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SELECTION OF BULKING AGENTS FOR COMPOSTING OF SEWAGE SLUDGE

The scope of this work covered: laboratory determination of bulk density, air-filled porosity, mechanical strength, water holding capacity of bulking agents, i.e. straw, woodchips and sawdust, and composting mixtures of sewage sludge and selected bulking agents at the ratios of 1:0.3; 1:0.6; 1:1 (d.b.), as well as simulation of bulk density and air-filled porosity in function of composting pile depth for the composting mixtures. Simulation of changes in bulk density and air-filled porosity was performed for a 2 m high composting pile. The results showed that mixing sewage sludge with woodchips in the ratio of 1:1 (d.b.) allows optimal moisture content, *C/N* ratio and air-filled porosity across the composting pile.

1. INTRODUCTION

Management of sewage sludge generated in the process of municipal wastewater treatment poses many challenges. Despite the fact that the total quantity of sewage sludge from municipal wastewater treatment plants in Poland in 2010 slightly decreased in comparison to previous years according to the Central Statistical Office, yet there is a new challenge that would require introducing advancements to management of sewage sludge going to landfills. It is expected that disposal of sewage sludge by landfilling will be banned from January 2013 [1]. This will require adjustment of existing approaches towards sewage sludge utilization.

Current methods of utilization of sewage sludge include agricultural application, landfilling, incineration, drying, and also composting and vermicomposting. Composting is a widely used cost-effective and socially acceptable method for treating solid or semisolid biodegradable waste. Composting of various biodegradable materials such

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as sewage sludge allows conversion of waste materials into stabilized compost. It reduces the volume of organic waste, eliminates costs of disposal, and the final product can be commercially profitable. However, composting of sewage sludge poses many difficulties. Sewage sludge shows high moisture content, high wet bulk density and low C/N ratio. The structure of sewage sludge is dense and plastic, and thus susceptible to compaction. High moisture content and lack of structure cause additional compressive stress and compaction on a compost bed resulting in poor air-filled porosity and permeability through a composting pile [2, 3]. Therefore, composting of sewage sludge requires addition of amendments such as bulking agents that allow optimal moisture, C/N ratio and provide structural support to obtain sufficient air-filled porosity for windrow composting. Insufficient ratio and inadequate type of a bulking agent in a composting mixture – especially in the case of high moisture substrates such as sewage sludge – results in limitation of aeration and moisture transfer within a composting pile. In consequence, the emission of gases (i.e. methane, hydrogen sulfide, ammonia, nitrogen oxide) and odors significantly increases. This disturbs dynamics of composting and results in poor quality composts.

Bulking agents that proved the effectiveness in research studies on composting of sewage sludge include various materials such as wheat, rye and corn straw [4, 5], rice straw, cotton waste, sawdust, woodchips, pruning waste [6], Acacia trimming residues [7], crushed wood pellets, green waste compost screening, grass clippings, bark, corn stalks [8], mixture of saw dust and grass. Straw and wood residues are primary bulking agents used in composting of sewage sludge in Poland. However, due to high market prices and seasonal availability of these materials there is a tendency to limit the addition of bulking agents at composting facilities to reduce processing costs [4, 5]. Due to complexity of composting parameters, requirements and processing costs, it is of utmost importance to determine the most optimal ratio of the bulking agent in a composting mixture.

Addition of a bulking agent to a composting mixture provides higher air-filled porosity and permeability, and thus oxygen concentration in a composting pile, but consumes space and increases processing costs [9, 10]. On the other hand, too high ratio of the bulking agent results in very high air-filled porosity, and thus permeability, leading to excessive convective heat loss. In consequence, this can prevent sewage sludge mixtures from achieving thermophilic temperatures required for sanitation [11]. A number of studies have been done aimed at determining the most suitable ratio of a bulking agent and sewage sludge to obtain the required air-filled porosity. Several different ranges of optimal air-filled porosity (AFP) for a wide variety of composting substrates and mixtures have been reported in the literature. According to reported values for the initial air-filled porosity in composting process, the minimum value for AFP is 20%. This allows obtaining the minimum oxygen level in the pore space over 5% [9, 12, 13]. However, Berhte et al. [14] observed that the initial air-filled porosity of 23% did not provide a sufficient amount of oxygen for microorganisms. The opti-

