Hort Innovation

Final Report

Feasibility of compost substrate alternatives for mushroom production

Project leader:

Dr Julia Jasonsmith

Delivery partner:

Murrang Earth Sciences

Project code:

MU17007

Project:

Feasibility of compost substrate alternatives for mushroom production MU17007

Disclaimer:

Funding statement:

This project has been funded by Hort Innovation, using the Mushroom research and development levy and contributions from the Australian Government. Hort Innovation is the grower-owned, not-for-profit research and development corporation for Australian horticulture.

Publishing details:

ISBN 978 0 7341 4597 0

Published and distributed by: Hort Innovation

Level 7
141 Walker Street
North Sydney NSW 2060

Telephone: (02) 8295 2300

www.horticulture.com.au

Content

Summary

This project identified alternative sources of carbon that could substitute for wheaten straw in mushroom compost substrate.

Agaricus bisporus is traditionally grown in substrate based on wheaten straw via a tightly controlled composting process. Wheaten straw is ideal for making mushroom compost, and it provides the carbon as a food source for the growth of *A. bisporus*. However, the availability of wheaten straw to mushroom farmers has decreased over recent years as a result of drought, the effects of climate change, changed farming practices and increased competition from the feedstock industry.

A literature review was conducted together with extensive stakeholder consultations to identify a range of possible carbon alternatives to wheaten straw. Aside from cereal straws, other examples of carbon-rich materials include crop residues (e.g. sugarcane bagasse), as well as the biomass of grasses, whole seeds, seed hulls and woody wastes (e.g. sawdust, wood chips and green waste).

Many potential carbon sources are subject to price-competition due to their use in other industries — especially the feedstock industry. This is a major problem because the development of alternative compost substrates would require security of supply at reasonable prices.

Wheaten straw has unique properties that are difficult to replicate. Most of the alternative carbon sources that are available in the market place cannot be considered to be suitable as complete replacements for wheaten straw, but many could be used as partial substitutes on an opportunistic basis.

Materials with good properties for composting that were also abundantly available were difficult to identify. However, blends of woodchips and bark could be sourced from sawmills and pre-prepared to specifications (e.g. by grinding and screening). But extensive composting and mushroom production trials would be required to ensure that good commercial yields are attainable with this type of substrate. Other carbon materials available for use include corn waste and sugar bagasse. These appear to be ideal for use as substitutes for wheaten straw, but transport distances could be a logistical hurdle for most mushroom composters. Waste paper is also in abundant supply, but it could only be used as a partial replacement for straw (say 20%).

Mushroom farming has been optimised over many decades of research and practice with wheaten straw substrate. Complete substitution for wheaten straw for another carbon source is unlikely to succeed without major investment in R&D. Investigating the potential use of other carbon sources therefore needs to consider what changes need to be made to the conventional production system, including the composting system and to culture practices for growing *A. bisporus*. Simply following the production processes that are known to work for wheaten straw may not be the best approach to use when alternative carbon sources are evaluated in composting and mushroom production trials.

Keywords

Mushroom; Agaricus bisporus; Mushroom substrate; Mushroom compost; Wheaten straw

Introduction

The Australian mushroom industry is worth more than $396 million annually, with over 67,000 tonnes of mushrooms produced in the 2016/2017 financial year (Hort Innovation 2018). The predominant species, *Agaricus bisporus*, is generally grown in all states of Australia. Major production areas include near Adelaide, metropolitan Melbourne, and the Sydney basin.

There is a range of pressures on the mushroom industry, as highlighted in the "*Mushroom Strategic Investment Plan 2017 – 2021*". The need to reduce input costs and consider the risks associated with climate change has been identified in particular, with wheaten straw, the preferred carbon source for compost, predicted to become more difficult to acquire and thus also more expensive. Alternative carbon sources are also needed to reduce carbon source acquisition risks in the future.

The aim of this strategic levy investment project was to find alternative sources of carbon for mushroom compost production as a contribution to future-proofing the mushroom industry against the impacts of climate change. Hort Innovation funded this project using the mushroom research and development levy, along with contributions from the Australian Government. Hort Innovation is the grower owned, not-for-profit research and development corporation for Australian horticulture.

Agaricus bisporus production is the main source of levies to Hort Innovation for the mushroom industry. Therefore, this project largely focused on the needs of *A. bisporus* growers. However, shimeji (multiple spp.) and oyster (*Pleurotus ostreatus*) mushroom growers may also benefit from aspects of this research.

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. Sometimes other organic raw carbon sources are added in small amounts as "supplements". Wheaten straw is a good example of a lignocellulose waste stream, i.e. plant residues containing a combination of cellulose, hemicellulose and lignin. Lignocellulosic carbon sources can be derived from agriculture, forestry or industrial processes (e.g. food processing). Aside from wheaten straw (and other cereal straws), other examples of lignocellulosic carbon sources include crop residues (e.g. sugarcane bagasse), as well as the biomass of grasses, whole seeds, seed hulls and woody wastes (e.g. sawdust, wood chips and green waste).

The production of *A. bisporus* (and other edible mushrooms) in Australia is a well-developed and technically sophisticated process that has evolved over decades of research, development and commercial practice. Wheaten straw is the preferred lignocellulosic substrate in Australia for good reason. It has unique physicochemical properties that are difficult to replicate – it has the right lignocellulosic content, excellent structural properties and excellent water absorbency.

In this report, we highlight possible alternatives for wheaten straw and the feasibility of their use within the industry based on a literature review, knowledge of the physicochemical properties of the carbon sources, access and cost, hazards, as well as stakeholder feedback. We present a thorough gap analysis highlighting research and development needs, as well as a Ready Reckoner and case studies for oyster and shimeji mushroom producers.

Methodology

Carbon alternatives were considered for their potential as both partial and complete replacements for wheaten straw. Where a carbon material lacks the particular physicochemical characteristics necessary to be viable as a complete substitute for straw, its use as a partial substitute (e.g. by replacing 30% of the straw) could still be worthwhile to reduce reliance on wheat.

