Hort Innovation

Final Report

Recycling spent mushroom substrate (SMS) for fertiliser in a circular economy

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Frontier Ag & Environment

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MU21006

Project:

Recycling spent mushroom substrate (SMS) for fertiliser in a circular economy (MU21006)

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Public summary

There is interest in understanding the opportunities for spent mushroom substrate (SMS) reuse back into the broadacre cropping systems from which wheaten straw is sourced to manufacture the original mushroom substrate. There are many competing uses for straw and getting access to it can be challenging, especially in times of drought. Strengthening linkages between the mushroom industry and grain growers via a circular economy may therefore improve access to wheaten straw by mushroom composters in the future.

This project was conducted in three stages. Firstly, a review was completed to investigate various means by which SMS could be transformed into value-added fertiliser or soil amendment. Desktop research and mushroom industry consultation were included as part of the review process to ensure that the findings were both technically sound and applicable in the “real world”. In the second stage, the SMS supply chain was examined by mapping sources of wheaten straw in relation to mushroom composting and production facilities. Finally, SMS was characterised to establish the potential value proposition of the product to the grains industry. This included consultation with the grains industry to gain insight into the opportunities and barriers associated with the reuse of SMS in broadacre agriculture.

Value-adding of SMS is technically feasible through processes such as drying and pelletisation with/without the addition of nutrients, producing a product which may be of greater perceived value to farmers. However, the project has identified a number of economic and logistical challenges which are difficult for the mushroom industry as a whole to overcome. These challenges include:

1. A significant geographical spread between the cropping farms from which the straw is sourced, compost manufacturers, and the mushroom growers who then generate the SMS. There are far fewer compost manufacturers than mushroom growers. The compost manufacturer has the relationship with the straw supplier, but SMS is generated from mushroom farms over a wider geographical area in each State.

2. Value-adding to SMS is likely to be a costly process that involves significant investment in new infrastructure as well as R&D into fertiliser product development and marketing. Such an investment is unlikely to be attractive for many businesses when re-sale arrangements for SMS are already in place without the burden of cost recovery that comes with value-adding.

3. The nutrient profile and carbon composition analysis indicate that SMS offers no particular advantage to grain growers over other types of organic by-products that may be locally available to them.

4. For cropping farmers to consider receiving SMS-derived products, a range of issues around product quality/integrity, transport, logistics and soil/plant benefits need to be addressed in order for them to understand the value proposition of using these products either instead or, or in-addition to other farm inputs.

The opportunity for entering into more favourable supply agreements for straw by returning value-added SMS to grain growers is probably therefore limited to larger farms that operate both composting yards and mushroom farms.

Keywords

Spent mushroom substrate; SMS; mushroom compost; circular economy; recycling; biofertilizer; organic amendment; organic fertilizer

Introduction

Spent mushroom substrate (SMS; also called spent mushroom compost) is a by-product of mushroom cultivation. In Australia, the growing substrate for *A. bisporus* is traditionally manufactured from wheaten straw, poultry manure and gypsum via a highly refined and tightly controlled composting process. Wheaten straw forms the backbone for mushroom cultivation in Australia because of its lignocellulosic profile and ideal physicochemical properties for composting.

In 2021 the Australian mushroom industry produced 68,936 tonnes of mushrooms (Hort Innovation, 2019). Based on the assumption that for every 1 tonne of mushrooms, 5 tonnes of SMS are produced, approximately 344,680 tonnes of fresh SMS are produced annually in Australia.

Presently the main consumer of SMS in Australia is the landscape industry with the SMS being used either in its raw state or after blending with other materials to make soil conditioners, mulches and manufactured soil mixes. This present usage of SMS does represent a type of circular economy, but in essence the nutrients are not returning to food production systems, where they would have the most benefit in feeding the population. Due to there being a range of competing organic materials available to the landscape industry, the price mushroom farmers receive is variable by location with some producers reporting the need to pay to have it removed (2019 Industry Survey).