mal values seem to be in the range of 30–36% [15, 16]. Annan and White [17] reported that the optimal level of air-filled porosity was between 30% and 60%. Also, other authors indicated that values below 60–65% provided proper performance of composting [14, 18]. Ahn et al. [13] reported that the optimal porosity for aerobic decomposition was 85–90%. However, Michel et al. [18] stated that air-filled porosity higher than 75% was excessive and did not allow thermophilic temperatures. Also, it was reported that for waste with low biodegradable organic matter, air-filled porosity over 60–70% was too high to achieve thermophilic temperatures. However, it is not clear whether these values refer to the optimal air-filled porosity of the initial composting mixtures or throughout the entire composting process [19]. Also, it is not clear whether these values considered the effect of compressive stress in a composting pile. In laboratory scale, the effect of compaction on air-filled porosity is often neglected [3]. Therefore further research is needed in order to determine the optimal air-filled porosity in a composting pile. Moisture content in composting is essential to microbial activity. Air-filled porosity and moisture content are interdependent in composting mixtures, and thus the optimal moisture content in a composting mixture should support microbial activity and enable adequate oxygen supply. It has been reported that the optimal moisture ranges from 50% to over 70% [20]. Other studies showed that the optimal moisture content of 50–60% results in the optimal air-filled porosity in the range of 30–60% of total volume [15, 21]. Also, it has been observed that the initial moisture content of 60–65% allowed air voids of 30–40% during the curing phases of the composting process [21]. In composting of materials with high nitrogen and low carbon content, the addition of bulking agents increases the initial C/N ratio of a composting mixture. Many researchers recommend the initial C/N ratio of a composting mixture between 20 and 30 [22]. Lower values (below 15) lead to emissions of ammonia as the excess nitrogen cannot be consumed by microorganisms. Composting of sewage sludge poses many difficulties due to low C/N ratio. Typical sewage sludge contains 4–5% of nitrogen (dry weight), and thus the C/N ratio is lower than 10. Therefore to reach C/N ratio above 20, the addition of a bulking agent should be much higher than the quantity of sewage sludge in a composting mixture, e.g. mixture with 40% of sewage sludge and 60% of straw and sawdust led to C/N ratio above 20 [5].

Composting of sewage sludge requires a balance between air-filled porosity, moisture content and C/N ratio. Therefore selection of a bulking agent for a composting mixture with sewage sludge should follow the recommendations on the optimal air-filled porosity, C/N ratio and moisture content in final mixtures.

The objectives of this work were: (1) to determine physical properties of selected bulking agents used in composting of sewage sludge, (2) to investigate the influence of type and ratio of a bulking agent in sewage sludge composting mixture on moisture content, C/N ratio, mechanical strength, bulk density and air-filled porosity, and (3) to determine the optimal quantity of the bulking agent required for adequate moisture content, C/N ratio and air-filled porosity in a 2 m composting pile.

2. MATERIALS AND METHODS

Composting substrates and bulking agents. Dewatered anaerobically stabilized sewage sludge (SS) was sampled from the Warta Municipal Wastewater Treatment Plant in Częstochowa. Air-dried wheat straw (ST), woodchips (WC) and sawdust (SD) collected from local farms were used as bulking agents. Prior to compaction measurements, sewage sludge and bulking agents were analyzed in triplicates for moisture content, organic matter content, water holding capacity, Kiejdahl nitrogen, carbon to nitrogen ratio, bulking density, air-filled porosity and mechanical strength [3, 13, 23]. Moisture content was determined by oven drying at 105 °C to constant weight. Organic matter was determined by igniting an oven dried sample overnight in a muffle furnace at 550 °C. Water holding capacity was determined for all bulking agents by soaking a wet sample in a beaker for 1 day and draining excess water through a paper filter. Water holding capacity was expressed as the moisture content (wet basis, w.b.) of a saturated sample.

