https://doi.org/10.34101/actaagrar/150/1715

Spent mushroom compost (SMC) – retrieved added value product closing loop in agricultural production

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Summary

Worldwide edible mushroom production on agro-industrial residues comprises of more than 11 million tons of fresh mushrooms per year. For 1 kg of mushrooms there is 5 kg of spent mushroom compost (SMC). This enormous amount of waste results in disposal problems. However, SMC is a waste product of the mushroom industry, which contains mycelium and high levels of remnant nutrients such as organic substances (N, P, K). The spent mushroom compost is usually intended for utilization, but there are increasing numbers of experiments focusing on its reuse in agricultural and horticultural production. Recently, the increase of the global environmental consciousness and stringent legislation have focused research towards the application of sustainable and circular processes. Innovative and environmentally friendly systems of utilisation of waste streams have increased interest of the scientific community. Circular economy implies that agricultural waste will be the source for retrieving high value-added compounds. The goal of the present work was to carry out a bibliographic review of the different scenarios, regarding the exploitation of this low cost feedstock with huge potential for valorisation.

Keywords: mushrooms cultivation, spent mushroom compost, fertiliser, circular economy, agricultural waste management

Introduction

Since consumption of mushrooms was always incorporated in human diet, has cultural and even mystical meaning the mushroom trade and use has been continuously increasing worldwide to over 11 million tons, generating huge amounts of solid residues. During mushroom cultivation for 1 kg of grown mushrooms fruiting bodies 5 kg of spent mushroom compost (SMC) is given (Lau et al., 2003). The average mushroom farm throws about 25 tons of SCM per month (Singh et al., 2011). The production of only *Agaricus bisporus* in Poland is about 330 000 tons per year (Royse, 2014). The substrate after growing mushrooms is usually a problem for their producers, who are most willing to get rid of the compost after harvest. Cultivation remnants and the substrate itself attracts flies and other insects that can transmit diseases and are a potential source of water and air pollution (Beyer, 1996; Zied et al., 2011). The spent mushroom compost is usually intended for utilization, some of the current disposal strategy of SMS/SMC in the world is by burning, spreading on land, burying, composting with animal manure, or very much common by landfilling. However, the European Union, through the Landfill Directive, has established that landfilling is no longer sustainable way aiming in decreasing amounts of agro industrial wastes disposed that way (Directive 1999/317EC, 1999). Other environmental regulations have forced mushroom farmers to look for more environmentally friendly ways of utilizing residual substrates (Dziennik Ustaw, 2001). Most commonly, the research on SMS/SMC focused on the enzymatic activity of the residual mycelium and its ability for production of lignocellulosic enzymes such as laccase, xylanase, lignin peroxidase, cellulase and hemicellulose as a cheap source of bioremediation, animal feed and energy feedstock (Santos et al., 2005; Machado et al., 2007; Azevedo et al., 2009). Introduced in 2008 principle "polluter pays" or "waste hierarchy", Waste Framework Directive, also encourage mushroom growers to exploit new means of simple and cheap mushroom waste management (Directive 2008/98/EC, 2008). At the same time, the demand for organic fertilizers and compost increased due to increasing restrictions on the use of synthetic pesticides and mineral fertilizers in agricultural and horticultural cultivation. Aiming to give the destination to this agro-industrial residue, studies have been made to retrieve spent mushroom compost with as much less processing as possible enabling almost direct reuse of this residue. The aim of this mini-review is focus on research describing properties of the SMS/SMC for direct use: recultivation of SMS/SMC with other mushroom species; combined cultivation with plants; direct use of fresh or dried SMS/SMC in horticulture for plant seedlings production and mature plants growth, and composting to produce peat-free plant growing substrates.

A circular economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing energy and material loops and is millennial activity using tool such as design thinking, systems thinking, product life extension, and recycling. This can be achieved through long-lasting design, maintenance, and repair, reuse, remanufacturing, refurbishing, and recycling (Geissdoerfer et al., 2017). This is in contrast to a linear economy which is a 'take, make, dispose' model of production (Ellen MacArthur Foundation, 2017). Horticulture is just one sector where this holistic concept make more than sense (Stoknes et al., 2016). Mushrooms as a decomposers and thus their cultivation seems to be a missing link in this circle of food production presenting possibilities of creating close loop and the zero waste mushroom cultivation with reuse of local waste resources (Jasinska et al., 2016ac).