Approximately 12.3 million hectares of wheat is grown in Australia annually (GRDC, 2018). After harvesting, large quantities of straw remain in the paddock. Previously, wheat straw was viewed as a waste product, however with the advent of conservation farming practices, stubble retention has become a widespread practice to mitigate soil degradation (Scott et al, 2013). Stubble retention also provides valuable surface mulch which aids in moisture retention and weed control. As a consequence, wheat straw is now highly valued by many producers. Additionally, many other industries seek to source straw including the horse and pig industries for bedding, bio energy industry, and even for the manufacture of items like drinking straws.

Straw quality is a major issue for the mushroom compost industry, with quality often being impacted by prevailing seasonal conditions. Therefore, sourcing the required quantity of high-quality straw can be an issue, with supplies being particularly difficult to source during droughts due to low yields and in wet summers where the cutting and baling of straw is difficult with poor quality due to weather damage.

The combination of farmers valuing their straw, low production in times of drought and competing uses all mean that sourcing straw for mushroom substrate production is becoming more challenging. On the other hand, the mushroom industry produces a by-product that could be attractive to wheat farmers as an organic soil amendment.

An SMS-grains industry circular economy could simply mean that straw exported from paddocks for use in mushroom production is returned to the soil in the following year as SMS to grow more straw. SMS may be valuable to broadacre farmers if it can be used to help rectify specific soil degradation issues. Ideally, if SMS was to be viewed as a high value input, demand for it from wheat farmers may incentivise them to supply their wheat straw back to mushroom compost producers in the following year. If this system was to work, it would benefit both parties and would in fact be a very tight circular economy with the only resources leaving the system being those which are from the intended sale of produce – i.e., mushrooms and grain.

Methodology

This project was conducted in three stages. Firstly, a review was completed to investigate various means by which SMS could be transformed into value-added fertiliser or soil amendment. Desktop research was conducted by reviewing past work (e.g., *MU17005 – Mushroom production waste streams – novel approaches to management and value creation, and MU17007 - Feasibility of compost substrate alternatives for mushroom production*) as well as international literature with a focus on the technical, economic and logistical challenges associated with value-adding to organic waste streams like SMS. Key mushroom industry stakeholders were included as part of the review process to ensure that the findings were both technically sound and applicable in the "real world".

In the second stage, the SMS supply chain was examined by mapping sources of wheaten straw in relation to mushroom composting and production facilities. An initial list of Australian mushroom producers was compiled using information provided by the Australian Mushroom Growers Association, Hort Innovation and an extensive internet search. The list was then filtered to only include the largest Australian mushroom producers and as per the scope of the project only focus on NSW, Victoria and South Australia. The larger producers were the focus of this study as they produce the majority of mushroom substrate in Australia and the smaller producers purchase from them. Consequently, it is the larger composters who have the relationships with the straw suppliers and would be most likely to develop circular economies with them.

All mushroom farmers were contacted personally, and an informal interview held with a company representative. All the above enterprises agreed to talk with us apart from Bulla Park. The enterprises were then asked to provide us with the towns or postcodes from which they sourced their straw. The producers were assured that all information would remain confidential and that the postcodes would simply appear as dots on a map with no linkages to who was purchasing the straw.

The locations of the major producers and composting yards were then mapped in QGIS along with the location by postcode of their straw suppliers. Additional information was sought in relation to the major wheat production areas of Australia. Additional information in relation to Australian vegetable production was also sought to compare distances between wheat and vegetable production. The 2015-16 Land use of Australia raster package (GeoTIFF and supporting Files) produced by the Australian Government – Department of Agriculture, Fisheries and Forestry was used to obtain this information.

Finally, SMS was characterised to establish the potential value proposition of the product to the grains industry. This included consultation with the grains industry to gain insight into the opportunities and barriers associated with the reuse of SMS in broadacre agriculture. Samples of SMS were obtained from six large mushroom producers in January 2023, with each producer submitting a sample of SMS that was 'Fresh' and/or 'Aged'. This was done to ensure that the results obtained were a true representation of the range of SMS quality which might be applied to agricultural land.