Preparation of composting mixtures. Sewage sludge and bulking agents were mixed in the following weight ratios (dry basis, d.b.): 77% of sewage sludge and 23% of bulking agent (1:0.3), 63% of sewage sludge and 37% of bulking agent (1:0.6), and 50% of sewage sludge and 50% of bulking agent (1:1). Table 1 shows sewage sludge and bulking agent ratios in composting mixtures expressed as weight and volume ratios.

Table 1

Ratios of the sewage sludge and bulking agents in composting mixtures

Ratios of the sewage sludge and bulking agent in the composting mixture by weight (d.b.)	SS + WC		SS + ST		SS + SD	
	Weight [w.b. t]	Volume [m ³]	Weight [w.b. t]	Volume [m ³]	Weight [w.b. t]	Volume [m ³]
1:0.3	1:0.07	1:0.36	1:0.06	1:1.7	1:0.07	1:0.64
1:0.6	1:0.14	1:0.72	1:0.12	1:3.5	1:0.13	1:1.27
1:1	1:0.23	1:1.18	1:0.2	1:5.9	1:0.22	1:2.09

Compaction device. The presented compaction device is a simplified version of a compaction-permeability device designed to investigate the impact of compaction on physical parameters of composting matrices such as mechanical strength, bulk density, air-filled porosity [3] but it lacks ability to determine permeability. It consists of a 16 dm³ PVC cylindrical container 24 cm in diameter and a set of 5 kg weight plates (Lauber-Sport) (Fig. 1). A perforated plate with legs was placed at the bottom of the container to form a plenum. Also, a perforated plate was placed at the top of the material. A PVC pipe was used for force distribution. 6 levels of weight plates (from 5 to

30 kg) were used to apply stress up to 6660.6 N/m² to the surface of the investigated sample materials.

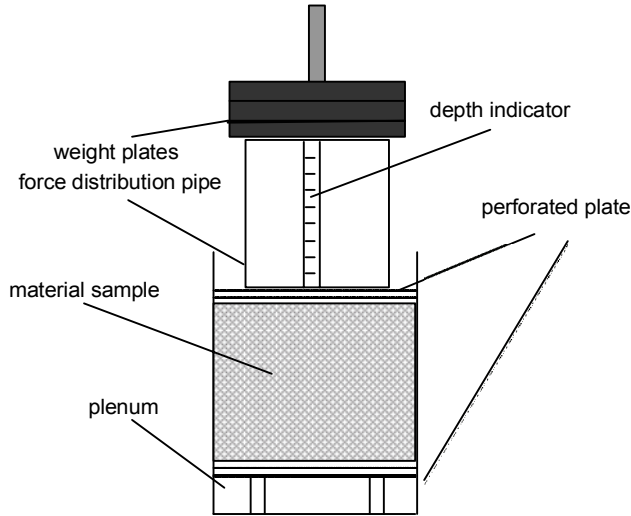


Fig. 1. Schematic diagram of the compaction device

Compaction measurements. Volume changes of the material due to applied compaction were measured directly at a given stress for sewage sludge, selected bulking agents and composting mixtures of various bulking agent ratios. 6 different compressive stress values were applied in the range of 0–6660.6 N/m².

Bulk density (kg/m³) was calculated from the sample weight divided by the compacted volume under each applied stress [12, 24]. Throughout this analysis bulk density is reported in terms of fresh weight (w.b.).