Mushroom substrate types

Generally, mushrooms do not have chlorophyll and cannot produce carbohydrates by photosynthesis. Mushroom mycelium secrete enzymes that break down compounds such as cellulose and lignin present in the substrate. Mushrooms are cultivated on a specially designed and selective medium that supplies the nutritional requirements of the mushroom crop. The best substrates are composed from so called agricultural wastes reach in lignocellulose components which are difficult to break down, however can be effectively be done by mushrooms. Their composition and method of preparation varies depending on the availability and geographic location of the crop. Depending on which mushroom is cultivated there are two kinds of substrates for cultivation: composted and pasteurised substrate to or sanitised with pasteurisation or sterilisation.

Characteristic of Spent Mushroom Substrate – SMS /Spent mushroom Compost SMC

Both types of substrates can be retrieved for direct use, are high in organic matter (22–40%), which can be a good source of nutrients for plants, mainly due to its rich content of nutrients, high cation exchange capacity and slow mineralization. However, their characteristics differs in terms of their initial components and methods of preparations. The amount of mineral elements constitutes for 66–78%. SMC is a good source of general nutrients such as NPK (1.3–4.2:0.1–0.4:0.5:1.8% respectively), Mg (0.2–0.4%), Na (0.05–0.2%) and full range of trace elements such as: Cu, Fe, Mn, Zn, Mo, B (values in ppm: 4–12; 1000–2500; 100–300; 50–200; 1–2; 6–15) and soluble salts does' not contain any pests or weed seeds. In addition, SMC contains 45% water, although it seems quite condensed substrate compared to manure, it has a low bulk density (Dann, 1996).

One cubic meter of SMC corresponds to 2 to 3 tonnes of solid manure in terms of nutrient content. It contains about 6–20% calcium in the dry matter, thanks to which it has deacidifying properties (Szudyga, 1987; Gapiński, 1996; Uliński, 1999).

Direct uses

Recultivation of other mushrooms

Many authors emphasize possibility of using the substrate after cultivation of one species of fungi to grow the same or other species of fungi. Thus better use of the remaining nutrients help to reduce problem of SMS removal (Fahy and Wuest, 1984; Royse, 1993; Poppe, 1995, 2000; Ahlawat and Sagar, 2007; Siddhant and Singh, 2009; Gea et al., 2012). The most research show that the most common is recultivation of various *Agaricus* species or *Shiitake* on substrates after cultivation of specialty mushrooms, most commonly oyster mushroom (Mamiro and Royse, 2008; Matute et al., 2011). Matute et al. (2011) proposed the cultivation of *A. blazei* on non-composted substrates with a low rate of contamination when using the spent mushroom substrate as the main component or combined 50:50 with sunflower seed hulls. The research show fastest growth of mycelium on substrates with additives that performed increased yield compared to control substrates.

Some studies show recultivation of *Pleurotus* mushroom on Shiitake SMS supplemented with some nitrogen sources such as wheat and rye bran, soya seeds, $CaCO_3$ (Royse, 1993; Ahlawat and Sagar, 2007). Chang and Miles (1989) studied reuse of substrate after *Volvariella volvacea* for cultivation of *Pleurotus pulmonarius* resulting in good yields of fruiting bodies.

