Journal of Environmental Management 196 (2017) 476–486

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Stabilisation of spent mushroom substrate for application as a plant growth-promoting organic amendment

Fabiana S. Paula [a, b, *], Enrico Tatti [a, b], Florence Abram [a], Jude Wilson [b], Vincent O'Flaherty [a]

[a] *Microbiology, School of Natural Sciences and Ryan Institute, National University of Ireland, Galway, Ireland*
[b] *Research and Development Department, Monaghan Mushrooms, Tyholland, Ireland*

A R T I C L E I N F O

Article history:
Received 12 December 2016
Received in revised form
13 February 2017
Accepted 14 March 2017
Available online 24 March 2017

Keywords:
Organic residue management
Peat-replacement
Compost stability
Compost microbial community

A B S T R A C T

Over three million tonnes of spent mushroom substrate (SMS) are produced in Europe every year as a by-product of the cultivation of *Agaricus bisporus*. The management of SMS has become an increasing challenge for the mushroom production industry, and finding environmentally and economically sustainable solutions for this organic residue is, therefore, highly desirable. Due to its physical properties and nutrient content, SMS has great potential to be employed in agricultural and horticultural sectors, and further contribute to reduce the use of non-renewable resources, such as peat. However, SMS is often regarded as not being stable and/or mature, which hampers its wide use for crop production. Here, we demonstrate the stabilisation of SMS and its subsequent use as organic fertiliser and partial peat replacement in horticulture. The stabilisation was performed in a laboratory-scale composting system, with controlled temperature and aeration. Physical and chemical parameters were monitored during composting and provided information on the progress of the process. Water soluble carbohydrates (WSC) content was found to be the most reliable parameter to predict SMS stability. *In situ* oxygen consumption indicated the main composting phases, reflecting major changes in microbial activity. The structure of the bacterial community was also found to be a potential predictor of stability, as the compositional changes followed the composting progress. By contrast, the fungal community did not present clear successional process along the experiment. Maturity and quality of the stabilised SMS were assessed in a horticultural growing trial. When used as the sole fertiliser source, SMS was able to support *Lolium multiflorum* (Italian ryegrass) growth and significantly improved grass yield with a concentration-dependent response, increasing grass biomass up to 300%, when compared to the untreated control. In summary, the results indicated that the method employed was efficient in generating a stable and mature product, which has a great potential to be applied in horticulture. This study represents a step forward in the management of SMS residue, and also provides an alternative to reduce the use of peat in horticulture, alleviating environmental impacts to peatland ecosystems.

1. Introduction

As the global demand for agricultural products rises, unsustainable practices become more evident. While the agriculture sector requires unprecedented amounts of synthetic fertilisers, organic residues from agriculture and the food industry are frequently regarded as a waste, and their residual nutrient content is often overlooked. The large scale use of non-renewable resources in the agricultural and horticultural sector is of major concern for long term sustainability. This is well depicted by the rapid decline of phosphate rock reserves worldwide (Cordell and White, 2013; Elser, 2012; Gilbert, 2009), and by the increasing environmental impacts on wetland ecosystems due to peat extraction (Moxey and Moran, 2014; Robertson, 1993). Meanwhile, overproduction and accumulation of organic waste has become a major problem in both developed and developing countries (Castaldi et al., 2008). Residues are frequently destined to landfills or inappropriately disposed of, threatening both the environment and public health. Transforming nutrient-rich organic residues into valuable crop fertilisers and/or growing substrates could contribute to the conservation of non-renewable materials, while reducing waste build up.

* Corresponding author. Microbiology, School of Natural Sciences Institute, National University of Ireland, Galway, Ireland.
E-mail address: fabianaspaula@gmail.com (F.S. Paula).

http://dx.doi.org/10.1016/j.jenvman.2017.03.038
0301-4797/

Peat is the main resource used by the horticultural industry to produce growing substrates. However, the extensive exploration and drainage of peatlands are causing unprecedented impacts to this ecosystem (Moxey and Moran, 2014; Robertson, 1993), with consequences to the dynamics in the flux of carbon stocks that have been accumulated over thousands of years (Yu, 2012). It is part of the current EU policy to protect peatlands by promoting the development of alternative horticultural products (Zhang et al., 2012).

Spent mushroom substrate (SMS) is a by-product of edible mushroom cultivation (Nakatsuka et al., 2016) and is of particular interest when compared to other potential peat replacement materials, such as green waste, which typically vary in consistency, safety and availability (Hartz et al., 1996). Substrates used for mushroom growth contain lignocellulose rich materials, such as wheat straw, manure and additional supplements to provide nutrients and appropriate pH (Hackett, 2015; Jordan et al., 2008). After mushroom harvest, SMS still holds high levels of organic matter, nitrogen (N), phosphorus (P), potassium (K), and other nutrients typically required for crop growth (Jordan et al., 2008; Roy et al., 2015). Approximately 5 kg of SMS are generated for each kg of mushrooms produced (Medina et al., 2012). In Europe, the production of the species *Agaricus bisporus* alone generates over 3.5×10^6 t of SMS every year (García-Delgado et al., 2013) and, therefore, finding environmentally and economically sustainable solutions for SMS has become an increasing concern.