As a first step in identifying potential alternative carbon sources for mushroom substrate production, research was conducted in the form of a literature review to compile a list of potentially viable carbon sources. We then consulted industry stakeholders, as well as Australian and international researchers to capture their experience and opinions on the potential viability of these carbon sources.

An initial list of potential carbon sources was categorised as follows:

- Alternative carbon sources used in the industry world-wide for mushroom compost production
- Alternative carbon sources that have been investigated in the scientific literature
- Other alternative carbon sources available in Australia that have not been previously investigated in research projects or by industry
- Other approaches to carbon source management, particularly partial substitution of wheaten straw with other carbon sources

Carbon sources short-listed for further investigation were subjected to a 3-stage feasibility study, which acted as an elimination method, whereby each part of the study eliminated carbon sources that were determined not to be feasible for use in mushroom composting. Where necessary, researchers were also consulted to assist us in clarifying important technical issues.

The first stage of the feasibility study was a technical assessment of the physicochemical characteristics of alternative carbon sources and the potential impact of these characteristics on composting and mushroom yields. The carbon sources making it through to the second stage were then examined to establish their availability in the main mushroom growing regions, and expected costs of procurement (including transport). Future climate-related limitations for each carbon source were also considered at this stage. In the final stage of the feasibility study, the short-listed carbon sources were subjected to a hazard analysis. The hazard analysis considered potential impacts of the carbon sources on mushroom worker health and safety, consumer health and safety, compliance to regulations and quality standards (e.g. environmental, food safety and compost standards) and mushroom farm productivity.

Following the completion of the feasibility study, a gap analysis was conducted to assist in the identification of future research priorities for the development of composted substrates from alternative carbon sources. We identified knowledge gaps and barriers to adoption for the short-listed alternative carbon sources through a review of the literature and also through consultation with industry stakeholders. We also considered the state of knowledge with respect to the biology of *A. bisporus*, and issues associated with substrate utilisation and compost process optimisation as they relate to the development of substrates from alternative carbon sources. From this evaluation, a list of prioritised research and development questions were identified.

Outputs

- A summary of alternative carbon sources as substitutes for wheaten straw in mushroom compost production. This is provided in tabular form and lists potential carbon sources identified in this study, how and where they are used, research and development stage (as appropriate) and relevant references (see Appendix A, Attachment A)
- A feasibility study with accompanying literature review outlining the process by which alternative carbon sources were assessed through a process of elimination (see full report, Appendix A)
- Gap analysis and recommendations for research in developing new substrates from alternative carbon sources (see full report, Appendix A)
- A record of stakeholder feedback on alternative carbon sources. Provided in tabular form from interviews conducted with mushroom industry stakeholders (see Appendix A, Attachment B)
- A Ready Reckoner to assist industry in choosing alternative carbon sources to trial on-farm (see Appendix Attachment C)
- Case studies for the shimeji and oyster mushroom industries on the applicability of the alternative carbon sources identified in this study

Outcomes

This project is aligned with the Hort Innovation investment priority of '*Support industry efficiency and sustainability*' and Outcome 2 of the SIP: '*Mushroom growers are profitable and sustainable through increased yields, reduced costs and effective risk management*'. It specifically delivers information to allow for the realisation of Outcome 2, Strategy 2 of the SIP, which is "*identification of an alternative compost source*". The alignment of the project and the outputs are described in the project logic (Figure 1) and Table 1 below.

