization (weeks)	8	10	12
Module			
Aerobic stabilization time (weeks)	4	4	4
Air supplied (m ³ /h)		540	
Fan operation time (s)		90	
Fan break time (s)		180	
Covered windrow			
Aerobic stabilization time (weeks)	4	4	4
Air supplied (m ³ /h)	810	405	540
Fan operation time (s)	60	60	90
Fan break time (s)	120	180	180
Final maturing in uncovered windrow			
Final maturing time (weeks)	–	2	4

stabilization in 18 MBT installations ranged from 42.5% to 53.9%.

3.2. Aerobic stabilization of the <80 mm fraction in two-stage system covered modules-windrows

3.2.1. Temperature in stabilized material during aerobic stabilization

In stage I of the study reported here, aerobic stabilization of the <80 mm organic fraction was carried out in covered modules for 4 weeks. Then in stage II, this material was stabilized in covered windrows, also for 4 weeks. In the case of SR8, stabilization was complete after 8 weeks. In the cases of SR10 and SR12, stabilization was prolonged in uncovered windrows by 2 and 4 weeks, respectively. In stage I, and in the covered windrows in stage II, the temperature was monitored at depths of 0.5 and 1.5 m in the material undergoing stabilization. The presence of organic matter in the <80 mm fraction and aeration caused the degradation of organic matter to start, which was accompanied by an increase in temperature.

In MBT plants, aeration during biological stabilization is important for supporting microbial activity, controlling temperature and removing excess moisture. The airflow rate is thus set to achieve either temperature control or removal of excess moisture. The regulations for the production of SR require the temperature profile to be high enough to prevent possible risks from the presence of pathogens.

The temperature profiles during stabilization of the <80 mm organic fraction are shown in Fig. 2. Slight differences in the temperature profiles may result from the heterogeneity of the <80 mm fraction and the differences in the intensity of aeration in covered windrows, which ranged from 405 to 810 m³/h. In general, however, the temperature was higher in the deeper part of the material (1.5 m in depth) than at the top of the material (0.5 m in depth). It can be seen that, in the covered windrows, there was