All samples were submitted for chemical analysis at Nutrient Advantage Laboratory as well as to Monash University for carbon composition analysis by solid-state ^{13}C CPMAS NMR (Cross Polarisation Magic Angle Spinning - Nuclear Magnetic Resonance). This analysis provides a representation of the various carbon forms in the material, in order to understand if the carbon will be readily broken down and decomposed, or if it is likely to be maintained in the soil for a longer period of time. These results were compared with equivalent materials in order to understand if there are any unique or highly beneficial aspects of the SMS, compared to other, equivalent products that farmers are likely to be able to access. This information will further refine the value proposition for farmers.

A series of interviews with grains industry people were held over the phone or in person. This included 8 farmers and 4 agronomists. The purpose of the interviews was to establish their experience and attitudes to the use of organic soil amendments/fertilisers in the grains industry, whether there was specific interest in using SMS, and to gain insight around the potential opportunities for an SMS-grains industry circular economy.

Project findings were then presented to the industry team via a webinar on 25th May 2023 to assist the project team make decisions around next steps for this project and future research needs. The presentation has been attached in the appendix to this report, and the webinar as also been published on YouTube (See here).

Results and discussion

On value-adding to SMS

A search for papers and research reports on the topic of value-adding (and related terms) to SMS and related products like manures and composts revealed relatively little useful information. This was because our search was specifically focussed on value-adding rather than the generic benefits of applying organic amendments to land. The most common topics encountered in the search results included:

- Value-adding to SMS by blending with other organic waste streams and re-composting
- Development and testing of products for either fuel or stockfeed
- Other bioenergy approaches such as anaerobic digestion, pyrolysis, ethanol etc
- Biorefining – i.e., extraction of potentially useful bioproducts from SMS
- Re-use of SMS as casing or for the growth of other mushroom species

Although the first dot point above (i.e., value-adding to SMS by blending with other organic waste streams and re-composting) appears to be about 'value-adding', blending and re-composting with other organic waste materials was not under consideration. Instead, our definition of value adding was best defined by the use of such processes as drying, nutrient fortification and pelletisation.

The practice of value-adding to compost products from municipal sources in Australia was also found to be limited to the creation of soil amendment blends with lime and gypsum. Discussion with industry insiders revealed that although these types of value-added blended products may provide greater access and opportunities within agriculture markets, they do not necessarily lead to significantly greater profit margins. Such a practice comes with additional cost and greater complexity which means that it is typically performed by specialist third party companies rather than the compost producer.

Within the research field of pelletisation of biomass, most of the focus has been on the production of pellets for energy/fuel. This means that it may be difficult to take the learnings from these studies and apply them to the production of fertiliser pellets, even when the same general manufacturing process is used, as a fuel pellet and a fertiliser pellet are two fundamentally different products. Whereas a fuel pellet is desired for its calorific value and combustion properties, an SMS fertiliser pellet will be valued for its nutrient and organic matter content and the way nutrients are mineralised in soil. High ash contents are undesirable in fuel pellets, but this is not so for fertilisers since ash constitutes the mineral portion of biomass.

Nevertheless, studies have shown that pelletisation can result in a volume and weight reduction of 50-90% for compost products. As a result, it could potentially increase the density of nutrients in SMS by a factor of between four and five since moisture content (MC) has a major impact on bulk density, and the MC of SMS can be as high as 70%. The densification of SMS through drying and pelletisation has obvious advantages in reducing product transport costs, and it also has the potential to increase SMS stability in storage and improve product useability within farm machinery. In spite of the numerous benefits of pelletization, the economics of the process can be a major challenge due to the cost of capital equipment and energy usage during processing (e.g., drying prior to or during pelletisation).

Formulation of pelletised products with SMS usually involves blending with other complimentary organic materials. However, although different types of organic materials may appear to be complimentary (e.g., in terms of particle types and chemical profile), they may not bind well together, adversely affecting pellet durability (Ryu et al. 2008a).

If SMS-based pellets are not formulated properly, they can be dusty during handling and transport. Small amounts of binders (up to 1 wt %) of either NaOH or starch can increase pellet tensile strength. In addition, the temperature at which pelletisation occurs can also influence pellet tensile strength.