The employment of SMS in agroecosystems has been identified as a sustainable solution for the management of this residue (Medina et al., 2012) and previous studies have shown the benefits of using SMS as organic fertiliser and soil conditioner (Courtney and Mullen, 2008; Hackett, 2015). Besides its agricultural use, SMS could also be employed in soil-less horticultural mixes (Zhang et al., 2012). However, despite its great potential as an organic amendment, the use of SMS as a soil conditioner/fertiliser is still not well established, mainly due to its lack of stability and/or maturity (Zhang and Sun, 2014). Stability and maturity are important proxies used to evaluate the quality of composted matrices and to verify if the product is suitable for crop amendment use. Although they measure different properties, their definitions are often intertwined and/or overlapping. Stability refers to the rate of microbial activity (Gao et al., 2010), which is directly related to the extent to which labile organic matter has been decomposed (Lasaridi and Stentiford, 1998). Stability must be carefully assessed in composts designed for agriculture, as high microbial activity in soil may lead to nitrogen immobilisation (Insam and de Bertoldi, 2007; Tiquia, 2005) and oxygen depletion, affecting root development (Butler et al., 2001). Additionally, non-stable composts are not suitable for storage, since the rapid oxygen consumption by aerobic microbes favours anaerobic metabolism, which may produce odorous and potentially harmful gases (Derikx et al., 1990). Methods quantifying microbial activity, such as oxygen consumption and respiration indexes are the most indicated approaches to assess compost stability (Barrena et al., 2014; Insam and de Bertoldi, 2007; Tiquia, 2005). Monitoring the availability of easily degradable compounds is also considered a reliable parameter (Castaldi et al., 2008). Furthermore, assessing changes in bacterial and fungal communities is becoming increasingly important to monitor compost evolution (de Gannes et al., 2013; Langarica-Fuentes et al., 2014b) and stability (Boulter-Bitzer et al., 2006). Maturity is defined as the degree of organic matter biodegradation, at which it is considered ready for agricultural use. Mature composts are expected to be free of organisms and/or substances that could impair plant development, such as pathogens and phytotoxic compounds (Insam and de Bertoldi, 2007). For instance, organic acids (Gao et al., 2010) are often the end-products of intense microbial metabolism in unstable composts (Bazrafshan et al., 2016).

Since SMS is produced following an extended composting process carried out prior to mushroom cultivation, it contains a large fraction of stabilised organic matter (García-Delgado et al., 2013). However, during cultivation, *A. bisporus* releases extracellular hydrolases and ligninolytic enzymes to breakdown recalcitrant compounds in labile molecules (García-Delgado et al., 2013; Ribas et al., 2009). These molecules, along with remaining *A. bisporus* mycelium (Zhang and Sun, 2014), increase the amount of easily degradable organic matter that requires further stabilisation. Additional SMS composting could provide stability and further transform this nutrient rich residue into a valuable product. Yet, studies focused on the optimisation of the composting process of SMS residues are still scarce. The quality of the end-product is crucial to provide actual benefits and to avoid negative impacts on crop productivity (Barrena et al., 2014), and it is largely affected by the composting operating procedures. If we are to produce high-value substrate for crop amendment from SMS residue, the composting procedures for this type of organic matter must be optimised, with suitable assessment of stability and maturity.

In the current study, we aimed to evaluate a short term composting process to stabilise and mature SMS, and further transform this residue into a plant growth-promoting organic amendment. We also tested different stability parameters and identified the best tools to monitor the process. To provide information on the microbial community succession, we assessed the main changes in bacterial and fungal community composition along the process. Finally, the quality and maturity of the end product was tested in a growing trial, using SMS as an organic fertiliser and partial peat replacement.

2. Methods

2.1. Characterization of spent mushroom substrate

The SMS used in this study was obtained from Monaghan Mushrooms Ltd facilities, located in Tyholland, Ireland. The samples were collected in March and May 2014. After *A. bisporus* harvesting, the SMS was subjected to a steaming process to eliminate possible pathogens (a minimum of 55 °C compost temperature for 6 h).

The entire SMS layer, comprising compost and casing, was used for the stabilisation experiment. The compost layer was originally produced from wheaten straw, stable horse manure, calcium sulphate (gypsum), poultry manure and ammonium sulphate, while the casing contained peat and lime (Gerrits, 1994). The SMS was mixed thoroughly, and stabilisation procedures were initiated within 24 h.

2.2. SMS stabilisation

2.2.1. Experimental set-up

SMS stabilisation was performed in laboratory scale composting system, adapted from Noble et al. (1997). Briefly, approximately 4 kg of moist SMS were loaded into 10 L Quickfit glass vessels (Scilabware, Staffordshire, UK), containing perforated stainless steel platforms at the bottom. The platform was used for bottom-up forced aeration, which was provided by an ancillary air pump system, promoting full aeration of the material. During the entire process, oxygen (O_2) levels were monitored with oxygen probe (ProSens, Regensburg, Germany), and regulated by adjusting airflow (250 cm^3/min) frequency cycles to keep O_2 levels above 8%, as suggested by Noble et al. (1997). The airflow was also adjusted to avoid excessive aeration and to maintain moisture between 50 and 60%, which is considered a suitable range for composting (Bazrafshan et al., 2016). The vessels