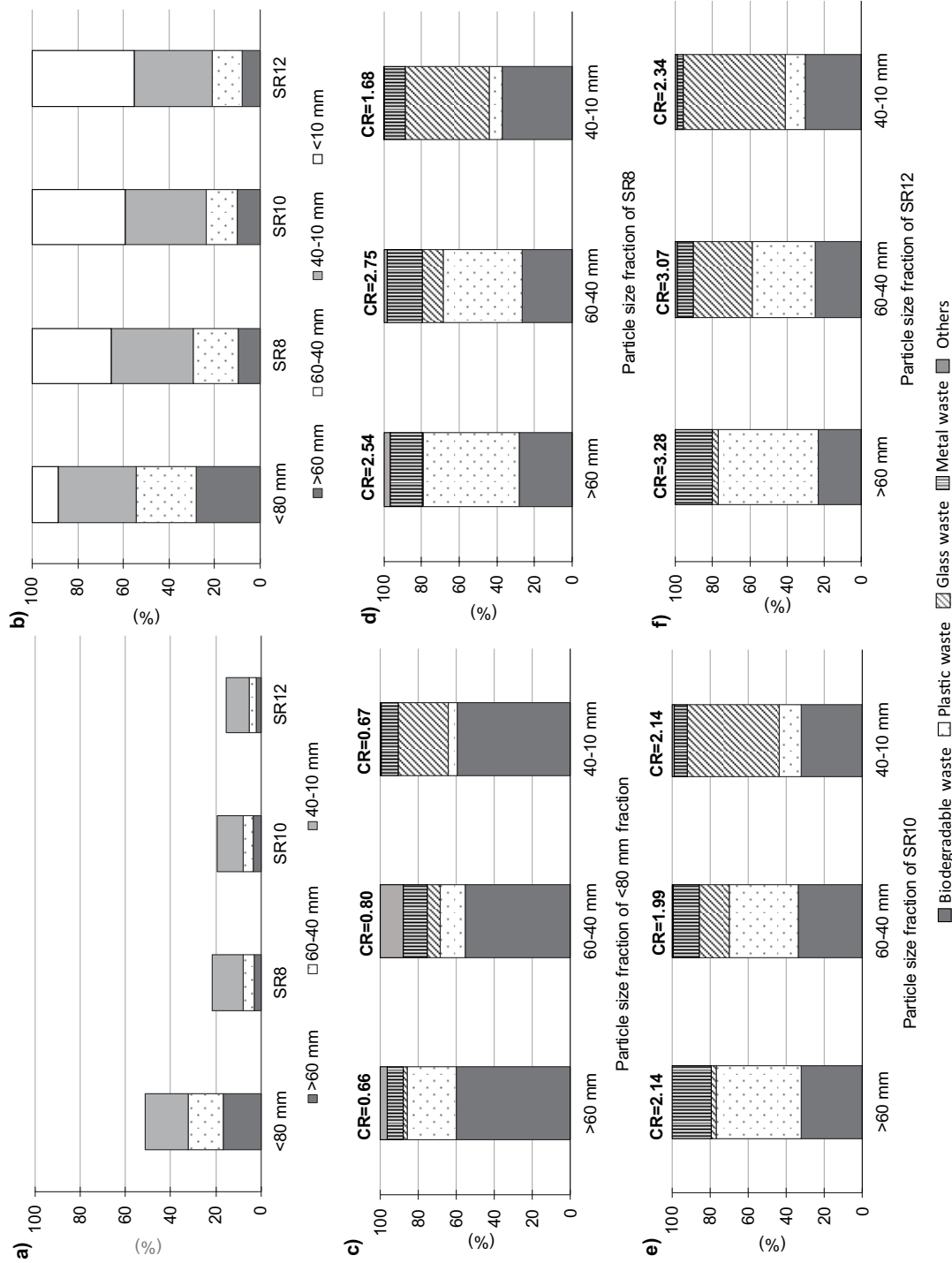


Fig. 1. The percent shares of the only biodegradable waste in the <80 mm fraction, SR8, SR10 and SR12 (a), the percentage share of the particle size fractions of the <80 mm fraction and SR8, SR10, SR12 (b), the composition (the legend at the bottom refers to the (c-f)) of the particle size fractions in the <80 mm fraction, SR8, SR10 and SR12 (as 100% of a particular particle size fraction, and excluding the <10 mm fraction); contamination ratio (CR) in the <80 mm fraction and the SRs is given (c-f); CR was calculated as the ratio of the percent share of a contaminants to that of the biodegradable waste.

a temperature gradient between the depths of 0.5 m and 1.5 m (Fig. 2, SR8), and the gradient was steeper when the intensity of aeration was higher.

In the modules in all experimental variants, the temperature reached maximum (ca. 80°C) at both measurement points after 3 d. Then, the temperature remained at this high level during the remaining time of stabilization in the modules. After 28 d of module stabilization, the material was transferred into covered windrows, which caused a temporary temperature decrease. In the covered windrows, due to turning and aeration of the material, the temperature increased sharply over 2–3 d, and thermophilic conditions were achieved again (above 70°C). After this increase, the temperature gradually decreased, and after more than 3 weeks, it dropped below 50°C. In variants SR10 and SR12, the temperature was not monitored in the uncovered windrows.

3.2.2. Moisture in stabilized material during aerobic stabilization

It is known that the moisture content during aerobic stabilization, which is similar to that during composting, is generally recommended to be between 55%–65%. When the humidity of the material is too low, microbiological transformations can be reduced or even inhibited. In contrast, when the moisture content is too high, the pores in the material can become filled with water, which may reduce oxygen penetration. This may cause the creation of anaerobic zones, and unpleasant and unwanted odours, which are very undesirable in municipal waste treatment plants. During stabilization of the <80 mm organic fraction, the humidity was monitored (Fig. 3). In covered modules, the moisture content was controlled. However, it should be emphasized that the humidity measured during aerobic stabilization of the <80 mm organic fraction is the result of irrigation of the stabilized material, formation of water during mineralization of organic matter, and evaporation of water through aeration. The humidity was maintained at around 50%, which means that the content of DM was also around 50%. In stage II, during stabilization in the windrows, the humidity was not controlled. After formation of the windrows, the humidity in the material started to decrease.

In SR8, with an aeration intensity in covered windrows of 810 m³/h, the humidity of the stabilized material decreased by about 40%, whereas, in SR12, with a lower aeration intensity of 540 m³/h, it decreased by 26% (Fig. 3).

In the uncovered windrows in the SR10 and SR12 variants, the moisture content was 30%–33%. Intensive mineralization of organic matter was observed up to 7 weeks of stabilization, during which a decrease in the content of OM was observed. After this time, changes in OM content were not visible.

3.2.3. Leachate from stabilized material during aerobic stabilization

Microbial transformation of organic compounds during anaerobic stabilization of the <80 mm organic fraction is accompanied by leachate formation. The quality of the leachate was used as an indicator of the intensity of

