biology and life sciences forum

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Proceeding Paper

Spent Cultivation Substrate (SCS) Management in Circular Farming Systems †

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† Presented at the 1st International Electronic Conference on Horticulturae, 16–30 April 2022; Available online: https://sciforum.net/event/IECHo2022.

Abstract: A spent cultivation substrate (SCS) is a growing medium which remains after the cultivation of mushrooms (SMS) or vegetables (SGS); for many years, it was considered to be a problematic waste product from farming. However, in the recent transition to sustainable, circular farming systems, it is seen as a valuable product which can be recycled. The SMS was characterized by a high organic matter content, low bulk density, high pH and soluble salt contents, and rich in macro- and microelements, with their contents generally decreasing in following order: K, Ca, Na, Mg, Mn, Fe, Si, Se, and Mo. The contents of heavy metals were acceptable for both SMS and SGS. SGS could potentially be used in horticulture for subsequent greenhouse vegetable cultivation, if composted/co-composted with additional waste products due to its high mineral salt content and to eliminate potential pests.

Keywords: mushroom cultivation; sustainable agriculture; vegetable and herb cultivation; bioeconomy; farm waste management; soil amendment

Citation: Jasinska, A.; Stoknes, K.; Roszak, M. Spent Cultivation Substrate (SCS) Management in Circular Farming Systems. *Biol. Life Sci. Forum* **2022**, *16*, 12. https://doi.org/10.3390/IECHo2022-12484

Academic Editor: Jose Antonio Pascual

Published: 15 April 2022

1. Introduction

Mushroom and plant crop cultivation is normally performed through energy- and resource-intensive processes (based on fossil or mineral resources), in specialized commercial operations (such as climate-controlled tunnels and greenhouses). These operations generate waste, and the CO_2 footprint of the produce is high [1]. During mushroom cultivation for 1 kg of grown mushroom fruiting bodies, 5 kg of spent mushroom compost (SMC) are produced [2]. SMCs from *Agaricus* are more degraded (more stabilized) than those from lignivorous fungi (e.g., *Pleurotus* and *Lentinula*), and are therefore more suitable in growing media in the greenhouse cultivation of vegetables [3,4]. Here, the mushroom growing composts were based on combined food waste and dairy manure digestate from an AD biogas plant and wheat straw. Digestates are rich in nutrients and can be used as a fertilizer, as well as growing media additives for both plant and mushroom production [5–11].

Bio-waste, which includes park and garden (green) waste, is often collected and treated together with food waste in European composting and biogas plants [12]. According to a 2016 report from the European Compost Network, only about 25% of biowaste (of which 'more than 50% is green waste') is recycled into high-quality compost and digestate [13]. However, using composts from waste streams as stand-alone growing media poses challenges, such as high pH, high salinity, and nitrogen immobilization [14]. Studies show that green compost can be improved through better aeration, selectivity of feedstock, quality control, and superiors composting processes [15,16]. Therefore, in the scope of the VegWaMus CirCrop project, we have focused on recycling spent mushroom substrate (SMS) into a growing medium or growing medium additive for vegetables and subsequent mushroom cultivation. We also investigated the reuse of spent growing substrate (SGS) and crop waste from greenhouse tomato production into a new cultivation substrate.

2. Materials and Methods

The spent mushroom substrate (SMS) after 120 days of *Agaricus subrufescens* cultivation comprised food waste, dairy manure digestate-based compost, combined with wheat straw and a casing layer—Norwegian black peat. Both components were thoroughly mixed and air-dried.

Three types of spent growing substrates (SGSs) from one year of greenhouse tomato cultivation were examined. The growing substrates were based on garden compost produced from mostly green waste (Lindum AS, Drammen, Norway), vermicompost, earthworm crusts fed with a combined food waste-dairy manure digestate [17], and aged bark. The compost mixes were fertilized by a liquid fraction of the digestate. Spent Growing Substrate mix 1 (SGS1): 30:70 vermicompost/garden compost. Spent Growing Substrate mix 2 (SGS2): 30:35:35 vermicompost/aged bark/garden compost. Spent Control Substrate peat 1 (SCS1): peat + mineral fertigation.

The examined substrates were analyzed for elemental content before and after crop cultivation and/or composting; changes in the initial constitution were evaluated. Chemical and physical features were measured, including the pH, EC, dry matter content (DM), ash, and organic matter content, and the values were compared.

2.1. Analysis of Substrate Ingredients, SMC, and SGS

Fresh samples (300 g) of thoroughly mixed composts or raw materials were taken. From this, 30 g was taken for pH assessment and 60 mL was taken for EC (electrical conductivity) measurement. The remaining samples were dried and weighed for dry matter determination, combined, and subsequently homogenized in a blender. This was used for ash content analysis.

