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Spent Mushroom Substrate as a Supplementary Material for Sewage Sludge Composting Mixtures

Zużyte podłoże popieczarkowe jako materiał pomocniczy do przygotowywania mieszanek kompostowych z osadów ściekowych

Spent mushroom substrate (SMS) is a byproduct from mushroom production. On average, it shows low content of organic matter but contains relatively high quantity of nitrogen (2.4%). SMS could be recycled as a soil amendment or could be an alternative for peat. Some studies indicate that SMS could be used as a supplementary material in composting of various biodegradable waste and municipal sewage sludge (SS). In composting, spent mushroom substrate could function as a bulking agent and provide structure in composting piles. The overall goal of this study was to determine whether SMS can be used as a supplementary material for preparation of composting mixtures of sewage sludge and could allow the achievement of the recommended values of moisture content (50÷60%), C/N ratio (25-35:1) and air-filled porosity (at least 75%) in the final composting mixtures. Due to high moisture content, low C/N ratio and lack of structure municipal sewage sludge cannot be composted alone. The addition of a supplementary material to municipal sewage sludge should provide adequate structure (for maintaining optimal air-filled porosity in a composting pile), moisture content and C/N ratio in the composting mixtures. The investigated SMS showed lower moisture content, organic matter, C/N ratio and mechanical strength in comparison to typical supplementary materials used in composting of sewage sludge (e.g. wheat straw or woodchips). The addition of SMS to SS (up to the ratio of SS:SMS 1:6) did not allow the achievement of the recommended values of moisture content, C/N ratio and air-filled porosity within a 2 m composting pile. Therefore, the investigated spent mushroom substrate cannot be considered a suitable bulking agent for preparation of municipal sewage sludge composting mixtures. However, SMS could be used for composting of other biodegradable waste which shows lower moisture content, higher C/N and better structure or for composting of sewage sludge together with lower quantities of other supplementary materials such as wheat straw.

Keywords: **spent mushroom substrate, bulking agents, composting, municipal sewage sludge**

Introduction

Due to excessively high moisture content and low C/N ratio municipal sewage sludge cannot be composted alone. High moisture content (80÷85%), low C/N ratio

(7÷10%), plastic and dense structure susceptible to compaction, high bulk density (800÷1050 kg m^{-3}) and low air-filled porosity (15÷30%) of sewage sludge do not allow fulfilling the requirements for successful composting [1, 2]. Some studies demonstrated that composting of municipal sewage sludge alone or with the addition of zeolites did not allow the increase in temperature to the thermophilic values which are typical for composting. According to some studies, the highest temperature observed during composting of municipal sewage sludge was of 33°C [2]. Therefore, composting of municipal sewage sludge requires the addition of supplementary materials that provide proper structure in a composting pile (allowing adequate air-filled porosity and permeability), optimal water content and C/N ratio.

There is a diverse group of supplementary materials (also referred to as additives or amendments) for composting which includes different types of materials. Straw or woodchips are the most commonly used in composting. Supplementary materials perform various functions at the initial stage of composting such as providing structure (referred to as bulking agents) or amending the composition of composting mixtures (referred as amendments). Different types of straw or woody biomass - that are often used in composting - are becoming less available for composting due to increasing number of other applications, and also the increase in price [3]. Therefore, there is a need for alternative supplementary materials that can be used in the process of composting. Different types of waste or agricultural resides can be used as supplementary materials in composting of sewage sludge or other biodegradable waste. Recently, there is an increased interest in spent growing media that are used in greenhouse cultivation of e.g. strawberry, tomato or mushroom [4, 5]. These materials demonstrate potentials for agricultural recycling e.g. as a soil amendment or producing value-added products [4, 5].