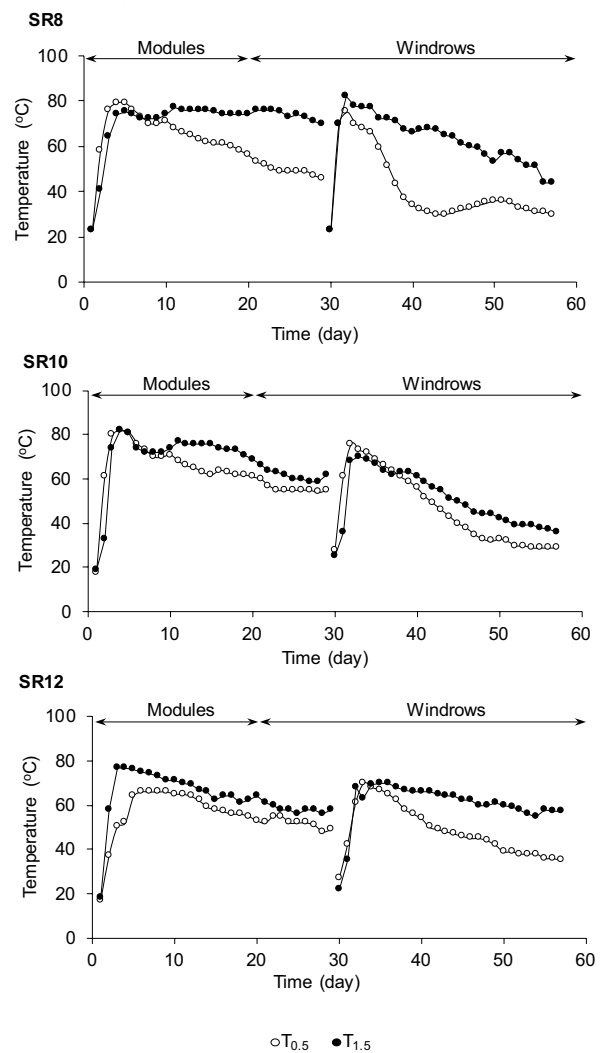


Fig. 2. Temperature profiles during aerobic stabilization of the <80 mm organic fraction in modules and covered windrows; $T_{1.5}$ – temperature at a depth of 1.50 m, $T_{0.5}$ – temperature at a depth of 0.5 m.

biotransformation of the organic fraction of the <80 mm fraction. Leachate did not form during the 4th week of stabilization, in the module, and also during the 5th, 6th and 7th weeks of stabilization, in the covered windrows. In leachate produced in the first week of stabilization, the organics concentration was 48–68 g COD/dm³. The TKN concentrations were 1.3–2.6 g TKN/dm³, and ammonium constituted about 50% of TKN. Together with the decrease of biodegradation of organic matter in the <80 mm organic fraction, the concentrations of organic and nitrogen compounds in the leachate produced during 8 week of stabilization decreased about 20- and 2-fold, respectively. No leachate was produced at the end of stabilization, in the uncovered windrows (Table 3). This resulted from the fact, that as it was mentioned, both, in covered and uncovered windrows, irrigation was not applied. Besides, the mineralization process of organic matter was ending.

The composition of leachate from aerobic stabilization is similar to that of young landfills leachate [34], which is

characterized by high concentrations of organic compounds expressed as both, chemical COD and biological (BOD) oxygen demands. According to the literature, the concentration of COD in this leachate ranges between 0.08 and 185 g O₂/dm³

[35]. That qualified it as highly susceptible to biodegradation [36]. This leachate cannot be discharged to the receiver without treatment, thus, it is gathered in a retention tank at the side at MBT plant. A part of his leachate can be applied for irrigation to accelerate the stabilization of organic matter. However, the great part of leachate need to be treated [37].