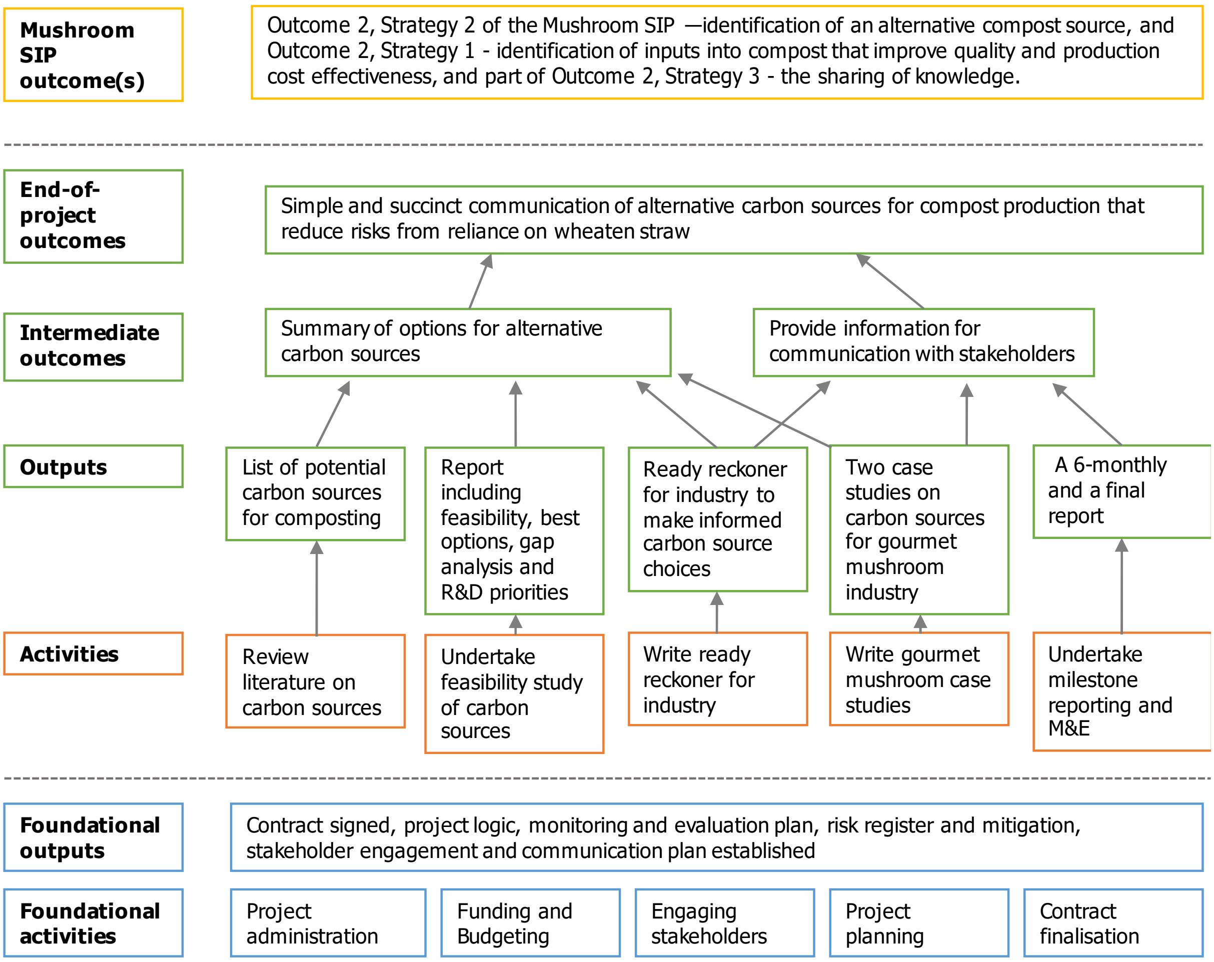

Figure 1 – Project logic

Table 1 – Aligned project outcomes and outputs

<table>
<tr><th>Instrument</th><th>Item</th><th>Project outcome</th><th>Aligned project output</th></tr>
<tr><td>Hort Innovation Annual Report
2017 – 2018</td><td>Hort Innovation investment priority (soil, water and managing natural resources)</td><td>Support industry efficiency and sustainability (plant nutrition, pollination, water use, natural resource management,
soil management, pest and disease
management, climate, etc.)</td><td rowspan="4">1. Potential carbon substrates summary
1.1. Identify alternative carbon sources used in the industry world-wide
1.2. Identify alternative carbon sources considered in scientific literature for mushroom compost
1.3. Identify other alternative carbon sources not currently identified by research or industry
1.4. Identify other approaches to carbon source management e.g. partial substitution etc.
2. Feasibility analysis
2.1. Technical assessment of the physicochemical characteristics of alternative carbon sources and the potential impact of these characteristics on composting
2.2. Review procurement costs and materials availability in the main mushroom growing regions and other areas</td></tr>
<tr><td rowspan="4">Mushroom Strategic Investment Plan
2017 – 2019</td><td>Outcome 2</td><td>Mushroom growers are profitable and sustainable through increased yields, reduced costs and effective risk management</td></tr>
<tr><td>Outcome 2, Strategy 1</td><td>Improve production by increasing yield and quality</td></tr>
<tr><td rowspan="2">Outcome 2, Strategy 2</td><td rowspan="2">Undertake research and development to enhance industry risk management and supply contingencies</td></tr>
<tr><td>2.3. Consider knowledge gaps, risks and barriers to adoption
2.4. Gaps in knowledge will be clearly identified for each of the short-listed alternative carbon sources</td></tr>
<tr><td>Mushroom Strategic Investment Plan
2017 – 2019</td><td>Outcome 2, Strategy 3</td><td>Sharing dedicated knowledge, efficient innovation, and research capacity</td><td>3. Ready Reckoner
4. Two case studies for Oyster and Shimeji mushroom growers</td></tr>
</table>

Monitoring and evaluation

All objectives outlined at the outset of this project were met with the delivery of this Final Milestone 190 report. All Milestone reports were delivered by the Project Team prior to project deadlines, to allow adequate time for review and feedback from Hort Innovation, and for update of the milestone reports based on the feedback received. The project was delivered within the stipulated budget.

Feedback on the project's outcomes was received from either current or former mushroom composters from all major mushroom growing areas, with these being Melbourne, Sydney and Adelaide (Table 2). To ensure the results from our research were as relevant as possible to the widest possible audience, feedback was received from small, medium and large mushroom growing and/or mushroom composting operations. Based on this information, we achieved all outcomes set out for this project in our successful proposal and in our Milestone 102 report.

Table 2 – Stakeholder engagement undertaken for the project

Stakeholder	Planned frequency	Frequency Achieved	Stakeholder engagement aims met?
Australian Mushroom Industry	As required, and outlined in Table 10	N/A	N/A
Hort Innovation Australia	Monthly	Approximately six times during the project	No. Discussions with Hort Innovation's Byron de Kock indicated the planned frequency of contact was not necessary
Reps. from small, medium & large mushroom composters	Two times between June & Nov	Two times between June and November 2019	Yes
Reps. from mushroom composters within Adelaide, metropolitan, and Sydney Basin regions	Two times between June & Nov	Two times between June and November 2019	Yes
Reps from small, medium, and large Oyster and Shimeji composters	Two times between June & Nov	Once	No. Outcomes of this research had limited application to Oyster and Shimeji growers due to the different substrates used for these mushrooms
Reps from Oyster and Shimeji composters within Adelaide, metropolitan Melbourne, and the Sydney Basin	Two times between June & Nov	Once	No. Outcomes of this research had limited application to Oyster and Shimeji growers due to the different substrates used for these mushrooms
Carbon substrate suppliers	Two times between June & Nov	Two times between June and November 2019	Yes
Mushroom researchers: Centre of Excellence, Marsh Lawson Research Centre, consultants	Two times between June & Nov	Two times between June and November 2019	Yes

Our performance on this project to evaluated using the performance indicators presented in Table 3.