The pH, electrical conductivity (EC), dry matter (DM), and ash content were determined immediately after sampling. A minimum of 10 g compost/substrate was dried at 120 °C in duplicate to determine the dry matter. Thereafter, the dried material was burned at 550 °C to determine the volatile solids/ash content. DM, VS, and ash values are given as the means of the two samples. Calculations: DM (%) = Dried material (g)/Fresh material (g). Ash (%) = Burnt material (g)/Dried material (g). The organic matter content was determined by the 'loss on ignition' method. To assess the pH, 30 mL fresh material was mixed with 100 mL distilled water at 20 °C. The pH was measured after 30 min using a pH meter. To assess the EC, 60 mL of fresh material was mixed with 300 mL distilled water at 20 °C. The EC was measured after 30 min using an EC meter (Milwaukee 802 pH/EC/TDS meter). Organic nitrogen (N) was analyzed using the Kjeldahl-N method, according to the Int/NS-EN 13342:2000 procedure developed by VestfoldLab, Sem, [18] or EN13654-1 m developed by Eurofins, Moss [19].

2.2. Element Contents in Substrate

Samples of substrates were preliminarily dried at 45 ± 2 °C for 120 h in an electric oven and ground in a laboratory mill. Accurately weighed 0.500 ± 0.001 g of dry samples of the substrate were digested by concentrated nitric acid in closed Teflon containers in a microwave sample preparation system. After digestion, samples were filtered through paper filters and diluted with water to a final volume of 15.0 mL. Inductively coupled plasma optical emission spectrometry (Agilent 5110 ICP-OES; Agilent, Santa Clara, CA, USA) was used for element determination. For multielement determination, common conditions were used. The detection limits were determined for the level of 0.0X mg/kg dry weight (dw) or better for all elements determined. The level of uncertainty for the whole analytical procedure (including sample preparation) was below 20%. Every individual sample was analyzed in triplicate. All element contents are given as milligrams per kilogram of dry matter (d.m.).

3. Results and Discussion

The air-dried SMS was characterized by a high organic matter content, low bulk density, high pH, and high soluble salt content. SMSs were rich in macro- and micro-elements important from a nutritional point of view, and their contents generally decreased in the following order: K, P, Na, Mg, Ca, Mn, Fe, Si, Se, and Mo (Table 1). The amounts of nutrients were higher than in the mushroom compost before cultivation. Those features make SMS almost ideal as a plant fertilizer or growing substrate additive. The advantage over chemical fertilizer is that SMSs deliver a slow release of nutrients, which does not cause nutrient burn of the crops [20]. However, excessive application can increase the salinity of soils and substrates. If the digestate in the circular food-loop were to be used for mushroom cultivation, it would be very useful if the SMS could be used as a plant-stimulating growth medium. This would also be of interest for existing greenhouse vegetable growers seeking more sustainable solutions. In one study [21], a high fraction of peat was substituted with a compost made from digestate solids, SMS, and manure for tomato and pepper seedlings; better growth and higher quality of the seedlings, with reduced *Fusarium* wilt, were obtained when using this compost.

Table 1. Substrate composition before and after mushroom cultivation—summary of changes.

	Before Use	**After Use**
	Mushroom Compost	**SMS**
OM%	87.6	83.2
DM%	30.2	35.5
pH	8.8	5.5
EC (dS/m)	4.3	3.6
Ash%	12.4	16.8
K (mg/kg)	10,968	14,334
P (mg/kg)	3100	3900
Na (mg/kg)	1955	3123
Mg (mg/kg)	1275	2410
Ca (mg/kg)	1420	1660
Mn (mg/kg)	51.6	96.6
Fe (mg/kg)	28.8	57.9
Si (mg/kg)	45.9	40.6
Se (mg/kg)	1.1	2.9
Mo (mg/kg)	0.5	1.6

Digestates, depending on the feedstock, can be also rich in elements such as non-essential and trace elements, heavy metals, various organic pollutants, and other unwanted compounds, which makes their usefulness in direct food production of vegetables and mushrooms questionable [22–25]. Therefore, to prove the usability, over 60 elements were analyzed in the abovementioned composts; however, we only explored three more closely. We chose elements important for human health which are also highly accumulative in plants and mushrooms: cadmium (Cd), copper (Cu), and zinc (Zn) (Table 2). In all examined SCSs, the levels of cadmium were acceptable, and ranged from 0.6 to 2.2 mg/kg. In all but one, substrates were within the limit of class Eco. Additionally, levels of Cu were quite low, even within limits of class 0 (SMS-3.3 mg/kg) or class Eco. A similar trend was observed with zinc, where SMS showed the lowest levels of class 0, whereas SGSs were within class Eco. Cadmium is toxic and accumulates in the body over time. There are naturally low concentrations of this element in the soil. Higher concentrations can be found in P fertilizers and some rocks [26]. Copper, however, is a necessary compound for human health. In small quantities, it is nutritional, but when values are too high, it can be toxic. Cu fertilizer should be used in areas where the Cu content in the soil is too low. Copper levels are often too high in animal manure. Zinc is one of the most important trace metals in human nutrition; however, the intake should be in small quantities. High levels of zinc ingestion can be very toxic, however. It is added to pig and salmon feed; thus, levels in milk and salmon meat can often be too high [27]. All examined SCSs showed acceptable levels of heavy metals, ranging in limit values of class 0 to Eco (Table 2). Therefore, SCS could be potentially used in horticulture for subsequent greenhouse vegetable cultivation [6].