While it is technically feasible to make pellets from SMS for either fuel or fertiliser, the economics of the process are markedly affected by the energy cost associated with drying. At 2006 electricity prices in the UK (£53 per MWh), drying SMC at 70% moisture content by using heat from fossil fuels was found not to be practical. Finding other means to dry SMS may be essential. One of the solutions Ryu at al. (2008b) offered was the co-location of pelletisation with a process plant that generates waste heat. The use of a screw press to lower the moisture content to about 40% can also be considered at the pelletisation plant or even at large mushroom farms before transportation (Ryu at al. 2008b).

In their recent study on value creation for mushroom production waste streams, Xinova (2021) also examined the impact of SMS moisture content on the viability of pelletisation for either fuel pellets or fertiliser. Their claim was that the moisture content of SMS can be reduced from 60% to <15% with moderate energy usage (<25kWh/tonne). In this arrangement, an auger or mixing blender is first used to dewater SMS from 65% to <30% with the use of "drying chemicals". Post-auger material is then fed into the pelletiser for further dewatering, producing pellets with <15% at a rate of 1-5 tonnes per hour. While the Xinova (2021) study listed the use of drying chemicals such as chitosans or PDADMAC (Polydiallyldimethylammonium chloride) as flocculating agents, these compounds are not commonly used in solid matrix organic materials, as their mode of action is to increase flocculation of particles, thus increasing particle size and reducing surface area for adsorbed/bonded water. As such, chemically enhanced drying is of greater efficacy and economic value in sewage sludge and other liquid-phase waste materials (e.g., Zhu et al., 2012).

Although the Xinova report seemed to place greater emphasis on pelletisation for producing fuel pellets, they proposed that the end-product could also be sold as a fertiliser, although elemental concentrations need modification with the inclusion of other co-inputs. Their suggestion is that off-site sales of pellets as fertiliser could be explored in partnership with fertiliser companies, with the fertiliser formulated on-site (Xinova, 2021). Apparently Modern Mushroom Farms in the USA is an example of successful implementation of this approach, though we haven't been able to obtain any further details at the time of writing.

In summary then, development of a fertiliser via a drying/pelletisation pathway appears to be technically feasible but it would be economically challenging. On its own, product development would be a very complex process involving significant business risk. Some of the steps for product development would include:

- Research on market requirements (e.g., market segments, competing products, required product attributes such as nutrient profiles, pellet size and durability etc)
- Pelletisation trials with SMS and other co-inputs examining processing conditions and their effect on the structural integrity of pellets, 'flowability' in farm application equipment, hygroscopic issues associated with storage etc
- Glasshouse trials with target crops examining nutrient release characteristics and application rates
- Multi-year field trials with target crops which may involve different soil types where the SMS product is used at different rates in combination with mineral fertiliser

Supply chain mapping of SMS in relation to grain production

All of the larger mushroom producers on the east coast are located either in or on the edge of major cities (Fig. 1). These locations tend to be remote from straw production areas. It is assumed that whilst location is largely historical, it does provide benefits in terms of access to labour and ready access to the fresh fruit and vegetable markets of capital cities.