Spent mushroom substrate is a by-product from mushroom mycelium left after harvesting of mushrooms. On average, spent mushroom substrate is rich in nitrogen. It is estimated that production of 1 kilogram of mushroom generates about 5 kg of spent mushroom substrate. China is the leader in mushroom production and generates about 150 thousand tons of spent mushroom substrate per year [6]. In some countries (e.g. China) the management of spent mushroom substrates poses many difficulties. It can be recycled as a soil amendment and a potential alternative for peat [7] but there are other applications currently under investigations such as composting of SMS with other waste materials [7], production of methane through anaerobic digestion with selected waste types [6] or converting SMS into biochar [6, 8]. The literature gives the examples of studies on using spent mushroom substrate for composting of various biodegradable waste and sewage sludge [7, 9]. For example, two types of SMS were used for composting of winery sewage sludge. Those types of SMS showed moisture content of 52.6 and 58.3%, pH of 7.2 and 7.8, total organic carbon of 24.9 and 48.3%, total nitrogen content of 2.16 and 1.61%, and C/N of 15.1:1 and 30.0:1, respectively [9]. Other researchers used spent mushroom substrate for composting of municipal sewage sludge with the addition of woodchips and pumice. The investigated SMS showed moisture content of 33%, organic matter of 80%, pH of 6.34 and C/N of 33.5:1 [10]. Recent study indicated that spent mushroom substrate (SMS) and sucrose (S) amendment had effects on the emission of NH_3 and N_2O and the quality of sewage sludge composts. According to this study, it can be concluded that the best composting results were obtained using 30% SMS and 2% S. Such composition of the composting mixture promoted dehydrogenase activity, humification, nitrification index and degradation of organic matter in the process of composting [11].

However, the literature does not provide sufficient information on the properties of spent mushroom substrate. In particular, there is little known about physical properties such as bulk density, air-filled porosity, mechanical strength that would allow evaluation of spent mushroom substrate as a supplementary material for composting of sewage sludge.

The overall goal of this study was to analyze the potentials of spent mushroom substrate as a supplementary material for preparation of sewage sludge composting mixtures. The scope of the study included: (1) determination of physicochemical and physical properties of spent mushroom substrate and sewage sludge, (2) preparation of composting mixtures, (3) determination of physicochemical and physical properties of composting mixtures prepared with sewage sludge and spent mushroom substrate and (4) simulation of bulk density and air-filled porosity changes in a composting pile built with the investigated composting mixtures.

1. Materials and methods

1.1. Materials

1.1.1. Substrates

Dewatered anaerobically stabilized sewage sludge (SS) was collected from a municipal wastewater treatment plant (located near Poznań, Poland). Spent mushroom substrate (SMS) was sampled from a local mushroom production facility (located near Poznań, Poland). The investigated materials were subjected to laboratory analysis of physicochemical and physical properties. This included: bulk density (BD), air-filled porosity (AFP), mechanical strength (MS), moisture (MC) and organic matter (OM) content, total organic carbon (TOC), total nitrogen (TN) and pH. Also, spent mushroom substrate was tested for water holding capacity (WHC).

1.1.2. Composting mixtures

Municipal sewage sludge was mixed with spent mushroom substrate in the weight ratio of 1:1.2, 1:2.4 and 1:6.0 (on dry basis, d.b.) (Table 1). In addition, the weight ratio (d.b.) was also expressed on wet basis (w.b.). Also, the volumetric ratio for the investigated mixtures (w.b.) was provided. The investigated composting mixtures were tested for bulk density, air-filled porosity and mechanical strength (in three replications).

Table 1. **Ratios of SS and SMS in the composting mixtures**

Composting mixtures	Ratios					
	Weight ratio (wet basis)		Weight ratio (dry basis)		Volumetric ratio (wet basis)	
	SS t	SMS t	SS t	SM t	SS m^3	SMS m^3
SS:SMS (1:1.2)	1	0.4	1	1.2	1	0.6
SS:SMS (1:2.4)	1	0.9	1	2.4	1	1.2
SS:SMS (1:6.0)	1	2.2	1	6.0	1	3.2