Table 3 – Performance indicators and performance assessment

Performance indicator	Performance assessment	Performance criteria met?
Mushroom growing costs will be maintained or reduced within 10 years following uptake of alternative carbon sources	This report has identified alternative carbon sources to wheaten straw which can be used in the production of mushroom composts, with the potential for this to reduce costs pending further research and development.	Yes
Mushroom yields will be maintained or increased over 10 years	The alternative carbon sources identified in this report have the potential to maintain or increase mushroom yields, pending further research and development.	Yes
The number of pests and diseases which threaten mushroom growers over a 10-year period from uptake, are the same or decrease as a result of alternative carbon sources being used in mushroom compost	A hazard and risk assessment of alternative carbon sources was undertaken within this report. The number of pests and diseases which threaten mushroom growers were found to be the similar to those resulting from wheaten-straw based mushroom composts.	Yes
The risks presented to mushroom growers by pests and diseases related to alternative carbon sources are considered to be of the same severity or less than current carbon sources	A hazard and risk assessment of alternative carbon sources was undertaken within this report. The risks presented by the pests and diseases of alternative carbon substrates identified were found to be the same as those resulting from wheaten-straw based mushroom composts.	Yes
The risks presented to mushroom growers in relation to food safety of alternative carbon sources, including in relation to on-selling, are considered to be of the same extent or less than current carbon sources	A hazard and risk assessment of alternative carbon sources was undertaken within this report. The risks presented to mushroom growers in relation to food safety by the alternative carbon substrates identified were found to be the same as those resulting from wheaten-straw based mushroom composts.	Yes
All mushroom composters have viable alternatives to wheaten straw as a source of carbon for composting requirements	Four carbon alternatives were identified as substrates to wheaten straw, with the geographical area of some or all of these occurring within all the main mushroom growing regions.	Yes

Responses to the Key Evaluation Questions (that is KEQs) developed for this project are presented in Table 4.

Table 4 – Project evaluation

Key evaluation questions	Relevant project-specific questions	Final answers
Effectiveness		
To what extent has the project achieved its expected outcomes?	1. Has the project achieved the objectives outlined in Section 1 [of the Milestone 102 report]? 2. Were all the project milestones achieved within allocated time frames? 3. Was the project delivered within the allocated budget?	1. By submitting a project management framework (1); identifying alternative carbon sources across Australia within a literature review (2); completing a 4-stage feasibility analysis and prioritisation (3); producing a Ready Reckoner (4) and producing two case studies, one for oyster and one for shimejii mushroom growers, all the objectives outlines in Section 1 of the Milestone 102 report were addressed within this Milestone 109 report 2. Milestone reports were submitted as follows • 102: submitted 28/05/2019; due 6/06/2019 • 103: submitted 9/08/2019; due 30/08/2019 • 190 (draft): submitted 25/10.2019; due 1/12/2019 • 190 (FINAL): submitted 29/11/2019; due 1/12/2019 All reports were submitted prior to final dates to allow for review by Hort Innovation and mark-ups to these reports within the allowed time-frames. All reports were submitted within the allocated due date 3. The project was delivered within the allocated $98,887.50 budget
Relevance		
How relevant was the project to the needs of the intended beneficiaries?	4. What percentage of composters considered the alternative carbon sources for compost identified as part of this project met their needs very poorly, poorly, adequately, well, very well, or didn't want to respond, respectively?	4. Of the seven stakeholders who responded to the questionaire sent, the following responses were received for this question (with the number of respondents in parentheses): Very poorly — 0 % (0) Poorly — 14 % (1) Adequate — 29 % (2) Well — 29 % (2) Very well — 29 % (2) Did not want to or did not respond— 0 % (0)
	5. What percentage of carbon substrate suppliers considered that supplies of their product to the market in 10 years could be achieved at the same cost as now, relative to inflation (very low, low, adequate, good, or very good potential, or did not want to answer)?	5. Rather than questioning suppliers on their views of product availability over the next 10 years, this report evaluated the sustainability of alternative carbon sources for mushroom compost based on supplier feedback and other information. This is presented in detail within Appendix 1 (Table 3).

Key evaluation questions	Relevant project-specific questions	Final answers
Process appropriateness		
3. How well have intended beneficiaries been engaged in the project?	6. What percentage of stakeholders were engaged from small, medium, and large mushroom composting operations during the duration of this project, respectively? 7. What percentage of stakeholders were engaged from composting operations near Adelaide, metropolitan Melbourne, the Sydney Basin, or elsewhere during this project, respectively?	6. Twelve stakeholders were engaged throughout the project. Of these, three (25%) were from large operations, three (25%) were from small operations, and six (50%) were from medium operations 7. Although twelve stakeholders were engaged throughout the project, some stakeholders had operations within only one region and others in a number of regions. Four stakeholders represented operations in the Melbourne area (33%), one (8%) in Adelaide, five (42%) in the Sydney area, and two in all areas (17%).
4. To what extent were engagement processes appropriate to achieving project outcomes?	8. What percentage of composters considered their composting problems were addressed by this project very poorly, poorly, adequately, well, very well, or didn't want to respond? 9. What percentage of composters considered it highly unlikely, unlikely, likely, very likely, or didn't want to respond, that the carbon substrates identified as part of this project would reduce their costs/improve sustainability of their operations?	8. Of the seven stakeholders who responded to the questionaire sent, the following responses were received for this question (with the number of respondents in parentheses): Very poorly — 0 % (0) Poorly — 14 % (1) Adequate — 29 % (2) Well — 14 % (1) Very well — 14 % (1) Did not want to or did not respond — 29 % (2) 9. Of the seven stakeholders who responded to the questionaire sent, the following responses were received for this question (with the number of respondents in parentheses): Highly unlikely — 0 % (0) Unlikely — 29 % (2) Unsure — 29 % (2) Likely — 29 % (2) Highly likely — 0 % (0) Did not want to or did not respond — 1 % (14)

Key evaluation questions	Relevant project-specific questions	Final answers
Additional data requirements		
	10. What percentage of mushroom growers could implement the information provided in the Ready Reckoner in under 2 minutes, 5 minutes, 10 minutes, 15 minutes, or required more time?	10. Of the seven stakeholders who responded to the questionaire sent, the following responses were received for this question (with the number of respondents in parentheses): 2 minutes or less — 14 % (1) 2 to 5 minutes — 14 % (1) 5 to 10 minutes — 0 % (0) 10 to 15 minutes — 29 % (2) 15 minutes or more — 29 % (2) Did not want to or did not respond — 1 % (14)
	11. What percentage of oyster and shimeji growers could implement the information provided in the case studies in under in under 2 minutes, 5 minutes, 10 minutes, 15 minutes, or required more time?	11. Oyster and shimeji growers were not engaged within the scope of this project.
	12. Is there anything the project team could have done better to deliver a better quality or quantity of project?	12. Stakeholders could not identify any ways in which to further improve the report. Further feedback from stakeholders is provided in Attachment B of Appendix 1.
	13. What could be done in the future to improve the outcomes of similar projects?	13. A number of stakeholders commented that investment in research and development is critical to the success of the industry and for developing new substrates on which to grow *A. bisporus.* Further feedback from stakeholders is provided in Attachment B of Appendix 1.