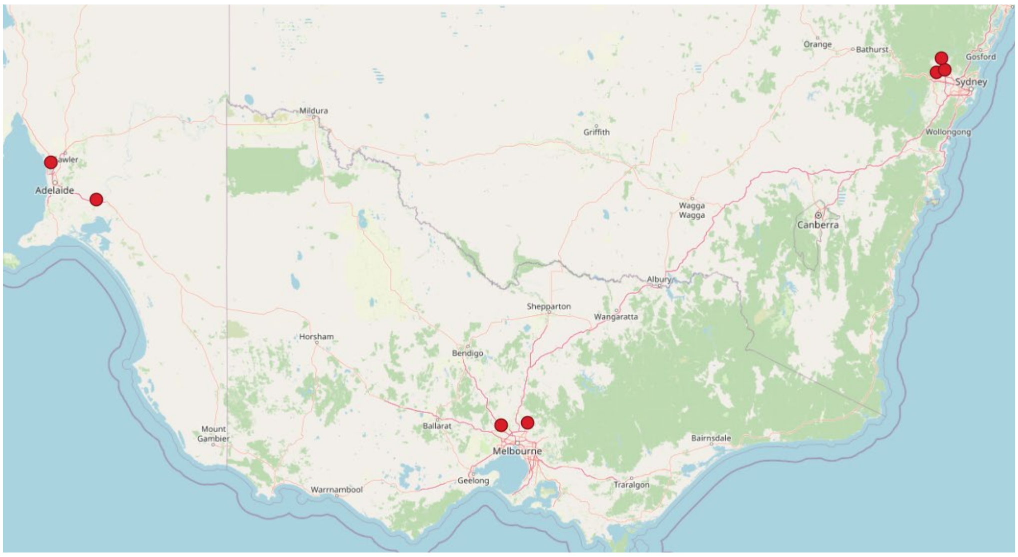

Figure 1: Major mushroom growing facilities in NSW, Victoria and South Australia

The method of securing straw supplies varied between producers. In some cases, producer representatives deal directly with farmers whilst others engage an agent or specialist straw cutting contractor to source and supply their needs. When considering how straw is transported to the compost yards, some producers own their own trucks and have very tight control over the transport process whilst others engage contractors and in other cases the transport is the responsibility of the agent or contractor. Where trucks were owned by the producer, they generally travel to the straw farms empty to pick up straw, this was also often the case where third parties were involved. These empty trucks present an opportunity for mushroom producers to potentially return SMS to the straw suppliers. The greatest limiting factor however is that the trucks used to transport straw are flat beds, where as a tipper trailer configuration would be required to transport SMS. It was suggested by one producer that the opportunity may exist to use walking floor type trailers to transport SMS, and these could be loaded with straw for the return trip to the composting yard. It was highlighted that a potential disadvantage of walking floor trailers is that less straw could be transported compared to a flatbed combination.

In NSW, wheat production is quite remote from mushroom production (Figure 2). There is no wheat production close to the Greater Sydney area due to several factors which include topography land use and land value. The NSW coastline is bordered by the Great Dividing Range, making the land unsuitable for wheat production. In NSW most wheat crops are therefore west of the great divide. The Great Dividing Range in particular the Blue Mountains, does also provide some significant transport issues to mushroom producers in the greater Sydney area.

Victoria is somewhat like NSW with the majority of wheat production being remote from mushroom production, being located north or west of the great divide. Some small-scale wheat production does occur in the high rainfall zones to the southwest of Melbourne, however none of the major producers interviewed currently source straw from these locations. Most of the straw is sourced from north, central and western districts of Victoria. It is important to note that the major mushroom producer in Victoria, does have their composting yard located in central Victoria closer to the wheat supply.

In South Australia some wheat straw is sourced from the north in relatively close proximity to Adelaide. Additional straw is also sourced from throughout the southeast wheat production areas and in some cases across the border into Western Victoria. Wheat production in South Australia is much different to the other states with it being much closer to the coastline and thus closer to Adelaide. Due to the closer proximity of straw supply to the mushroom farms, South Australia potentially presents the best opportunity to develop a tight circular economy model where the SMS is returned to straw farmers. Whilst it may not be possible to return the SMS to the furthest suppliers it may well be possible to return it to the closer ones particularly those located less than 100km to the north of Adelaide.