1.2. Methods

Sewage sludge and spent mushroom substrate were subject to laboratory analysis for moisture content (MC), organic matter content (OM), total organic carbon (TOC), total Kjeldahl nitrogen (TN), pH and bulk density (BD) (performed in three replications). Moisture content, organic matter, C/N ratio of the investigated mixtures were calculated from the initial values of moisture content, organic matter, total organic carbon and total Kjeldahl nitrogen of each of the substrates. Moisture content was determined by oven drying in 105°C and organic matter was determined by loss on ignition at 550°C for 6 h. pH of the investigated materials was measured in water extracts in the ratio of 1:10 (v/v) using a pH/conductivity meter (CPC 411). Water holding capacity (WHC) was determined by soaking a wet sample in a beaker for 1 day and draining the excess water through a paper filter. Bulk density was measured by weighing the sample in a known volume [1, 12]. Air-filled porosity (AFP) was calculated based on easily measured parameters such as bulk density (w.b.), dry matter, organic matter and densities of water, organic matter and ash according to the formula: $AFP = 1 - BD[(1 - DM)/\rho w + (DMOM)/\rho OM + (DM(1 - OM))/\rho ash]$ [1, 12, 13]. Mechanical strength (MS) was determined by the compaction device described in the previous work [1, 12] from the initial bulk density, known applied stress, and the maximum and minimum bulk densities for the investigated materials and calculated from the formula described in the previous work [13]. Simulation of changes in bulk density and air-filled porosity with the depth of a composting pile was performed for a 2 m high pile built with the investigated substrates and composting mixtures, as described in the previous work [1].

2. Results and discussion

2.1. Characteristics of substrates

The physicochemical and physical properties of the investigated sewage sludge and spent mushroom substrate are presented in Table 2. Municipal sewage sludge demonstrated typical properties for this kind of material. The content of moisture

(83%), organic matter (74.9%, dry basis, d.b.) and total nitrogen (6%, d.b.) were high. However, the content of organic carbon (41.6%) was rather low, and thus the C/N ratio of SS was of 7. SS demonstrated plastic and dense structure and susceptibility to compaction. The bulk density (BD, d.b.) was high (889 kg m^{-3}) whereas mechanical strength (MS, N m^{-2}) was extremely low (6992 N m^{-2}). Air-filled porosity was of 27%.

The reported physicochemical and physical parameters showed that sewage sludge cannot be composted without the addition of a supplementary material that would provide structure to the initial mixture, and thus increase air-filled porosity and mechanical strength, and also amend the moisture content and C/N ratio. Spent mushroom substrate as a by-product from mushroom production showed low content of organic matter but it showed relatively high content of nitrogen (2.4%). Due to low content of organic carbon (33%) SMS demonstrated low C/N ratio (14:1). Similar properties were reported by other researchers [9, 14]. As for physical properties, spent mushroom substrate demonstrated rather high bulk density (538 kg m^{-3}), and thus low air-filled porosity when compared to typical composting supplementary materials such as wheat straw or woodchips. Mechanical strength of SMS - the property which shows the susceptibility to compaction in a composting pile - was about 70 000 N m^{-2} and was significantly lower than typical bulking agents. Other researchers investigated the potential of spent growing media (e.g. strawberry or tomato growing media) for composting as alternatives for supplementary materials such as woodchips or straw. For example, spent strawberry substrate showed bulk density of 375 kg m^{-3}, organic matter of 88.2%, dry matter of 12.9%, C/N ratio of 35.5:1 and pH of 6.68. Spent tomato substrate showed similar properties to spent strawberry substrate (except from bulk density which was of 205 kg m^{-3}) - dry matter of 28.1%, organic matter of 78.6%, total nitrogen of 1.6% and C/N ratio of 27.4 and pH of 6.45 [5].