Air-filled porosity, also referred to as free air space (FAS), is the volume fraction of air in a porous matrix. Air-filled porosity can be theoretically calculated based on easily measured parameters, including wet bulk density, dry matter, organic matter, and densities of water, organic matter, and ash [23, 25]:

$$\varepsilon_a = 1 - \rho_{wb} \left(\frac{1 - DM}{\rho_w} + \frac{DM \times OM}{\rho_{om}} + \frac{DM(1 - OM)}{\rho_{ash}} \right) \quad (1)$$

where: ε_a – air-filled porosity (m³/m³), ρ_{wb} – total bulk density (kg/m³) wet basis (w.b.), DM – dry matter (g/g) (w.b.), OM – organic matter (g/g) (d.b.), ρ_w – density of water (1000 kg/m³), ρ_{om} – density of organic matter (2500 kg/m³), ρ_{ash} – density of ash (1600 kg/m³).

It has to be pointed out that air-filled porosity determined by this theoretical approach [3, 4, 23] correlated well with that obtained by the empirical methods for la-

boratory determination of air-filled porosity. According to Ruggieri et al. [19], this is the most accurate method for correlating air-filled porosity with bulk density for all type of composting materials.

Mechanical strength (MS) determines the resistance of materials to compaction, thus determining bulk density, air-filled porosity, and permeability. It can be determined from the bulk density ($\rho_{wb,\sigma}$), a known applied stress (σ), and the maximum and minimum bulk densities for that particular mixture. The following equation has been used to quantify these relationships and predict bulk density within a large composting pile [3, 13, 23]:

$$\rho_{wb,\sigma} = \rho_{wb,\max} - (\rho_{wb,\max} - \rho_{wb,0}) \exp\left(-\frac{\sigma}{MS}\right) \quad (2)$$

where: $\rho_{wb,\sigma}$ – bulk density at any applied stress, $\rho_{wb,\max}$ – maximum bulk density (kg/m^3 w.b.), $\rho_{wb,0}$ – bulk density of uncompacted material.

Bulk density of uncompacted material is measured at the surface of a composting pile, whereas the maximum bulk density is the density of compressed material at the base of a composting pile. It can be calculated by rearranging Eq. (1) and setting air-filled porosity to zero. With these parameters determined, and a set of data indicating bulk densities of a sample at a particular applied stress, the mechanical strength parameter can be estimated directly using non-linear techniques, or Eq. (2) can be rearranged and log-transformed to allow estimation of the linear parameter.

3. RESULTS AND DISCUSSION

3.1. CHARACTERISTICS OF SEWAGE SLUDGE AND SELECTED BULKING AGENTS

General characteristics of sewage sludge and selected bulking agents are presented in Table 2. Throughout this study moisture content, organic matter, water holding capacity, Kiejdahl N and bulk density were measured, whereas air-filled porosity and mechanical strength were calculated from the measured values of moisture content, organic matter, bulk density (Eqs. (1) and (2), respectively) for sewage sludge, selected bulking agents and prepared composting mixtures. Sewage sludge (SS) showed high moisture content of almost 80%, low air-filled porosity and low mechanical strength. These physical properties did not enable composting sewage sludge without addition of a bulking agent. Also, the C/N ratio of sewage sludge is not sufficient for composting. Selected bulking agents, i.e. woodchips (WC), straw (ST) and sawdust (SD) showed very low moisture content and high C/N ratio. Bulk densities of bulking agents were significantly lower than in the case of sewage sludge, and thus resulted in higher air-filled porosities of 87–98%. Selected bulking agents showed high resistance to compaction whereas sewage sludge demonstrated susceptibility to compaction mostly due to high moisture content and lack of structure. Generally, dry materials tend to resist compaction in

a composting pile more than wet materials such as sewage sludge or apple pomace [3, 13, 23]. Selected bulking agents due to high dry matter content (from 5.2% to 16.7%) and favorable properties of water holding capacity enable significant reduction in moisture content in composting high moisture substrates. Also, high *C/N* ratio of these bulking materials, especially sawdust with *C/N* ratio of 533:1, can increase the *C/N* ratio in the composting mixture of substrates with high nitrogen content and low carbon content.