Recommendations

This project came up with a prioritised list of recommendations for research into the development of new substrates from alternative carbon sources.

The issues associated with the development of new substrates based on alternative carbon sources are potentially very complex — it is not necessarily the case that simple substitution for wheaten straw will be successful. Major changes to a production system as significant as complete replacement of wheaten straw are likely to have a chain reaction of effects, which could not only affect mushroom productivity, but also other factors affecting business viability.

More research is needed on mushroom biology, as well as the factors that lead to the production of growth substrates selective for *A. bisporus*. Changes to production systems can be more confidently proposed when the industry is armed with greater foundational knowledge such as this.

Priority should be given to research that approaches the problem in an integrated fashion. That is, experiments with alternative carbon substrates should consider process optimisation, rather than simply following the production processes that are known to work for conventional substrates. Therefore, although these recommendations are listed in order of priority, they are not necessarily discrete. In summary, our recommendations are listed in Table 5 below.

Table 5 - Research recommendations for the development of new substrates from alternative carbon sources. Items with the same number are of equal priority

1. Composting and mushroom production trials	
1.1 Corn stover and bagasse	Compost process optimisation • Process development and control • Effect of moisture content-porosity conditions on capacity to produce selective growth substrates • Effect of nitrogen, ammonia and aeration strategies in relation to producing selective growth substrates Substrate utilisation • Effect of cultural conditions • Characterisation of substrates that reliably effect potential mushroom yield
1.2 Paper waste	Hazards • Addressing risks associated with *Trichoderma*
1.2 Other strategies	Safe reuse of spent mushroom substrate in new growth substrate
2. Further research on lignocellulosic carbon sources	
2.1 Green & food waste	Identification of potential clean and consistent sources of these waste streams
2.1 Forestry residuals	Further evaluation of bark and wood waste streams, particular pre-treatment options
2.2 Characterisation	Benchmarking of lignocellulosic waste streams used in substrate production
3. Mechanisms of lignocellulosic biodegradation by *A. bisporus* and other edible fungi	
3.1 Exploration of the genetic diversity of *A. bisporus* to develop strains that are able to better utilise alternative carbon substrates	
3.1 Exploration of other *Agaricus* species and other edible fungi to better utilise alternative substrates	
3.2 Factors affecting gene expression for lignocellulosic enzyme production	
3.3 Potential for genetic manipulation of *A. bisporus* to better utilise alternative carbon substrates	
4. Alternative approaches to mushroom cultivation	
4.1 Non-composted substrates	Australian research on the potential use of non-composted substrates, especially those derived from forestry residuals
4.2 Potential for development of hydroponic systems for mushroom cultivation	

Refereed scientific publications

Not applicable

References

Adjapong, A.O., Ansah, K.D., Angfaarabung, F. and Sintim, H.O. 2015. Maize residue as a viable substrate for farm scale cultivation of oyster mushroom (*Pleurotus ostreatus*). Advances in Agriculture.

Agnew, J.M., Leonard, J.J., Feddes, J. and Feng, Y. 2003. A modified air pycnometer for compost air volume and density determination. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada, 45: 6.27–6.35.

AgriFutures. 2017a. Grain sorghum. Accessed on 27 June 2019. <https://www.agrifutures.com.au/farm-diversity/grain-sorghum/>.

AgriFutures. 2017b. Sugarcane. Accessed on 27 June 2019. <https://www.agrifutures.com.au/farm-diversity/sugarcane/>.

AgriFutures. 2017c. Canola. Accessed 28 June 2019. <https://www.agrifutures.com.au/farm-diversity/canola/>.

Allison, L. 1965. Decomposition of wood and bark sawdusts in soil, nitrogen requirements and effects on plants. USDA Technical Bulletin 1332.

Altieri, R., Esposito, A., Parati, F., Lobianco, A. and Pepi, M. 2009. Performance of olive mill solid waste as a constituent of the substrate in commercial cultivation of *Agaricus bisporus*. International Biodeterioration and Biodegradation, 63(8): 993–997.

Amin, R., Khair, A., Alam, N. and Lee, T.S. 2010. Effect of different substrates and casing carbon sources on the grow the and yield on *Calocybe indica*. Mycrobiology, 38(2): 97–101.

Arcadis (2019). National food waste baseline: final assessment report. Accessed on 27 June 2019. <https://www.environment.gov.au/system/files/pages/25e36a8c-3a9c-487c-a9cb-66ec15ba61d0/files/national-food-waste-baseline-final-assessment.pdf>.

Arce-Cervantes, O., Saucedo-Garcia, M., Leal Lara, H., Ramírez-Carrillo, R., Cruz-Sosa, F. and Loera, O. 2015. Alternative supplements for *Agaricus bisoporus* production and the response on lignocellulolytic enzymes. Scientia Horticulturae, 192: 375–380.

AS4454 2012. Composts, soil conditioners and mulches. Standards Australia, Sydney.

Australian Bureau of Agricultural and Resource Economics and Sciences. 2019. Australian Crop Report: June edition. Accessed on 27 June 2019. <http://www.agriculture.gov.au/abares/research-topics/agricultural-commodities/australian-crop-report>.

Australian Bureau of Statistics. 2019. Broadacre crops. Accessed 27 June 2019. <https://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/7121.0Main%20Features412017-8?opendocument&tabname=Summary&prodno=7121.0&issue=2017-18&num=&view=>.

Baldrian, P., and Valaskova, V. 2008. Degradation of cellulose by basidiomycetous fungi. FEMS Microbiology Reviews, 3: 501–521.