Table 2. Some heavy metal levels in substrates after cultivation (mg/kg) with reference to limits and initial substrates.

	Cadmium Cd	Copper Cu	Zinc Zn
Limit value class 0	0.4	50	150
Limit value class Eco	0.7	70	200
Limit value class 1	0.8	150	400
Limit value class 2	2.0	650	800
Limit value class 3	5.0	1000	1500
Average digestate	0.32	60	250
Average garden compost	0.37	50	170
Peat substrate	0.38	470	250
Initial substrate mushroom cultivation	0.62	1.99	47
SGS mix 1	2.2	62	190
SGS mix 2	0.60	67	210
SMS mg/kg	0.72	3.30	109

White background: limit values for soil classification; light gray background: substrates and substrate additives before cultivation; dark gray background: substrates after cultivation.

Changes in substrates were observed after one year of greenhouse tomato cultivation (Table 3). There were notable increases in the total nitrogen (tot-N), phosphorus (P), and calcium (Ca) contents in both SGSs. Strong decreases in the amounts of potassium (K) and chloride (Cl) were observed in both SGSs. There was a notable decrease in the amount of nitrate in SGS1, whereas in SG2, nitrate levels stayed the same. No accumulation of sodium (Na) was measured; however, both substrates noticeably accumulated sulfur (S). Ash values stayed at a similar level.

Table 3. Substrate nutrients before and after tomato cultivation—summary of changes.

	Before Use mg/L			After Use mg/L		
	Peat	**SGS1**	**SGS2**	**Peat**	**SGS1**	**SGS2**
tot-N, mg/kg fresh weight	3200	2500	2300	8896	10,002	12,104
Nitrate, mg/L	170	83	3.0	16	14	3.5
Ash%	95	40	45	92	38	45
Phosphorus (P), mg/L	200	59	53	5.0	585	466
Potassium (K), mg/L	1200	1000	740	10	197	132
Calcium (Ca), mg/L	2000	2000	1900	291	5850	4905
Sodium (Na), mg/L	280	270	170	25	246	196
Sulphur (S), mg/L	500	200	170	148	776	662
Chloride (Cl), mg/L	230	250	130	6.0	72	51

Organic growing media are easier to recycle; however, when using food and green waste composts as peat-free plant growing media, there is a risk that nutrient immobilization and high pH and salt contents limit plant growth. The initial substrates were much poorer in nutrients than the SGSs after cultivation, which may either indicate release of the immobilized nutrients or residues of fertilization after cultivation. Either way, a richer initial substrate is advantageous. Some studies state that depending on the feedstock, compost from green waste can exhibit high salinity, and therefore recommend no more than 20% to 50% additional salt [28,29].

However, composting or co-composting with additional waste products is recommended to eliminate potential pests and because of high mineral salt contents. SGSs exhibit good composting potential with a sufficiently high C/N ratio and organic matter content (50–65%) to heat up during composting. Good-quality compost from food and other organic wastes is rich in valuable nutrients, which can be recycled back into food production by its use as an excellent soil amendment [15].

4. Conclusions

- The features of SMS show that it could be used air-dried as an addition to plant cultivation media.
- SMSs could be also used as a substrate additive for the cultivation of other mushrooms or as a casing material.
- If used fresh, directly after cultivation, both SCSs should be composted or co-composted with additional waste products to eliminate potential pests and due to high mineral salt content.
- After composting, SGS could potentially be used in horticulture for subsequent greenhouse vegetable cultivation
- SGSs can be also targeted for direct use in outdoor agriculture and landscaping as a soil fertility amendment.

Author Contributions: Conceptualization, A.J. and K.S.; methodology, A.J.; software, A.J.; validation, K.S.; formal analysis, A.J.; investigation, A.J. and M.R.; resources, A.J.; data curation, A.J.; writing—original draft preparation, A.J.; writing—review and editing, A.J. and K.S.; visualization, A.J.; supervision, K.S.; project administration, A.J.; funding acquisition, A.J. and K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the EUROPEAN UNION'S HORIZON 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 751052 and Innovation Norway—Sirkulærøkonomi No 2018/1004404.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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