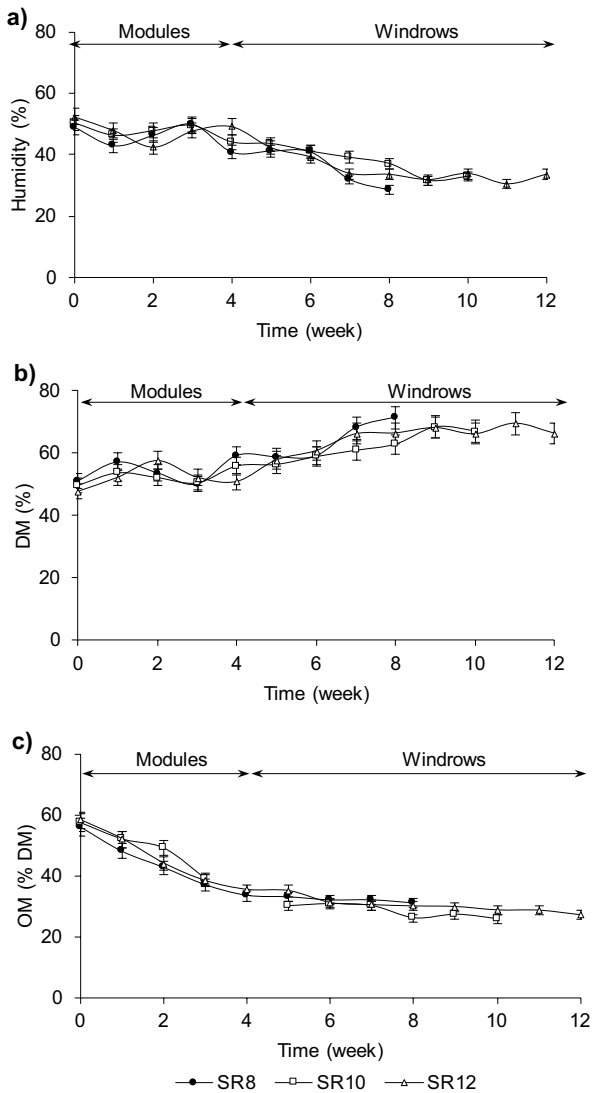


Fig. 3. The humidity (a), and contents of dry matter (DM) (b) and organic matter (OM) during aerobic stabilization of the <80 mm organic fraction of municipal solid waste.

Table 3
Characteristics of the leachate produced during aerobic stabilization of the <80 mm fraction

Time (week)*	TKN (mg/dm ³)			N-NH ₄ (mg/dm ³)			COD (mg/dm ³)		
	SR8	SR10	SR12	SR8	SR10	SR12	SR8	SR10	SR12
1	2,621.0	1,246.0	1,291.0	1,096.3	602.0	880.0	48,687.0	68,067.0	56,160.0
2	968.8	958.3	1,406.0	552.0	552.0	800.0	29,955.0	39,955.0	56,000.0
3	851.0	669.9	1,764.0	434.0	266.5	840.0	3,469.0	9,904.6	35,360.0
8	726.2	700.0	788.4	404.0	377.0	409.0	2,857.0	3,314.0	2,864.0

*Leachate did not form during weeks 4, 5, 6 and 7 of aerobic stabilization.

3.2.4. Changes in contents of organic matter and total carbon, and in AT4 values during the stabilization process

Fig. 4 shows the changes in contents of organic matter and total carbon (in g/kg DM) and the AT4 values of the material during the stabilization process. The initial content of organic matter in the <80 mm organic fraction ranged from 560 to 582 g OM/kg DM, whereas the content of total carbon was 300–320 g TC/kg DM. The AT4 value was 65.9–72.5 mg O₂/g DM. After 8 weeks of the process in all variants, the contents of OM and TC and the AT4 value of the material reached 260–320 g OM/kg DM, ca. 200 g TC/kg DM and 13.5–20 mg O₂/g DM. These values remained on a similar level until the end of stabilization in each variant. The effectiveness of OM decrease (calculated with the equation of Peredes et al. [38]) was 64%–75%.

The initial values of the OM and TC contents of the <80 mm organic fraction and its initial AT4 value were similar in each stabilization variant. Moreover, despite the fact that the intensity of aeration in the covered windrows from ranged 405 to 810 m³/h, the final values of these measurements were similar in all stabilized residuals (SR8, SR10 and SR12). Slight differences were due to the heterogeneity of the organic fraction that was subjected to aerobic stabilization. The similarity of the stabilization process in all variants was confirmed by the similar tendencies in the changes in AT4 values and contents of OM and TC in the material throughout the process (Fig. 4); these values all decreased according to first order kinetics. The materials in the closed modules were all aerated at the same intensity; thus, the rate constants for the decreases in the AT4 values (k_{AT4}) and the contents of OM (k_{OM}) and TC (k_{TC}) differed only slightly between variants: 0.35–0.51 week⁻¹, 0.28–0.43 week⁻¹ and 0.49–0.62 week⁻¹, respectively.

The values of the rate constants corresponded to the rates of the decreases in AT4 value and contents of OM and TC (r_{AT4} , r_{OM} , r_{TC}), which ranged from 18.3 to 37.8 mg O₂/(g DM week), 90.3 to 107.5 g OM/(kg DM week), and 54.9 to 68.2 g TC/(g DM week).

Studies on the kinetics of changes in the characteristics of municipal waste during the stabilization process