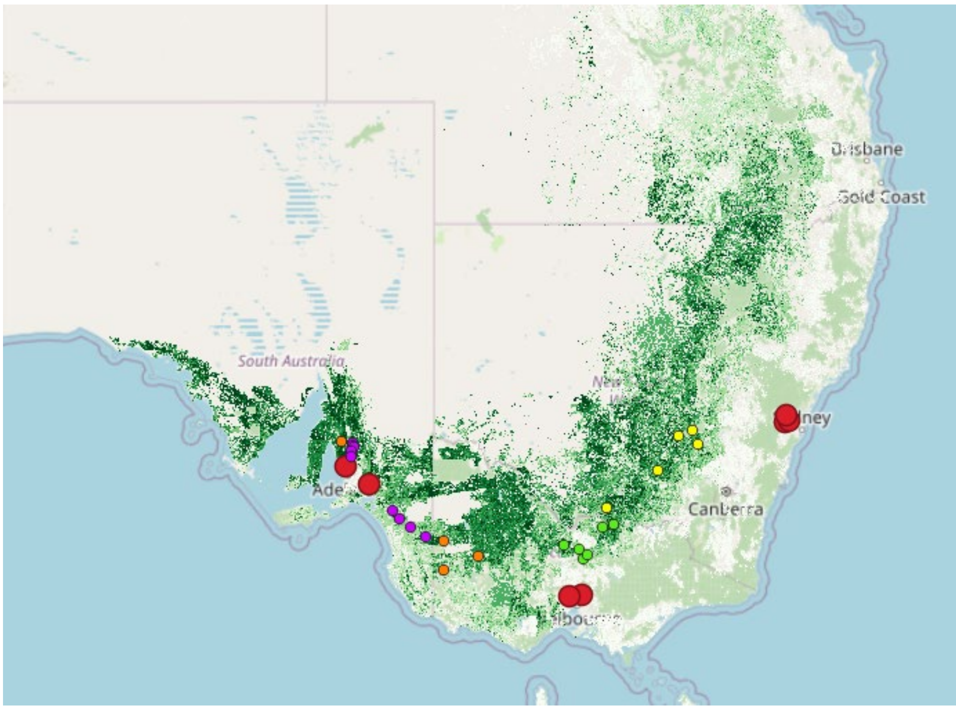

Figure 2: Major wheat production areas relative to major mushroom growing facilities. The darker green areas indicate the highest tonnages of production (Based on grain production. There is a direct relationship between the tonnages of wheat produced and the amount of straw produced) Source: Land use of Australia 2015-16 agricultural probability grids raster package (Australian Government – Department of Agriculture, Fisheries and Forestry). Yellow, Purple, Green and Orange dots indicate locations that mushroom producers presently source straw.

In summary, for a tight loop circular economy to be viable, where SMS is returned to wheat straw producers, a number of logistical and economical challenges need to be considered. The most significant of these issues is the distance between the production of SMS and wheat farms that supply straw. Economically transporting wheat straw to mushroom farms over these significant distances is feasible as the wheat straw has value to the mushroom producer. However, the economics of transporting SMS back to wheat farmers is not as simple, as the SMS does not have the same significant value to the wheat farmer. While empty trucks do travel to wheat farms to pick up straw, they are unfortunately not the right configuration for transporting SMS. Unless the transport issue can be resolved, the present value of SMS is diminished due to the high cost of transport over large distances.

On the value proposition of SMS

Chemical analysis has shown that the carbon and nutrient profile of SMS is similar to many other organic materials (green waste compost, manures). Further, carbon composition analysis indicates that most of the carbon in the SMS is in highly labile forms. As such, this material would be rapidly decomposed by soil microbes, with little residual carbon benefit. The nutrient profile and carbon composition analysis indicate that SMS offers no particular advantage to grain growers over other types of organic by-products that may be locally available to them.

SMS has a mean total carbon content of around 32%, a C:N ratio of about 13 and an N content of about 2.5% while total phosphorus is around 6,500 mg/kg and total potassium 19,000 mg/kg. SMS can be characterized as an "immature compost" product as most of the available nitrogen is in the form of ammonium.

The salt content of SMS has previously been raised as a concern when considering application to land. While sodium is the key ion of concern when considering if organic materials should be applied to land, the measurement of electrical conductivity (EC) does not differentiate between sodium and other soluble salts. SMS contains significant amounts of soluble salts present as potassium, sulphur and calcium in significantly greater quantities than sodium. This means that while the absolute EC value is high at around 9.5 dS/m, the application of SMS will not have deleterious impacts on soil structure if applied to agricultural land due to the high calcium content.

These data suggest that SMS has a relatively low nutrient content like other sources of organic amendments and that while the product may result in short-term benefits to soil health, it cannot replace on-farm fertiliser inputs and it will have only a transient contribution to soil carbon levels. Combining these challenges with the large distances between mushroom production and broadacre cropping land, an economically viable circular economy would be difficult to achieve for the industry as a whole.