According to the author's knowledge, the *Agaricus* SMC is rarely used for re-growing mushrooms. Oei (1991) and Poppe (2000) describe in their research the use of SMC of *Agaricus bisporus* for cultivating of *Volvariella volvacea*. It may be related to the aforementioned rather strong process of decomposition of the SMC and its significant salinity. The research of Jasinska et al. (2018) propose reuse of SMC after *A. brasiliensis* cultivation for *Pleurotus ostreatus, Agrocybe cylindracea and Hericium erinaceus*. Advantage of this substrate is the low content of mineral salts, sulphates and pH close to the neutral pH 5.1–6.0, because due to long period of mushroom harvesting – 110 days, thanks to which it can be used immediately after cultivation, without the need for prior composting (Lopes et al., 2015). Mamiro et al. (2007) and Mamiro and Royse (2008) describe subsequent cultivation of *A. bisporus* performed on sterile, non-composted substrate (sawdust, millet, rye, peat, ground alfalfa, ground soybean, wheat bran and $CaCO_3$) and spent compost after *Agaricus* cultivation and their mixes. Mushroom yields and BEs on substrate mixtures of NCS (sawdust, millet, rye, peat, ground alfalfa, ground soybean, wheat bran and $CaCO_3$) and SMC were comparable to non-supplemented Phase II compost.

On the other hand, the SMC as an addition to the casing or as a casing soil in the production of mushrooms is much more often described (Nair and Brandley, 1981; Shandilya, 1989; Singh et al., 1992, 2000; Szmidt, 1994; Bhatt and Singh, 2002; Dhar et al., 2003; Ahlawat and Vijay, 2004). In commercial *Agaricus* mushroom cultivation so called casing soil is used to cover the compost, after the substrate is fully colonized by mushroom mycelium to encourage fructification. Sphagnum peat moss, as the most common casing material is "slow-renewable" factor and its geographic availability is limited. Recently the use of alternative cheap and easily available casing material is investigated, such as soil, gravel and tuffeau stone, calcium carbonate in different forms and spent *Agaricus bisporus* compost are the most common (Pardo et al., 1999). Casing soil to trigger fruiting bodies development must represent certain properties such as low bulk capacity, high water holding capacity, pH around 7.0 and foremost low electrical conductivity. Flegg (1961) concluded that fruiting of *Agaricus bisporus* was related to the electrical conductivity of the casing layer, thus the mushroom response was related to the osmotic pressure and, therefore, moisture stress in the casing layer. SMS as a casing has promising features with high water holding capacity and low bulk density but it is characterised by high EC. The high electrical conductivity of the mixture containing the highest proportion of SMS would limit its use as a crude casing layer. Therefore the most successful casing from were obtained when SMS was either aged, leached or mixed with some other organic components to dilute its EC. The research by Giménez and González (2008) demonstrated the viability of reincorporating freshly aged SMS as an ingredient of casing mixtures with coconut fibre in new cycles of mushroom cultivation. Instead of leaching Sharma et al. (1999) used chelating agents like citric acid, ethylene diaminetetraacetic acid (EDTA) to reduce metal cations from the casing. Their experiments showed that dry matter of mushrooms cultivated on chelated casing was much higher than the control. Ahlawat and Vijay (2004) described the composted *Agaricus* SMC used as a casing produced an effect comparable to the most commonly used peat casing. Additionally, they found that when using a SMC, the risk of bacterial blot on fruiting bodies was much lower than with the traditional peat-based casing.

Horticulture

Combined cultivation with plants

Combined or combination cultivation is the process of mixing different kinds of crops with each other which enable crops positively influence each other, which has some advantages: prevention of pests and diseases, larger yields and healthier plants. However not only plan-plant systems are known and described, but also plant-mushroom. The best and the most know example of mushroom-plant system is omnipresent mycorrhiza dependence between higher plants and mushrooms.

Corporate cultivation of plants and saprotrophic mushrooms has been described in several researches where the impact of mushroom on the plant is shown. Mushroom hyphae wrap around roots and increase water and minerals availability for plants, thus higher biomass production, higher yields. In the other hand, mushroom compost is nutrient rich product, highly assimilable by plants. *Stropharia rugoso-annulata* is grown together with maize – 20% of yield increase, while combination of *Hypsizygus ulmarius* and Brussel sprouts because 25% of yield increase (Wang et al., 1984; Dallon, 1987; Levanon and Danai, 1995; Maher et al., 2000; Mullen and McMahon, 2001; Williams et al., 2001; Prabu et al., 2014). In study, Jasinska et al. (2016b) evaluated possibility of combined cultivation of edible mushroom- *Agaricus brasiliensis*, and vegetables – *Vigna ungiculata*, as a sustainable, vertical system of growing. Climbing plants formed shades for mushroom and created specific microclimate and CO_2 produced by mushrooms in respiration process was used by plants for plant tissue production. Results of experiment show the potentiality incorporating plant (legumes) cultivation system with mushroom growing.