Table 2

Characteristics of sewage sludge and bulking agents before compaction

Composting material	<i>MC</i> [w.b., %]	<i>OM</i> [d.b., %]	<i>WHC</i> [w.b.,%]	<i>C/N</i> [%]	<i>N</i> [%]	ρ_{wb} [w.b., kg/m ³]	ϵ_a [%]	<i>MS</i> [N/m ²]
Substrates								
Sewage sludge (SS)	79.7	60.7	ND	11:1	3.1	929	16	7010
Bulking agents								
Woodchips (WC)	16.7	95.9	69.2	35:1	1.5	179	87	622 377
Straw (ST)	5.2	95.6	79.5	24:1	2.2	31	98	667 193
Sawdust (SD)	7.4	99.6	73.8	533:1	0.1	95	94	619 887

MC – moisture content, *OM* – organic matter content, *WHC* – water holding capacity, *C/N* – carbon to nitrogen ratio, *N* – Kiejdahl nitrogen, ρ_{wb} – bulk density, ϵ_a – air-filled porosity, *MS* – mechanical strength, *ND* – not determined.

Table 3

Characteristics of composting mixtures before compaction

Composting mixture	<i>MC</i> [w.b., %]	<i>OM</i> [d.b., %]	<i>C/N</i> [%]	<i>N</i> [%]	ρ_{wb} [w.b., kg/m ³]	ϵ_a [%]	<i>MS</i> [N/m ²]
1:0.3 (SS:WC)	75.1	67.4	28:1	1.8	824	27	16 836
1:0.6 (SS:WC)	71.0	73.5	29:1	1.7	673	41	31 971
1:1 (SS:WC)	69.3	75.1	30:1	1.4	549	52	57 314
1:0.3 (SS:ST)	75.3	66.2	17:1	2.2	418	63	28 979
1:0.6 (SS:ST)	71.3	70.6	20:1	2.0	290	75	48 717
1:1 (SS:ST)	64.9	76.8	31:1	1.4	199	83	62 567
1:0.3 (SS:SD)	74.8	69.2	18:1	2.1	611	46	16 819
1:0.6 (SS:SD)	73.1	71.7	31:1	1.3	527	54	34 676
1:1 (SS:SD)	62.8	81.4	50:1	0.9	366	69	82168

MC – moisture content, *OM* – organic matter content, *C/N* – carbon to nitrogen ratio, *N* – Kiejdahl nitrogen, ρ_{wb} – bulk density, ϵ_a – air-filled porosity, *MS* – mechanical strength.

Therefore, in order to reduce moisture content and to increase air-filled porosity and *C/N* ratio, it was necessary to mix sewage sludge with bulking agents at ratios allowing the optimal moisture content of 50–60%, adequate air-filled porosity in

a composting pile of 30–60% and *C/N* ratio between 20:1 and 30:1. Table 3 shows characteristics of composting mixtures with the selected ratios of bulking agents.

3.2. EFFECT OF BULKING AGENT RATIO ON THE INITIAL MOISTURE CONTENT, *C/N* RATIO AND AIR-FILLED POROSITY

The addition of bulking agents to sewage sludge mixtures resulted in reduction of the moisture content and in increase of the organic matter, *C/N* ratio, air-filled porosity. Close to the optimal moisture content of 50–60% was obtained for the mixture of sewage sludge and sawdust in the ratio of 1:1. Higher moistures than the optimal one were obtained for the mixtures of sewage sludge with woodchips (SS:WC 1:1) and straw (SS:ST 1:1) – 69% and 65%, respectively. According to Richard et al. [20] the optimal moisture ranges from 50% up to 70%, therefore the moisture content of these mixtures can also be considered optimal. In the case of all the remaining mixtures with bulking agent ratios of less than 1:1, the moisture content seemed to be too high for composting. The optimal *C/N* ratio was obtained for the mixtures of sewage sludge and woodchips at all the investigated ratios, i.e. 1:0.3; 1:0.6 and 1:1, and was in the range of 28:1 (SS:WC 1:0.3) and 30:1 (SS:WC 1:1). Also, the optimal values of *C/N* ratio were obtained for the mixture of sewage sludge and straw – 20:1 for SS:ST 1:0.6 and 31:1 for SS:ST 1:1 and for the mixture of sewage sludge and sawdust – 31:1 for the ratio of 1:0.6. For the mixture of sewage sludge and sawdust at the ratio of 1:1, the *C/N* ratio was excessively high, i.e. 50:1. For the remaining mixtures, the *C/N* ratio was lower than the optimal values, and this could lead to nitrogen loss during composting of sewage sludge.