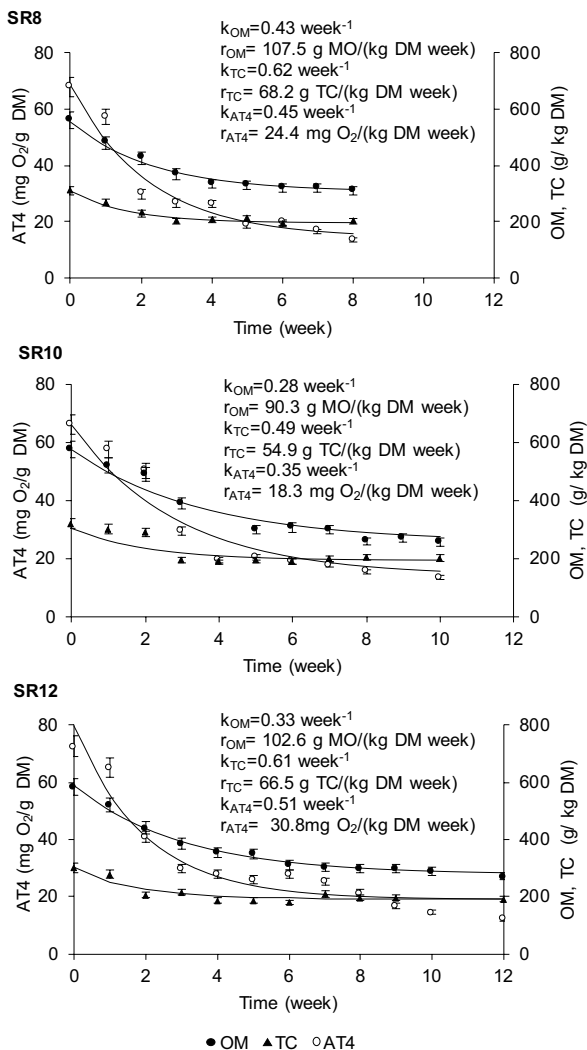


Fig. 4. Changes in contents of organic matter (OM) and total carbon (TC) and in the AT4 values during aerobic stabilization.

are not numerous. The kinetic constant of degradation of organic matter depends on the organic substrate being composted/stabilized, its chemical composition, the composting conditions or the technology being used. For example, with a passively aerated reactor, Wojnowska-Baryła et al. [39] investigated the effectiveness of aerobic stabilization of the organic remaining fraction (ORF) from full-scale autoclaving of unsorted municipal solid waste. The ORF constituted 30% of the waste after autoclaving and could not be landfilled without further stabilization. The authors found that the rate constants of organic matter removal were $0.033\text{--}0.068 \text{ d}^{-1}$, with a process rate of $8.4\text{--}12.0 \text{ g OM}/(\text{kg DM d})$ ($58.8\text{--}84.0 \text{ g OM}/(\text{kg DM week})$). The rate constants and the rates for the decreases in the AT4 values were 0.14 d^{-1} and $2.8\text{--}3.1 \text{ g O}_2/(\text{kg DM d})$ (ca. $21 \text{ g O}_2/(\text{kg DM week})$). Those values are similar to the ones obtained in the present study. However, it should be emphasized that all of the ORF had a particle size of $<10 \text{ mm}$, and an initial AT4 value of $25 \text{ mg O}_2/\text{g DM}$, which decreased to its minimal value (less than $10 \text{ mg O}_2/\text{g DM}$)

over 20 d. In the present study, the decrease in the AT4 value required more time because the initial AT4 value was almost 3-fold higher and the particle size fractions in the $<80 \text{ mm}$ organic fraction were much larger.

Baptista et al. [40] indicated that the rate constants of mineralization of organic matter during MSW composting in three full-scale MBT plants ranged from $0.043 \pm 0.002 \text{ d}^{-1}$ to $0.082 \pm 0.011 \text{ d}^{-1}$. When waste with a higher paper content was composted, the kinetic value was lowest. This could be explained by the fact that paper waste has a high content of fibrous compounds, such as hemicellulose, cellulose and lignin, which may decrease its susceptibility to biodegradation. These fibrous compounds usually have complex structures consisting of lignin and other cell-wall polysaccharides, which lowers biodegradability [41].

Linear regression showed strong associations between the OM content and the AT4 value, the TC content and the AT4 value, and the contents of OM and TC during aerobic stabilization of the $<80 \text{ mm}$ organic fraction (Fig. 5). There was good agreement between the linear regression models and the observed values of OM content and AT4 ($R^2 = 0.94$ (SR8), $R^2 = 0.99$ (SR10), $R^2 = 0.96$ (SR12)), and those of TC content and AT4 ($R^2 = 0.93$ (SR8), $R^2 = 0.92$ (SR10), $R^2 = 0.84$ (SR12)). There was also a strong linear relationship ($R^2 = 0.94$ (SR8), $R^2 = 0.87$ (SR10), $R^2 = 0.82$ (SR12)) between the OM and TC values (Fig. 5). The lowest values of OM and TC corresponded to the lowest value of AT4. However, it should be emphasized that at the beginning of stabilization, the values were highest and then decreased gradually during the time of stabilization.

3.3. Characteristic of stabilized residuals after 8, 10 and 12 weeks of aerobic stabilization

As was mentioned, biodegradable waste constituted on average around 52% of the $<80 \text{ mm}$ fraction subjected to stabilization (excluding the $<10 \text{ mm}$ fraction). In the stabilized residuals after 8, 10 and 12 weeks of stabilization, the analysis showed that biodegradable waste did not exceed 22% when taking into account three of the particle size fractions. It should be emphasized that the content of biodegradable waste decreased when the stabilization time was extended (Fig. 1a). Examination of the composition of the biodegradable waste of the SRs revealed that, regardless of the stabilization time, in the $>60 \text{ mm}$ and $60\text{--}40 \text{ mm}$ particle size fractions, the shares of paper waste and textiles were the largest, while a large amount of the $40\text{--}10 \text{ mm}$ fraction consisted of other organic waste (Table 2).