Table 2. **Characteristics of the investigated substrates**

Substrates	Parameters									
	DM %	OM % d.b.	TOC %	TN %	C/N	pH	WHC %	MS N m^{-2}	BD kg m^{-3}	AFP %
Sewage sludge	12.4 ±0.03	74.9 ±0.02	41.6 ±0.01	6.00 ±0.10	7.0	7.0	–	6992 ±506	889 ±23	27.0 ±1.0
Spent mushroom substrate	34.2 ±1.1	58.9 ±0.7	32.7 ±0.4	2.35 ±0.06	13.9	7.3	84.2 ±1.5	70000 ±18	538 ±42	54.8 ±3.4

2.2. Characteristics of composting mixtures

The addition of spent mushroom substrate to municipal sewage sludge in the selected ratios (Table 1) resulted in the changes of initial moisture content, bulk density and air-filled porosity, and C/N ratio of the investigated mixtures (Table 3).

Table 3. **Selected parameters of the investigated composting mixtures**

Parameters	Composting mixtures		
	SS:SMS (1:1.2)	SS:SMS (1:2.4)	SS:SMS (1:6.0)
MC, %	81.0	77.5	72.6
OM, % d.b	66.2	63.6	61.2
C/N	9.0	10.0	12.0
MS, N m^{-2}	9452 ±245	15902 ±353	39478 ±2068
BD, kg m^{-3}	684 ±9	725 ±41	612 ±13
AFP, %	37.5 ±0.9	34.9 ±3.7	46.5 ±1.1

With increasing ratio of spent mushroom substrate in the mixtures moisture decreased from 81.0 to 72.6%, organic matter decreased from 66.2 to 61.2%. Bulk density also decreased which in turn resulted in the increase of air-filled porosity. Also, there was an increase in the C/N ratio. Mechanical strength of the investigated mixtures increased with the addition of spent mushroom substrate.

2.3. Changes in bulk density and air-filled porosity with the composting pile depth

The initial physical properties of composting mixtures, i.e. moisture content, bulk density, air-filled porosity and mechanical strength, determine the changes in bulk density and air-filled porosity within the composting pile. In consequence, this can affect the aeration and moisture transfer during composting. Therefore, sewage sludge should be mixed with supplementary materials that assure optimal parameters of composting mixtures. The investigated municipal sewage sludge demonstrated excessively high moisture content (87%), low mechanical strength (6992 N m^{-2}) and very high bulk density (889 kg m^{-3}), and therefore sewage sludge is susceptible to compaction. Simulation of changes in bulk density and air-filled porosity with the depth of composting pile constructed only with sewage sludge showed that bulk density increased with the pile depth, and thus air-filled porosity decreased from 27% to 3÷4% at the base of the pile (Fig. 1). As for a composting pile constructed with only spent mushroom substrate bulk density and air-filled porosity did not change significantly with the depth of the pile (Fig. 1). This means that spent mushroom substrate is not susceptible to compaction in a pile.

Simulation of bulk density and air-filled porosity for the composting piles constructed with the investigated mixtures (i.e. SS:SMS 1:1.2, SS:SMS 1:2.4, SS:SMS 1:6) demonstrated that the addition of spent mushroom substrate to sewage sludge had the impact on the changes in bulk density and air-filled porosity with the composting pile depth. The addition of 2.2 tons of SMS to 1 ton of SS (or 3.2 m^3 of SMS to 1 m^3 of SS) allowed maintaining air-filled porosity within the composting pile in the range of 46÷38%. According to many researchers this air-filled porosity does not allow adequate moisture and oxygen transport within the pile [13].

Increasing the ratio of SMS in the mixture would result in increased volume of the mixture which means lower quantities of SS to be composted.