Organic fertiliser

A common way to use of SMC is to use it as an organic fertilizer in agriculture and gardening. The advantages of using SMC as a soil fertilizer over a chemical fertilizer is that it delivers slow-release of nutrients that will not burn crops upon application. Besides, SMC has a low bulk density that indicates its relatively porous medium that can enhance the structure of the soils it is amended to (Curtis and Suess, 2006). However excessive application of SMC to the soil can lead to nutrient losing through leaching, which may cause water or soil pollution. One method of pre-treatment of SMS before use is, passive leaching by rainfall and snowmelt (Guo and Chorover, 2006). However, Bradley et al. (2015) and Lou et al. (2017) suggested the application of biochar could prevent the loss of nutrients from SMC. Lou et al. (2017) conducted very interesting research, where production of biochar from spent mushroom compost and spent mushroom substrate was proposed in order to improve nutrient retention during SMC application. Findings from this study suggested that combined application of SMC and SMS-based biochar was an effective strategy in nutrient conservation without any extra material consumption. On the contrary, spent mushroom compost leachates can be potentially recycled in plant culture as a rich source of nutrients as Jarecki et al. (2005) reported it. Seedlings of tomato and marigold were treated with amendment leachates from SMC and commercial composting site showing species dependent response. While tomato showed good growth in amendment commercial compost leachate, but poor growth in SMC amendment leachate, whereas excellent, growth of marigold was observed in SMC amendment leachate. Also Young et al. (2002) performed successful study on marigold cultivation with SMC leachates, as a source of nutrients via fertigation, with recommendation that SMC should be used in amounts not exceed 50% – EC levels become difficult to maintain. Mixed application of both air-dried *Pleurotus* SMS and *Agaricus* SMC and their leachates were demonstrated on performance of pepper plants by Roy et al. (2015). The experiment proved overall increase of growth and protein, chlorophyll and carotenoids content.

Another issue connected with the SMC/SMS application is the nutrients; especially nitrogen is still immobilized in straw and mycelium and may causes temporary malnutrition in plants. Research by Stewart et al. (1998) showed the feasibility of SMS as a cultivation substrate amendment.

Yields of sweet corn, cabbage and potato were increased when SMC was supplemented at 40 and 80 t ha^{-1} (moist), however temporarily immobilization of nitrogen occur at 20 t ha^{-1}, suggesting addition of inorganic fertiliser. Therefore Medina et al. (2012) suggest the appropriate timing for spent mushroom substrate additions to the soil should be approximately one month prior to the planting. Their investigation also showed the addition of spent mushroom substrates increased soil respiration rate and phosphatase activity.

Many authors considered using it as an alternative substrate for the production of vegetable seedlings, among others lettuce, tomato, pepper, pumpkin, as well as soil mulching in orchards and strawberry plantations (Uzun, 2004; Medina et al., 2009; Fidanza et al., 2010; Zhang et al., 2012; Sendi et al., 2013). Ahlawat and Sagar (2007) described reuse of SMC as good growing medium for vegetables like cucumber, tomato, broccoli, tulip, cauliflower, peppers, spinach etc. but the response of the plants varies at different levels of SMS incorporation.

In experiment of Peksen and Uzun (2008) spent mushroom compost passively leached on the field for 18 months was used as potting soil for broccoli and kale seedlings alone and in mixture with conventional seedling medium (mixture of decomposed farmyard manure, sand and garden soil at a rate of 2:1:1) or peat. Results showed that both mixtures could successfully be used as the medium for seedlings growth. Polat et al. (2009) used SMC, seasoned for 6 months, and examined as the organic matter source and amendment of greenhouse soil and successfully used for cucumber production. The experiment showed the highest values of fruit width and the nitrogen contents in cucumber were found at 80 t ha^{-1} SMC application.