Bulking agents provide structural support for materials with high moisture content, plastic and dense structure by increasing mechanical strength of composting mixtures. Mechanical strength increased in all investigated mixtures with the increase in the ratio of a bulking agent. Selected bulking agents showed similar mechanical strength (Table 2). For all mixtures, mechanical strength increased with the increase in bulking agent ratio and with the decrease in the moisture content. However, the highest mechanical strength was observed for the mixture of sewage sludge and sawdust of 1:1 and the lowest moisture content of ca. 63%. In the mixtures of the same bulking agent ratio of 1:1 mechanical strength differed which was due to moisture content. Malińska and Richard [3] investigated the effect of various ranges of moisture content and bulking agent ratio on mechanical strength of mixtures of apple pomace and woodchips. They found that above 65% of moisture, mechanical strength was similar for all investigated composting mixtures and the addition of a bulking agent did not increase the resistance to compaction in this high moisture range.

The addition of a bulking agent significantly increased air-filled porosity in all investigated mixtures. The highest air-filled porosities were obtained for the uncompact-ed mixtures of sewage sludge and straw. For all ratios, i.e. SS:ST 1:0.3; 1:0.6 and 1:1,

air-filled porosity was above the optimum range of 30–60% and ranged from 63% to 83%. For the mixture of sewage sludge and sawdust at all ratios, air-filled porosity was in the optimal range. The lowest air-filled porosities were obtained for the mixture of sewage sludge and woodchips in the ratio of 1:0.3 – 27%. For the remaining ratios of this bulking agent air-filled porosities were in the optimal range.

With reference to the results presented in Tables 2 and 3, the optimal moisture content in the range of 50–70%, *C/N* ratio of 20:1–30:1 and air-filled porosity of 30–60% across the pile as the initial characteristics of composting mixtures were obtained for the mixture of SS:WC 1:1 (Table 4). In the case of SS:WC 1:0.6, air-filled porosity across the pile is lower than the optimal 30–60%. As for the mixtures of SS:ST 1:0.6 and SS:ST 1:1 air-filled porosities were higher than recommended optimal values.

Table 4

Initial characteristics of composting mixtures (before compaction) showing the optimal values of *MC*, *C/N* and ϵ_a

Composting mixture	<i>MC</i> [w.b., %]	<i>C/N</i> [%]	ϵ_a [%]
SS:WC 1:0.6	71.0	29:1	41
SS:WC 1:1	69.3	30:1	52
SS:ST 1:0.6	71.0	20:1	75
SS:ST 1:1	65.0	31:1	83

MC – moisture content, *C/N* – carbon to nitrogen ratio, ϵ_a – air-filled porosity.

3.3. BULK DENSITY AND AIR-FILLED POROSITY AS A FUNCTION OF COMPOSTING PILE DEPTH

Bulk density and air-filled porosity for sewage sludge, selected bulking agents and prepared composting mixtures with different bulking agent ratios were modeled as a function of composting pile depth. Bulk density and the resulting overburden stress were calculated numerically for a 2 m high composting pile using 0.1 m increments (Eq. (2)). Air-filled porosity was calculated from the bulk density resulting from overburden stress caused by these increments (Eq. (1)) [3, 13].