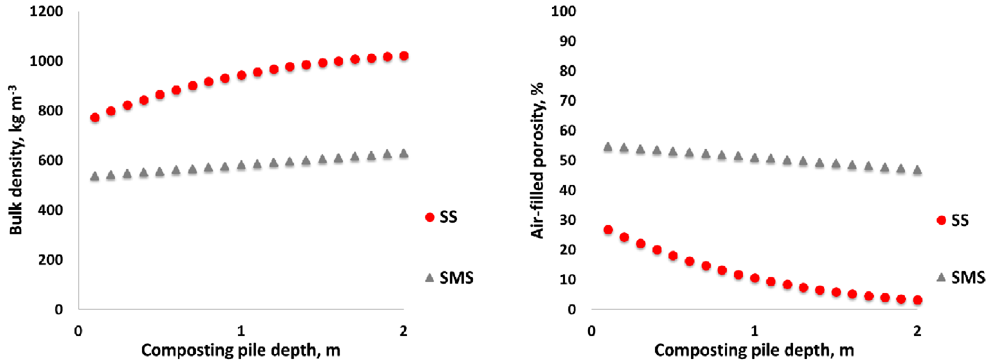

Fig. 1. Changes in bulk density and air-filled porosity with the composting pile depth

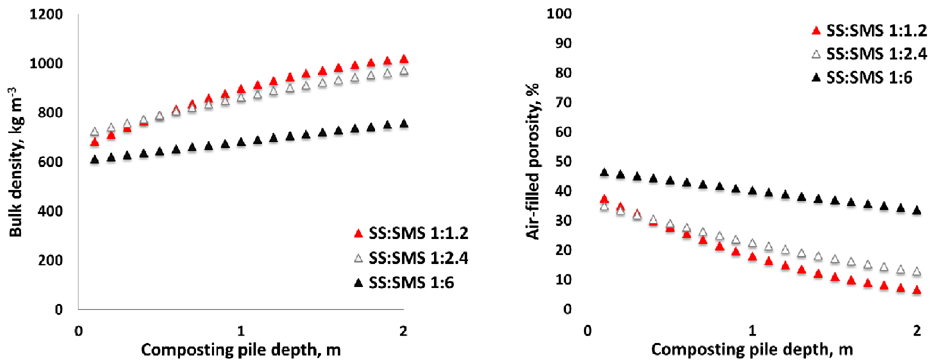

Fig. 2. Changes in bulk density and air-filled porosity with the composting pile depth

2.4. Spent mushroom substrate as a supplementary composting material

Supplementary materials used for composting of sewage sludge should allow achieving the recommended values of moisture content, C/N ratio and air-filled porosity in the initial mixtures. The most common supplementary materials include wheat straw or woodchips that function as bulking agents and amendments. Due to high C/N ratio wheat straw can amend the C/N ratio and provide structure to sewage sludge mixtures. However, as the availability of wheat straw or other commonly used materials can be limited, there is a need for alternatives. Spent mushroom substrate has been considered a supplementary material and an alternative for materials commonly used in composting. The investigated spent mushroom substrate showed significantly higher moisture content and lower C/N ratio than other typical materials. For example, MC and C/N ratio for wheat straw was about 14% and 69:1 [15] whereas MC and C/N for woodchips was about 17% and 35:1 [1], respectively. As for physical properties such as bulk density, air-filled porosity and mechanical strength, the investigated spent mushroom substrate showed higher bulk density (538 $kg\,m^{-3}$) than e.g. wheat straw (31 $kg\,m^{-3}$) or woodchips (179 $kg\,m^{-3}$), and thus lower air-filled porosity (54.8%) than e.g. wheat straw (98%) or woodchips (87%) [1]. Also, spent mushroom substrate demonstrated lower mechanical strength (70 000 $N\,m^{-2}$) than e.g. woodchips (622 377 $N\,m^{-2}$). However, mechanical strength is a function of moisture content and increases with the decrease in water content of the material [16, 17]. Due to high moisture content (66%) and water holding capacity (84%), spent mushroom substrate did not allow to significantly reduce moisture content of the investigated sewage sludge mixtures.