Spent mushroom substrate after cultivation specialty fungi is not as often recycled as the *Agaricus* growing substrate. The reason could be inadequate decomposition of substrate components and immobilisation of nutrients however, it should not be underestimated. Kadiri and Mustapha (2010) proposed reuse of oven-dried SMS after *L. subnudus* cultivation mixed with loamy soil, for growing cowpea and tomato seedlings, which showed the best performance as growing medium. Zhang et al. (2012) investigated the potential use of SMS after *Flammulina velutipes* cultivation as a growing medium for cucumber and tomato seedlings. Research was concluded that spent *F. velutipes* mushroom substrate mixed with perlite or vermiculite had suitable physical and chemical properties for the growth of tomato or cucumber seedlings. Another study from Segun et al. (2018) shows the four common Nigerian vegetables (*Abelmoschus esculentus*, *Lycopersicum esculentum*, *Capsicum annum* and *Capsicum chinense)* were successfully cultivated on depleted garden soil supplemented with fresh SMS after *Pleurotus pulmonarius* cultivation.

However not only growth of vegetables and cereals has been investigated on spent mushroom substrates. Container plant cultivation may provide to some limitation in SMC/SMS application as a growing media or media additive because of its high salts content under conditions with little or no provision (Wang et al., 1984). In the study of Chong et al. (1991) the objective was to evaluate desirability of various spent mushroom composts as medium components in container culture of a wide assortment of woody species and concluded, all shrubs were of marketable quality when harvested, in all SMC compost-amended regimes. Under the conditions of their study, adaptation of container-grown plants to SMC-amended media was due to rapid elimination of high salinity by the constant and adequate supply of water through irrigation to well-drained media.

Pre-processing

Composting for soil amendment

Composting has gained high attention as an environmentally friendly way to dispose of and utilise organic wastes, in comparison with traditional disposal methods. Composting is commonly defined as process of biological destruction and balancing of organic wastes under aerobic conditions (Peredes et al., 2002). The composts may comprise from one type of waste or mixed type of waste, than the process is called co-composting. The term co-composting refers to the simultaneous composting of several types of residual materials. This process simultaneously disposes different organic wastes and enhance compost quality by the comprehensive use of diversified waste properties (Peredes et al., 2002). What is more, when two or more organic wastes are composted together it shortens the fermentation period (Das et al., 2011).

Because the largest share in the production of mushrooms in the world has *Agaricus* mushroom, also the most of this type of spent substrate remains after completion of cultivation. Due to the high content of mineral salts, a high content of sulphates, which can inhibit the growth and development of plants, the most common treatment for the SMC to be used is composting (Abad et al., 2001; Rinker et al., 2002; Niżewski et al., 2006; Ribas et al., 2009; Medina et al., 2009; Marques et al., 2014).

During this process, the excess of mineral salts is washed out so that the substrate can be reused as an organic fertilizer for the cultivation of cereals, fruits, vegetables and ornamental plants (Ahlawat and Sagar, 2007; Medina et al., 2009; Hackett, 2015; Lopes et al., 2015).

Zhang and Sun (2014) presented recently a research on two-stage composting of green waste _GW, comprised from park and garden litter and trimmings, with spent mushroom substrate – SMS and biochar – BC. According to their work, combination of GW with 35% SMS and 20% BC produced compost of the highest quality in the shortest time of only 24 days. Researchers also concluded that this combination extended the duration of thermophilic period, enhanced particle size distribution and nitrification, and increased microbial numbers, enzyme activities, and nutrient content during composting, which consequently accelerated the degradation and humification of organic wastes in two-stage composting.

This finding puts a promising attention on use SMS/SMC to produce high quality added-value product for peat free horticulture. On the other hand, Paula et al. (2017) demonstrate the stabilisation of SMS and its subsequent use as organic fertiliser and partial peat replacement in horticulture by composting system, with controlled temperature and aeration within the period of 21 days.

Composting of liquid organic matter such as cattle, pig manure or sewage sludge is problematic in terms of high moisture content also small particles would cause poor gas permeability (Zhao et al., 2016) thus it cannot be composted alone. What is more, low C/N ratio cause large amount of ammonia volatilization (Wang et al., 2014; Kulikowska, 2016).