Interviews with the cropping industry also indicated significant uncertainty as to whether investment in SMS value-adding would be worthwhile. Of specific concern to growers and their advisors is the cost:benefit associated with the use of any new product. Although alternatives to high analysis fertilisers are of increasing interest, a higher value SMS product would need to compete on its own merits. Another important issue for growers is the fact that application of fertiliser products in the grains industry generally occurs at the autumn break, yet SMS is produced year-round, and stockpiling in the paddock would not be feasible as the product would need to be kept dry.

Outputs

Table 1. Output summary

Output	Description	Detail
Desktop review	A review focusing on the potential for value adding to SMS from a technical, economic and logistical perspective	Included as part of Milestone 102 via the Hort Innovation project portal
Supply chain mapping	A report focusing on mapping of mushroom industry facilities in SE Australia in relation to grains industry (i.e., supplies of straw)	Included as part of Milestone 103 via the Hort Innovation project portal
Value proposition of SMS	A report encompassing a summary of chemical analysis of SMS and consultation with grains industry stakeholders	Included as part of Milestone 104 via the Hort Innovation project portal

Project presentation	A Powerpoint presentation made to mushroom industry stakeholders on project findings	Webinar held via the MushroomLink communications project on 25th May 2023. The webinar has also been posted on YouTube (See here).
Project article	An article on the project written and published with the cooperation of the MushroomLink communications project team.	Article was published in MushroomLink winter edition – see attachment in Appendices and online here: https://www.mushroomlink.com.au/magazine

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Knowledge and awareness	Outcome 2.1: Enhance the efficiency of mushroom production systems including casing, compost, labour and energy and Outcome 2.2: Improve on-farm sustainability and efficiency through waste product development and recycling opportunities	Mushroom industry is in a better position to make informed decisions about opportunities for value-adding to SMS and creating a circular economy with grain industry	By technical review and industry (mushroom and grain) consultation. Feedback received through individual interviews as well as at the project webinar
Future R&D investment opportunities in SMS product development	As above	Applies to both individual growers as well as Hort Innovation. There is a limited role for further work at the fund level (i.e., by Hort Innovation) but opportunities may exist at the individual business level as circumstances allow (opportunities are highly ‘site specific’).	As above

Monitoring and evaluation

An M&E Plan was not required as part of project delivery.

Recommendations

Project findings demonstrate that there is a limited opportunity to create a whole of industry circular economy for value-added utilization of SMS in the grains industry. Commercial opportunities may exist at the individual business level particularly for the larger integrated mushroom composters/producers depending on their specific circumstances and risk profile. The uncertain economics of this type of circular economy model involving SMS use in the grain industry means that the opportunities for individual businesses will be dependent on a number of factors including:

- The location of any given mushroom facility and compost yard in relation to grain producers and other high-value agricultural markets
- Whether the business has a current reliable outlet for SMS at low cost and whether there is a perceived risk for this to be maintained over the medium to long term
- The willingness of the individual business to invest in significant infrastructure and R&D given that SMS product development is not part of core business
- Risks to future supply of straw in any given region and the relationships that can be established with individual suppliers of straw
- The appetite of individual businesses to risk taking (given the high uncertainty)

There is also limited scope for further work by Hort Innovation in this space given that the opportunities are more likely to apply at the individual business level rather than the industry as a whole. However, the scope for this project was quite tight (i.e., value-added SMS for grains industry), and so further work may be warranted by Hort Innovation in SMS recycling projects that are of more general interest. For example, feedback obtained during the project webinar suggested that industry would support further work on getting a better handle on the economics of pelletisation.

Hort Innovation could also consider conducting research into the use of bulk (unamended) SMS in other agricultural sectors like vegetable production. However, the rationale for this needs to be carefully considered given that most mushroom producers already have an outlet for SMS in the domestic landscaping industry. Furthermore, trials of SMS products in the vegetable industry would need to be conducted with different soil types, crops and over several seasons. The risk of taking this approach is that a significant investment in levy funds would have to be made, despite the uncertain outcome, to address a problem that does not need fixing (at least in many cases).

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Intellectual property

No project IP or commercialisation to report.

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