Barman, S., Acharya, A., Chakraborty, W. and Chakraborty, B. N. 2017. Evaluation of the effect of different compost formulation and casing carbon sources on button mushroom production. International Journal of Science and Nature, 8(2): 377–385.

Bechara, M.A. 2007. Alternative mushroom production system using non-composted grain-based substrates. PhD Thesis. Penn State University.

Bechara, M.A., Heinemann, P., Walker, P.N. and Romaine, C.P. 2006a. Non-composted grain-based substrates for mushroom production (*Agaricus bisporus*). Transactions of the American Society of Agricultural Engineers, 49(3): 19–824.

Bechara, M.A., Heinemann, P., Walker, P.N., Romaine, C.P. and Wilkinson, V.L. 2006b. Evaluating non-composted grain substrates for the production of *Agaricus bisporus* and *Agaricus blazei* mushrooms. American Society of Agricultural and Biological Engineers. 2006 American Society of Agricultural Engineers Annual Meeting.

Bechara, M.A., Heinemann, P., Walker, P.N. and Romaine, C.P. 2006. *Agaricus bisporus* mushroom cultivation in hydroponic systems. Transactions of the ASABE, 49(3): 825−832.

Beckingham, C. 2007. Sweet corn growing. Accessed on 15 July 2019. < https://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/commodity-growing-guides/sweet-corn>.

Beyer, D.M. 2017. Basic procedures for *Agaricus mushroom* growing. Accessed on 17 June 2019. <https://extension.psu.edu/basic-procedures-for-agaricus-mushroom-growing>.

Bishop, E.L., Pecchia, J.A., Wilkinson, V., Albert, I., and Royse, D.J. (2016). Effects of Spent Mushroom Compost (SMC) as an ingredient in phase I compost on production of *Agaricus bisporus*. Compost Science & Utilization, 24(4): 246–258.

Bisht, N.S. and Harsh, N.S.K. 1985. Biodegradation of *Lantana camara* and waste-paper to cultivate *Agaricus bisporus* (Lange) singer. Agricultural Wastes. 12(3): 167–172.

Bouasker, M., Belayachi, N., Hoxha, D. and Al-Mukhtar, M. 2014. Physical characterization of natural straw fibers as aggregates for construction carbon sources applications. Carbon sources, 7(4): 3034–3048.

Calvo-Bado L., Noble R., Challen M., Dobrovin-Pennington A. and Elliott T. 2000. Sexuality and genetic identity in the *Agaricus* section Arvenses. Applied and Environmental Microbiology, (2): 728–734.

Calvo, M.H. 2010. Development of a growth model system for *Agaricus bisporus*. M.Sc. dissertation, Wageningen University, The Netherlands.

Campbell, A. 2012. Organics recycling in Australia: industry statistics 2012. Department of Sustainability, Environment, Water, Population, and Communities' Recycled Organics Unit, Canberra.

Cao, W., Xu, H., and Zhang, H. 2013. Architecture and functional groups of biofilms during composting with and without inoculation. Process Biochemistry. 48: 1222–1226.

Carrasco, J., Zied, D.C., Pardo, J.E., Preston, G.M. and Pardo-Gimenez, A. 2018. Supplementation in mushroom crops and its impact on yield and quality. AMB Express, 8: 146–154.

Castillo, J.V. 2004. Inoculating composted pine bark with beneficial organisms to make disease suppressive compost for container production in Mexican forest nurseries. Fall 2004, pp. 181–185.

Chalfin, J. Date unknown. Mushroom compost Q & A. Accessed on 15 June 2019. <https://pasafarming.org/mushroom-compost-qa/>.

Chen, Y., Chefetz, B., van Heemst, J.D.H., Hatcher, P.G., Rosario, R. and Romaine, C.P. 2000. Chemical nature and composition of compost during mushroom growth. Compost Science & Utilization, 8(4): 347–359.

Coelle-Castillo, M.M., Sánchez, J.E. and Royse, D.J. 2009. Production of *Agaricus bisporus* on substrates pre-colonized by *Scytalidium thermophilum* and supplemented at casing with protein-rich supplements. Bioresource Technology. 100: 448–4492.

Coker, C. 2012. Odor defense strategy. BioCycle, 53(5): 35.

Coker, C., Goossen, D., Kelly, J., Hazelrigg, A. and Maia, G. 2016. Compost bioassay tests show persistent herbicide impacts. BioCycle, 57(3): 53–57.

Colmenares-Cruz, S. Sanchez, J.E., and Valle-Mora, J. 2017. *Agaricus bisporus* production on substrates pasteurized by self-heating. AMB Express. 7: 135.

Commonwealth of Australia. 2017. National food waste strategy halving Australia's food waste by 2030. Commonwealth of Australia, Canberra.

Costa, M.S.S. de M., Bernardi, F.H., Costa, L.A. de M., Pereira, D.C., Lorin, H.E.F., Rozatti, M.A.T. and Carneiro, L.J. (2017). Composting as a cleaner strategy to broiler agro-industrial wastes: Selecting carbon source to optimize the process and improve the quality of the final compost. *Journal of Cleaner Production*, 142: 2084–2092.

Ekman, J. 2017. Pre- and post-harvest management of mushrooms: A review. Horticulture Innovation Australia Limited, Sydney.

Epstein, E. 1997. The science of composting. Technomic Publishing Co., Inc., Lancaster, Pennsylvania.

Finstein, M.S. and Hogan, J.A. 1992. Integration of composting process microbiology. Facility structure and decision-making. Renaissance Publications, Columbus OH, Proceedings of the International Composting Research Symposium.

Forbes, L. 2019. Australia's livestock feed supplies in precarious position due to drought. Accessed on 27 June 2019. < https://www.abc.net.au/news/rural/2019-05-09/livestock-feed-supplies-shortage-due-to-drought/11092472>.

Gbor, N. Date unknown. War on waste: It's time to step off the fashion trend-mill. Accessed on 22 July 2019. <http://about.abc.net.au/war-on-waste-its-time-to-step-off-the-fashion-trend-mill/>.