Simulation of bulk density and air-filled porosity for the investigated materials and composting mixtures with the depth of a 2 m composting pile is presented in Figs. 2 and 3. Bulk density of sewage sludge increased with the pile depth whereas bulk densities of bulking agents remained almost the same throughout the pile. Increasing pile depth caused increasing compressive stress due to overburden weight of the investigated mixtures. In consequence, bulk densities increased, resulting in lower air-filled porosities toward the bottom of the composting pile (Fig. 3). For sewage

sludge air-filled porosity at the bottom of a pile was close to 0 whereas for bulking agents remained unchanged.

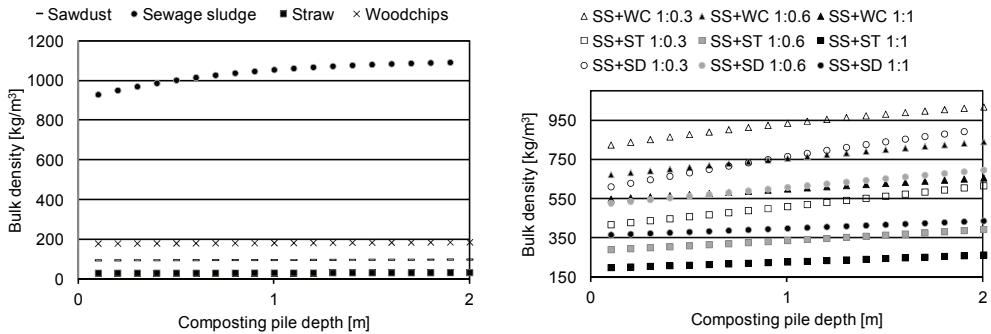


Fig. 2. Bulk density in function of composting pile depth for sewage sludge, selected bulking agents and the mixtures with various bulking agent ratios

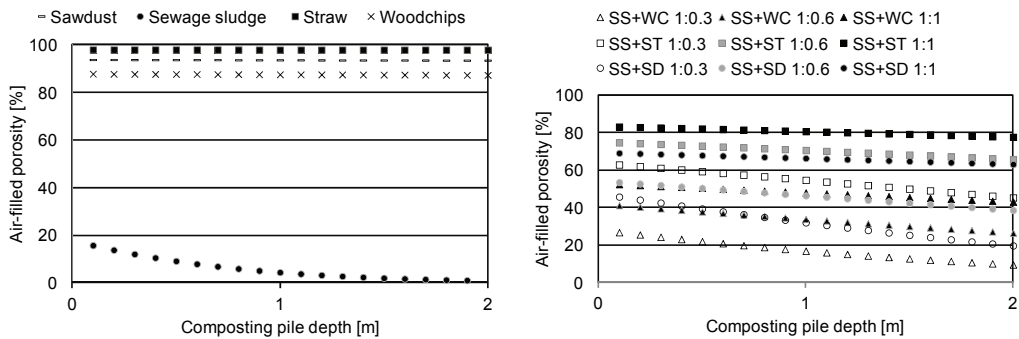


Fig. 3. Air-filled porosity in function of composting pile depth for sewage sludge, selected bulking agents and the mixtures with different bulking agent ratios

The results of simulation indicate that air-filled porosity in the range from 30% to 60% can be achieved across the composting pile for the mixtures of SS:WC 1:1 and SS:SD 1:0.6. The mixture of SS:ST 1:1 with the optimal moisture and *C/N* ratio showed too high air-filled porosity across the pile. This may lead to excessive convective heat loss and prevent compost from achieving thermophilic temperatures required for sanitation of the sewage sludge [11]. In practice, preparation of this mixture would require mixing 1 t of sewage sludge with 0.2 t of straw which corresponds to 1 m³ of the sewage sludge and 5.9 m³ of straw. The bulking agent ratio in this mixture was 50% (d.b.). Dach [5] pointed out that in many composting facilities, the ratio of a bulking agent in a mixture of sewage sludge could even be lower than 20% (d.b.). The air-filled porosity across the pile for the mixture of SS:WC 1:0.6 did not show the