Therefore mixing sludge or manure with some other organic waste with higher amount of dry matter and lower moisture would benefit greatly the process of composting (Awasthi et al., 2015). The work of Kulcu et al. (2008) showed co-composting of SMS with chicken and cattle manure and carnation waste and defining the optimum ratio of those three.

They concluded the best compost mixture, with the highest dry material losses and temperature values, of carnation waste, chicken manure and spent mushroom compost is 50%, 20% and 25%, respectively, without cattle manure. Incorporation of cattle manure to composting mixtures decreased fermenting temperatures and provided the lowest dry matter loss. Co-composting of sewage sludge (SS) with mushroom substrate (SMS) and wheat straw (WS) conducted for 20 days was evaluated in study performed by Meng et al. (2017). Their investigation suggested that adding SMS and WS could not only improve the degradation of organic matter and the quality of compost product, but also stimulate ammonia assimilation and reduce ammonia emission.

Also Meng et al. (2018) investigated on composting digestate after biogas production, SMS and pig manure in order to develop medium for partial or total replacement for peat in growth medium for tomato and pepper seedlings. The results suggest that biogas residues and SMS compost is a good alternative to peat, allowing 100% replacement, and that 20–50% replacement produces tomato and pepper seedlings with higher morphological growth and lower *Fusarium* concentrations.

Another research was performed by Brunetti et al. (2009) on composition and structural characteristics of humified fractions during the co-composting process of spent mushroom substrate and wheat straw in 90 days static piles with periodic turning ensuring adequate aeration. The results of the study confirm that composting is an appropriate treatment to transform fresh organic matter (OM) from SMS into humified forms, thus enhancing their quality, agronomic efficiency, and environmental safety as a soil OM resource for application as soil amendment.

Vermicomposting

Vermicomposting is biological process where earthworms convert organic materials into a humus-like material known as vermicompost. It is a value added product containing more available nutrients per kg weight than the organic substrate from which it is produced.

Vermicomposting seems to be a sustainable solution because of the new regulations of organic waste treatment, reducing the disposal costs, decrease waste transportation and abide by regulatory standards. The most commonly used, for the breakdown of organic wastes, are two species of earthworm are *Eisenia foetida* and its related species *Eisenia andrei*. Their biological requirements have been studied extensively showing that, these two species are prolific, robust for temperature changes, and can grow and produce well in many kinds of organic wastes with a wide range of moisture content (Edwards and Lofty, 1972; Hartenstein et al., 1989; Edwards and Bater, 1992). Tajbakhsh et al. (2008) demonstrated that vermicomposting could be considered as an alternate technology for recycling and environmentally safe management of SMC which generate in abundance as residues using epigamic earthworms *E. foetida* and *E. andrei*. The studies showed the vermicomposted SMC was rich in the micro and macronutrients which are essential elements for plant growth, had good physical properties, low conductivity, low C: N ratio, optimal stability and maturity. Bakar et al. (2011) demonstrated vermicomposting by employing red worms, *Lumbricus rubellus* of sewage sludge (SS) using spent mushroom compost from *Pleurotus sajor-caju* as feed material. The experiment was conducted to determine the effect on the concentration of heavy metals, namely Cr, Cd, Pb, Cu, and Zn. The results of the research show that a lower percentage of SS in vermibeds is recommended (25:75 ratio of SS:SMC) if the main objective is vermiculture (i.e. earthworm production). Notably, applying SS vermicompost as a soil stabilizer or fertilizer would not have an adverse impact on heavy metal content.

Conclusions

The presented review research shows great potential for SMS/SMC recycling for agricultural and horticultural industry strongly promoting peat free plant cultivation, but also pinpoint the medium to be not stable and/or mature, hindering its wide use for crop production. Developing standard methods of stabilising the SMS/SMC such as composting and co-composting, on spot leaching, combined cultivation etc. will reduce the environmental impact of these residues. In this role, SMS has considerable potential as a substitute for peat in greenhouse production.

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