González-Matute, R. and Rinker, D.L. 2006. Compatibility of ammonia suppressants used in poultry litter with mushroom compost preparation and production. Bioresource Technology, 97: 1679–1686.

González-Matute, R., Figlas, D. and Curvetto, N. 2010. Sunflower seed hull based compost for *Agaricus blazei* Murrill cultivation. International Biodeterioration & Technology, 64: 742–747.

Grains Research and Development Corporation. 2018. Grownotes. Accessed 28 June 2019. <https://grdc.com.au/__data/assets/pdf_file/0035/369287/GrowNote-Canola-West-0-Introduction.pdfhttps://grdc.com.au/about/our-industry/growing-regions>.

Grains Research and Development Corporation. 2019. Growing regions. Accessed 27 June 2019. <https://grdc.com.au/about/our-industry/growing-regions>.

Grant, B. 2012. Horse stable organics resource recovery opportunity assessment. Blue Environment/BEAM Mitchel Environment Group, Surry Hills.

Grimm, D. and Wösten H.A.B. 2018. Mushroom cultivation in the circular economy. Applied Microbiology and Biotechnology, 18: 7795–7803.

Grocycle. Date unknown. Growing mushrooms in coffee grounds. Accessed 12 June 2019. <https://grocycle.com/growing-mushrooms-in-coffee-grounds/>.

Haug, R.T. 1993. The practical handbook of compost engineering, L. Publishers, Boca Raton, Florida.

Hoa, H.T., Wang, C. and Wang, C. 2015. The effects of different substrates on the yield, and nutritional composition of two mushrooms (*Pleurotus ostreatus and Pleurotus cyctidiosus*) Mycobiology, 43(4): 423–434.

Hochman, Z., Gobbett, D.L. and Horan, H. 2017. Climate trends account for stalled wheat yields in Australia since 1990. Global Change Biology, 23(5): 2071–2081.

Hoitink, H.A.J. and Fahy, P.C. 1986. Basis for the control of soilborne pathogens with composts. *Annual Review of Phytopathology*, 24: 93–114.

Hort Innovation. 2018. Australian horticulture statistics handbook. Horticulture Innovation Australia Limited, Sydney.

Hort Innovation. Date unknown. Mushroom strategic investment plan 2017–2021. Horticulture Innovation Australia Limited, Sydney.

Howard, R.J., Garland, J.A. and Seaman, W.L. (eds) 1994. Diseases and pests of vegetable crops in Canada: an illustrated compendium. The Canadian Phytopathological Society and the Entomological Society of Canada.

Janssen, J. 2016. Aerated composting. A silent practical breakthrough. Proceedings of the International Society for Mushroom Science, 19: 175–179.

Jurak, E. 2015. How mushrooms feed on compost: Conversion of carbohydrates and lignin in industrial wheat straw based compost enabling the growth of *Agaricus bisporus*. Dissertation, Wageningen University.

Kamenik, I. and Marecek, J. 2011. The use of waste cellulose in production of white mushroom substrate. Acta Universitatis Agriculturae Et Silvicultura Medelianae Bruensis, Volume 15(5): 131–136.

Kertesz, M.A., Bell, T.L. and Safianowicz, K. 2015. Improving consistency of mushroom compost through control of basic biotic and abiotic parameters. Final Report MU10021. Horticulture Innovation Australia Limited, Sydney.

Krupodorova, T.A. and Barshteyn, V.Y. 2015. Alternative substrates for higher mushrooms mycelia cultivation. Journal of BioScience and Biotechnology, 4(3): 339–347.

Kumar, A.P., Kumar, C.D., Anil, P. and Johri, B.N. 2011. Bacterial diversity in a bagasse-based compost prepared for the cultivation of edible mushrooms *Agaricus bisporus*. Journal of Agricultural Technology, 7(5): 1303–1311.

Kyung, K., Lee, H., Jung, Y., Jang, K. and Yoon, M. 2010. Influence on composting of waste mushroom bed from *Agaricus bisporus* by using mixed organic carbon sources. Korean Journal of Soil Science and Fertilizer, 43.

Leiva, F.J., García, J., Martínez, E., Jiménez, E. and Blanco, J. 2017. Scenarios for the reduction of environmental impact in *Agaricus bisporus* production. Journal of Cleaner Production, 143: 200–211.

Linnenlueacke, M. 2019. Sugarcane industry weathers climate change. Accessed 26 July 2019. <https://future.business.uq.edu.au/sugarcane-industry-weathers-climate-change>.

Liu, R., Yu, H. and Huang, Y. 2005. Structure and morphology of cellulose in wheat straw. Cellulose, 1: 25–34.

Lyons, G.A., Sharma, H.S.S., Cheung, L., Moore, S. and Kilpatrick, M. 2006. Monitoring of changes in substrate characteristics during mushroom compost production. Journal of Agricultural and Food Chemistry, 54(13): 4658–4667.

Mammiro, D.P. and Royse, D.J. 2008. The influence of spawn type and strain on yield, size and mushroom solids content of *Agaricus bisporus* produced on non-composted and spent mushroom compost. Bioresource Technology, 99(80): 3205–3212.

Manu-Tawiah, W. and Martin, A.M. 1986. Cultivation of *Pleurotus ostreatus* mushroom in peat. Journal of the Science of Food and Agriculture, 37: 833–838.

Matute, R.G. 2011. *Agaricus blazei* production on non-composted substrates based on sunflower seed hulls and spent oyster mushroom substrate. World Journal of Microbiology and Biotechnology, 27(6): 1331–1339.

Mellilo, J.M., Aber, J.D., Linkins, A.E., Ricca, A., Fry, B., Knute, J. and Nadelhoffer, J. 1989. Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic matter. Plant and Soil, 115(2): 189–198.

Miller, F. and Macauley, B. 1989. Substrate usage and odors in mushroom composting. Australian Journal of Experimental Agriculture, 29: 119–124.