When considering the composition of the SRs including, in addition to biodegradable waste, plastic waste, glass waste, metal waste and others (as 100% of the particular particle size fraction), the share of plastic waste was highest in the $>60 \text{ mm}$ and $60\text{--}40 \text{ mm}$ fractions. Glass waste in the SRs constituted only about 3% of the $>60 \text{ mm}$ fraction, but its contribution increased to over 40% in the $40\text{--}10 \text{ mm}$ fraction. The content of plastic waste was highest, at more than 50%, in the $>60 \text{ mm}$ particle size fraction; its content was slightly lower in the $60\text{--}40 \text{ mm}$ particle size fraction (Figs. 1d-f).

The contamination ratios (CR) in the $<80 \text{ mm}$ fraction and the SRs were calculated as the ratio of the percent share of a contaminants to that of the biodegradable

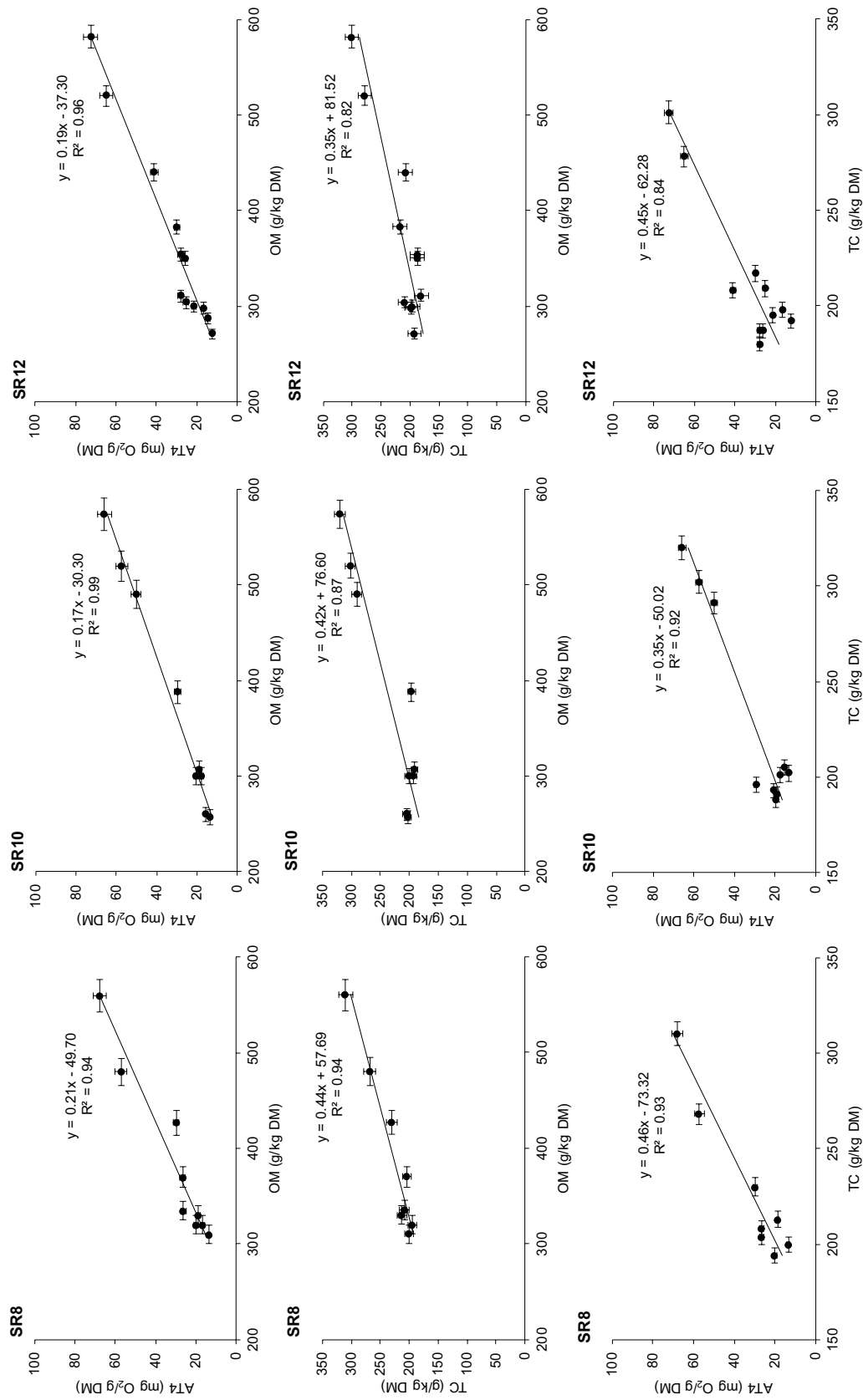


Fig. 5. Relationships between the OM content and the AT4 value, the TC content and the AT4 value, and the contents of OM and TC during aerobic stabilization of the <80 mm organic fraction, linear regression equations and the coefficient of determination (R²) are given