optimal range of 30–60%. However, these porosities may be sufficient for composting. The ratio of a bulking agent in this mixture may correspond to critical bulking agent requirement. Eftoda and McCartney [9] introduced a concept of critical bulking agent requirement (CBAR) which is defined as the minimum amount of bulking agent required to maintain adequate pore space oxygen levels in the composting matrix. It is based on a target air-filled porosity over 20% and minimum pore space oxygen over 5%. These authors investigated CBAR for composting of biosolids and woodchips. Air-filled porosity over 20% and pore oxygen over 5% was obtained for biosolids and woodchips at the volumetric ratios of 1:2.5 and 1:2.8. Other authors investigated windrow composting of dewatered sewage sludge with pruning waste as a bulking agent in volumetric ratios of sewage sludge and pruning waste of 1:2, 1:2.5 and 1:3. The C/N ratio was 10.6 for the composting mixture with the ratio of 1:2 whereas C/N ratio of 14.7 and 17.5 was for the composting mixtures of 1:2.5 and 1:3, respectively. The windrow with the composting mixture of 1:2 did not reach temperatures necessary for sanitations whereas windrows with the ratio of 1:2.5 and 1:3 achieved thermophilic temperatures. The C/N values were lower than those recommended for composting. It was observed that for composting of sewage sludge and pruning waste as a bulking agent the volumetric ratio between 1:2.5 and 1:3 assured proper composting process [6]. In the investigated mixtures of sewage sludge and straw SS:ST 1:0.6 and sewage sludge and woodchips SS:WC 1:1, the volumetric ratios of bulking agent was 1:3.5 and 1:1.2, respectively. Yanez et al. [10] investigated various ratios of Acacia trimmings (A) and sewage sludge (SS) of 1:0, 1:1, 1:2 and 1:3 (w/w). With reference to loss of organic matter and thermophilic temperatures, the suitable ratio of Acacia trimmings and sewage sludge was 1:1.

Windrow composting of materials with high moisture and nitrogen content and high susceptibility to compaction requires addition of a bulking agent at a ratio that would assure optimal moisture content, C/N ratio and air-filled porosity across a composting pile. The optimal values for these parameters may vary for various materials. Literature provides many studies on the optimal ratio of a bulking agent in composting mixtures of wide range of substrates. However, these recommended ratios of a bulking agent differ for various substrates and composting systems, often neglect compaction in a pile and are provided only on weight or volumetric ratios. Direct measurements of air-filled porosity in a composting pile are not always possible or practical. Therefore, the presented method enables selection of a bulking agent in order to obtain optimal air-filled porosity for required pile configurations.

4. CONCLUSIONS

Due to high moisture, low C/N ratio and air-filled porosity, and high susceptibility to compaction composting of sewage sludge requires addition of a bulking agent in

order to obtain the optimal moisture content of 50–70%, C/N ratio of 20:(1–30):1 and air-filled porosity of 30–60% across a composting pile. This could be achieved by mixing sewage sludge with woodchips in the ratio of 1:1 (d.b.). Also, mixing sewage sludge with straw in the ratio of 1:0.6 (d.b.) would assure the optimal values of MC and C/N, however the air-filled porosity is slightly elevated, and thus it may lead to heat losses.

The presented method for experimental determination of bulk density, air-filled porosity and mechanical strength and mathematical simulation of changes in bulk density and air-filled porosity across the composting pile enable selection of an optimal ratio of a bulking agent in a composting mixture. Also, this method can be used for designing various composting systems, selecting bulking agents for composting mixtures, determining pile dimensions and aeration systems, and also designing biofilters for composting facilities.

Due to the fact that the effects of compaction on air-filled porosity in laboratory scale experiments are often neglected, further research is needed in order to determine the optimal air-filled porosity in a composting pile. Future research will include wind-row composting of the mixtures of sewage sludge and the investigated bulking agents in the field scale and evaluating the effect of air-filled porosity on composting dynamics.

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