Conclusions

In this study, spent mushroom substrate was investigated as a supplementary material for preparation of initial sewage sludge mixtures and as an alternative for commonly used bulking agents such as straw or wood chips. We analyzed the potential of spent mushroom substrate for proving structure to sewage sludge mixtures and amending C/N ratio of those mixtures. Spent mushroom substrate showed lower C/N ratio (13.9:1) in comparison to other bulking agents. Also, it demonstrated lower mechanical strength and air-filled porosity. The addition of spent mushroom substrate to sewage sludge up to the ratio of SS:SMS 1:6 did not allow achieving the recommended values of C/N ratio and air-filled porosity within a composting pile. Therefore, it has to be concluded that spent mushroom substrate is not a suitable bulking agent for preparation of the initial mixtures of sewage sludge. However, spent mushroom substrate could be used as a supplementary material for other types of biodegradable waste with higher C/N, lower moisture content and the structure less plastic and susceptible to compaction than sewage sludge. Also, spent mushroom substrate could be used for mixing sewage sludge together with the addition of lower quantities of other supplementary materials, e.g. wheat straw. However, this will require further studies.

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Streszczenie

Zużyte podłoże popieczarkowe (ZPP) to odpad powstający po produkcji pieczarki. Charakteryzuje się niską zawartością materii organicznej, ale zawiera relatywnie znaczne ilości azotu (2,4%). Zużyte podłoże popieczarkowe może być wykorzystane w rolnictwie jako polepszacz do gleby lub alternatywa dla torfu. Doniesienia literaturowe wskazują, że zużyte podłoże popieczarkowe może być również wykorzystane jako materiał pomocniczy w kompostowaniu różnych odpadów biodegradowalnych czy też komunalnych osadów ściekowych (OŚ). W procesie kompostowania zużyte podłoże może pełnić funkcję materiału strukturotwórczego i zapewniać odpowiednią strukturę pryzm kompostowych. Głównym celem badań była ocena możliwości wykorzystania zużytego podłoża popieczarkowego jako materiału pomocniczego do przygotowania mieszanek kompostowych z osadów ściekowych tak, aby zapewnić w tych mieszankach wymaganą zawartość wody (50÷60%), odpowiedni stosunek C/N (25÷35:1) oraz zalecaną porowatość powietrzną w pryzmie (powyżej 75%). Z uwagi na wysoką zawartość wody, niski stosunek C/N i brak odpowiedniej struktury osady ściekowe nie mogą być samodzielnie poddawane kompostowaniu. Materiał pomocniczy dodany do

osadów ściekowych powinien zapewnić odpowiednią strukturę (pozwalającą na utrzymanie optymalnej porowatości powietrznej w pryzmie), zawartość wody oraz stosunek C/N w otrzymanej mieszance kompostowej. Badane zużyte podłoże popieczarkowe charakteryzowało się niższą zawartością wody oraz materii organicznej, niższym stosunkiem C/N oraz niższą wytrzymałością mechaniczną w porównaniu do innych materiałów pomocniczych stosowanych w kompostowaniu komunalnych osadów ściekowych (takich jak słoma zbożowa czy ścinki drzewne). Dodatek zużytego podłoża popieczarkowego do osadów ściekowych (udział w mieszance OŚ:ZPP wynosił do 1:6) nie pozwolił na uzyskanie zalecanych wartości zawartości wody, stosunku C/N i porowatości powietrznej w pryzmie o wysokości 2 m. Z tego względu badane zużyte podłoże popieczarkowe okazało się nieprzydatne jako materiał strukturotwórczy wykorzystywany do przygotowania mieszanek kompostowych z osadów ściekowych. Jednakże zużyte podłoże popieczarkowe może być wykorzystane jako materiał pomocniczy w kompostowaniu innych odpadów biodegradowalnych, które charakteryzują się niższą zawartością wody, wyższym stosunkiem C/N i korzystniejszą strukturą, lub też w kompostowaniu osadów ściekowych wspólnie z innymi materiałami pomocniczymi (np. słomą) użytymi w mniejszej ilości.

Słowa kluczowe: **zużyte podłoże popieczarkowe, materiały strukturalne, kompostowanie, komunalne osady ściekowe**