waste. In the study presented here, the following were considered contaminants: plastic waste, glass waste, metal waste and others. The composition of the <80 mm fraction showed that the CR changed from 0.7 to 0.8 in all size fractions except the <10 mm fraction, which means that the content of contaminants was relatively low and that of biodegradable waste was relatively high. Thus, the <80 mm fraction is rich in organic matter and suitable for biological stabilization. However, in the SRs, the CR increased up to even 3.3, and the higher the CR value, the higher the content of contaminants. Due to stabilization and reduction of the organic matter and the total mass of SR, the contaminants were compacted and their share increased to even 75% of the total mass of the SR (Figs. 1d-f).

Sieve analysis showed the changes in the percent share of the following particle size fractions in the samples of the <80 mm fraction and SRs: >60 mm, 60–40 mm, 40–10 mm, and <10 mm. The content of the 40–10 mm particle size fraction was similar both in the <80 mm fraction and in all stabilized residuals, irrespective of the time of stabilization. The content of the 60–40 mm particle size fraction was lower in the SRs than in the <80 mm fraction. The greatest changes took place with the largest and smallest particle size fractions, and the share of the >60 mm fraction decreased from about 28% in the <80 mm fraction to less than 10% in the SRs. However, because the components of the <80 mm fraction were fragmented during aerobic stabilization, the share of the <10 mm fraction increased from about 12% in the <80 mm fraction to 35%–45% in the SRs. Moreover, it should be emphasized that the share of the <10 mm fraction increased from 35% (SR8) to 45% (SR12) when the time of stabilization was extended from 8 weeks to 12 weeks (Fig. 1b). Other studies have also indicated that, in the product of aerobic stabilization of OFMSW, the content of the <10 mm fraction is high [42,43]. Połomka and Jędrzak [42] found that the <10 mm particle size fraction constituted 51.4%–52.5% of compost-like output after aerobic stabilization. Dias et al. [43] reported an even higher content (about 80%) of this fraction in the residual material after aerobic stabilization.

3.4. Possibilities of application of SR and the fine fraction from landfill mining

Recently, some studies on landfill mining (LFM) have been carried out. These studies provided information regarding the composition and characteristics of the different fractions that were excavated from landfills. The wastes mined from landfills consisted of 20%–30% combustible materials, 50%–60% fine-grained degraded matter, 10% inert materials and a small percentage of metals [44]. The fine fraction (commonly the material with a particle size <60 mm) makes up a considerable portion of the total amount of waste disposed of and may range from 40% to 80% of the mined material. It consists of decomposed organic substances (e.g., humic substances), mineral waste (e.g., sand, fragments of brick or concrete), and also particles of metal and plastics, paper and other calorific fractions [45]. Mönkäre et al. [46] compared the fine fraction from old (operation began 20–40 y before landfill mining) and young landfills (it began 10–15 y before landfill

mining). They found that the old landfills contained more (70%) fine fraction (considered as <20 mm) than the young landfills (60%). In old landfill fine-fractions, the average organic matter content was 10% of the wet weight. Their nitrogen and phosphorus contents were 3 g/kg TS and 1.0 g/kg TS, respectively. In young landfill fine-fractions, organic matter content was 15%, and nitrogen and phosphorus contents were 5 g/kg TS and 1.2 g/kg TS, respectively. According to Zhao et al. [47] the fine fraction is similar to soil. Bhatnagar et al. [48] found that the <40 mm fraction had the following composition: 22% inert materials (glass and stones), 5.4% biodegradable waste (paper and wood), 5% combustibles (including plastic, textile and rubber waste) and 1% metals. A large amount consisted of unidentified materials. Hull et al. [49] reported that about 20% DM of the <25.4 mm fraction consisted of metal, plastic, glass, textile/rubber/leather and stone/brick/concrete materials. However, although the calorific fractions of the fine fraction might be used for energy recovery, and some other materials (especially metal and glass) could also be recovered, the cost of recovery would be increased by landfill mining. Therefore, it would be more profitable to recover some materials from the SR before it is landfilled.

Information on the relative amounts of the particle size fractions separated from SR seems to be especially important in the context of possible utilization of these fractions. This results from the fact that, for example, plastic waste can be recovered from larger particle size fractions (in the present study, the >60 mm and 60–40 mm fractions). However, glass waste can be recovered from smaller particle size fractions, for example, the 40–10 mm fraction in this study. Only a few studies have shown that further mechanical processing of the fine fraction of SR is possible in an additional installation. The material can then be recycled and utilized, for example, for road construction or concrete production. Another proposed application is the use of the 0–5 mm fraction of SR for winter road maintenance [42]. However, despite the fact that the grain size of the SR complied with the European standards, it was too light and contained too much organic matter, which led to this research direction being abandoned. In contrast, those authors found that the 5–10 mm particle size fraction of SR can be used as part of a concrete mix formula, and that the 0–10 mm fraction of SR can be used for constructing road foundations.

Taken together, the results of the study reported here and those of other studies indicate that the use of an additional line to ensure valorisation of the SR at an MBT plant should be considered. This is because, some valuable materials can be recovered from the stabilized residual, such as material fractions like glass, plastics, and metals; microelements, like phosphorus and nitrogen; or carbon compounds, like humic substances. Moreover, valuable substances are present in higher amounts in the SR than in the fine fraction excavated from landfill sites.

Preliminary studies have shown that it is necessary to develop and improve the processes of glass recovery from the residual material from the biological stage of MBT plants because its content of glass waste may be as large as 75%–85% [50,51]. Those authors used simple, small-scale equipment for glass recovery and found that

the effectiveness of recovery was 82%–91%. However, a considerable percentage of contaminants was still present in the final glass concentrate. The glass recycling industry, which requires at least 98% glass content, did not accept this concentrate. A technological line designed for glass recovery from SR was tested in a further study by Połomka et al. [52]. In the entire mass of the SR, the amount of glass ranged from ca. 11.4% to ca. 17.3%. After separation of the SR into three fractions (0–10 mm, 10–35 mm and 35–80 mm), they found that the middle fraction contained 31%–41% glass waste. Glass recovery from this fraction produced material containing 92.8%–99.5% glass (calculated on the basis of sample weight). Because this material contained very few contaminants and had the appropriate particle size, it was accepted by glass recycling plants.

Montejo et al. [31] determined the physicochemical properties of the product of stabilization of OFMSW (MSW composts), of which 90% of the particles must pass through a 25 mm sieve. On average, 70% of the fresh compost samples consisted of particles smaller than 3.35 mm, and more than 16%, of particles smaller than 1 mm. Those authors found that the average nitrogen content was 20.8 ± 3.3 g/kg DM. They also found rather large amounts of phosphorus compounds (2–5 g/kg DM), which was larger than the amount in sewage sludge, for example. Potassium content in the samples of MSW compost averaged 14.68 ± 4.33 g/kg DM. This value is even higher than that in a study by Almendro-Candel et al. [53]. These relatively high contents of nutrients in stabilized residuals, higher than those in fine fractions excavated from landfill sites, may indicate that stabilized residuals are more profitable resources for nutrient recovery. Other studies have also indicated that it is possible to recover humic substances (HS) from stabilized residual. For example, Kulikowska et al. [54] examined humification during aerobic stabilization of the organic residual fraction (ORF) after autoclaving of MSW. Those authors found that, during stabilization, the organic matter content decreased from ca. 60%–70% to ca. 42%, and that humification proceeded intensively for up to 50 d with a rate of HS formation of 3.31–3.92 mg/(g OM d). The maximum HS concentrations in the SR from ORF ranged from 82 to 120 mg HS/g OM, which was similar to those in composts from different organic wastes, for example, sewage sludge or agricultural waste. A high HS concentration in ORF means that, before it is landfilled, HS can be recovered. After extraction, HS can be used in remediation/phytoremediation of soils, for example, as a washing agent for removal of heavy metals [55,56].

4. Conclusions

The stability of material remaining after stabilization of the <80 mm fraction, the so-called stabilized residual, can be determined with the use of indicators such as the AT4 value, the contents of organic matter or total carbon, or the quality of the leachate produced. The share of the <10 mm size fraction can serve as another stability indicator, as its percent share increases in the stabilized residual. The study presented here showed that extending the stabilization time of the <80 mm fraction from 8 to 12 weeks intensified fragmentation of stabilized material. It also changed the percent

shares of the particle size fractions in the SRs, particularly that of the fine fraction, which increased from 35% in SR8 to 45% in SR12.

Obtaining the fine fraction from SR originating from aerobic stabilization (used at many full-scale MBT plants) seems to be preferable to obtaining it from landfill mining. Thus, the inclusion of an additional line at MBT plants should be taken into consideration to ensure valorisation of SR and the recovery of valuable materials, such as phosphorus compounds or carbon compounds, for example, humic substances. Moreover, the high content of contaminants, for example, glass or metals, concentrated after stabilization in SR, means that it can also be profitable to recover them from specific size fractions of SR.

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