Miller, F.C., Harper, E.R., Macauley, B.J. and Gulliver, A. 1990. Composting based on moderately thermophilic and aerobic conditions for the production of commercial mushroom growing compost. Australian Journal of Experimental Agriculture, 30(2): 287–296.

Mupondi, L.T., Mnkeni, P.N.S. and Brutsch, M.O. 2006. The effects of goat manure, sewage sludge and effective microorganisms on the composting of pine bark and the nutritional value of composts. Compost Science and Utilization, 14: 201–210.

Nair, N.G. and Markham, J. 2008. Recycling solid waste from the olive oil extraction process. Rural Industries Research and Development Corporation, Canberra.

Nell, J.H. and Krige, P.R. 1971. The disposal of abattoir waste by composting. Water Research, 5: 1177–1189.

New South Wales Department of Primary Industries. 2007. Sweet corn growing. Accessed 27 June 2019. <https://www.dpi.nsw.gov.au/agriculture/horticulture/ vegetables/commodity-growing-guides/sweet-corn>.

Noble, R. 2008. Mushrooms: Carbon and nitrogen sources for organic and odourless mushroom composts. Final report for the Agriculture and Horticulture Development Board, United Kingdom.

Noble, R. 2010. Mushrooms: Effect of mixing proportions of phase II and phase III composts on cropping. Final report for the Agriculture and Horticulture Development Board, United Kingdom.

Noble, R. and Dobrovin-Pennington, A. 2005. Partial substitution of peat in mushroom casing with fine particle coal tailings. Scientia Horticulturae, 104(3): 351–367.

Noble, R., Fermor, T.R., Lincoln, S., Dobrovin-Pennington, A., Evered, C., Mean, A. and Li, R. 2003. Primordia initiation of mushroom (*Agaricus bisporus*) strains on axenic casing carbon sources. Mycologia. 95(4): 620–629.

Noble, R. and Gaze, R.H. 1996. Preparation of mushroom (*Agaricus bisporus*) composts in controlled environments: Factors influencing compost bulk density and productivity. *International Biodeterioration and Biodegradation*, 37: 93–100.

Noble, R., Hobbs, P.J., Dobrovin-Pennington, A. and Mead, A. 2002. Influence of straw types and nitrogen sources on mushroom composting emissions and compost productivity. Journal of Industrial Microbiology & Biotechnology, 29(3): 99–110.

Noguerira de Andrade, M.C., Zied, D.C., Minhomi, M.T. and de Filho, A. J. K. 2008. Yield of four *Agaricus bisporus* strains in tree compost formulations and chemical composition analyses of the mushrooms, Brazilian Journal of Microbiology, 39(3).

Norstedt, R.A., Barkdoll, A.W. and Schroeder, R.M. 1993. Composting of yard wastes. In Science and engineering of composting: Design, environmental, microbiological and utilization aspects, HAJ Hoitink and H Keener (eds). Renaissance Publications, Ohio.

Owaid, M.N., Abed, A. M. and Nassar, B.M. 2015. Recycling cardboard wastes to produce blue mushroom *Pleurotus ostreatus* in Iraq. Emirates Journal of Food and Agriculture, 27(7): 537–541.

Owaid, M.N., Barish, A. and Shariati, M.A. 2017a. Cultivation of *Agaricus bisporus* (button mushroom) and its usages in the biosynthesis of nanoparticles. Open Agriculture, 2: 537–543.

Owaid, M., Muslat, M. and Al-Assaffii, I. 2017b. Cultivation of *Agaricus bisporus* X25 on reed plant (*Phragmites australis*) straw decomposed by using actinomycetes. Hacettepe Journal of Biology and Chemistry, 45.

Pardo-Gimenez, A. and Pardo-Gonzalez, J.E. 2008. Evaluation of casing carbon sources made from spent mushroom substrate and coconut fibre pith for use in production of *Agaricus bisporus* (Lange) Imbach. Spanish Journal of Agricultural Research, 4: 683–690.

Pardo-Gimenez, A., Pardo-Gonzalez, J.E. and Zied, D.C. 2011. Evaluation of harvest mushrooms and viability of *Agaricus bisporus* growth using casing carbon sources made from spent mushroom substrate. International Journal of Food Science and Technology, 46(4).

Pardo-Gimenez, A., Zied, D.C. Alvarez-Orti, M. Rubio, M. and Pardo, J.E. 2012. Effect of supplementing compost with grapeseed meal on *Agaricus bisporus* production. Journal of the Science of Food and Agriculture, 92(8).

Peace, C. 2016. Crops for hay understanding the local regional and export markets. Grains Research Development Corporation, Canberra.

Peace, C. 2019. Hay — how is it stacking up?. Grains Research Development Corporation, Canberra.

Penn State University. 2011. Substrate preparation for white button mushrooms. Accessed 12 June 2019. <https://extension.psu.edu/substrate-preparation-for-white-button-mushrooms>

Penn State University. 2017. Basic procedures for *Agaricus* mushroom growing. Accessed 12 June 2019. <https://extension.psu.edu/basic-procedures-for-agaricus-mushroom-growing>.

Philippousis, A.N. 2009. Production of mushrooms using agro-industrial residues as substrates. In: P. Singh nee' Nigam, A. Pandey (eds.), Biotechnology for agro-Industrial residues utilisation, pp. 163–196. Springer Science & Business Media, Berlin.

Pickin, J., Randell, P., Trinh, J. and Grant, B. 2018. National waste report 2018 final. Department of the Environment and Energy, Canberra.

Potočnik, I. Vukojević, J., Kosanović, D., Rekanović, E., Stepanović, M. and Milijašević-Marčić, S. 2012. Impact of fungicides used for wheat treatment on button mushroom cultivation, Pesticidi I Fitomedicina, 27:9–14.

Rangel, J.L., Leal, H., Palacios-Mayorga, S., Sanchez, S., Ramirez, R. and Mendex-Garcia, T. 2006. Coconut fiber as casing material for mushroom production. Terra Latinoamericana, 24(2): 207–213.

Rao, M.S., Reddy, P.P. and Tewari, R. P. 1991. Comparative efficacy of certain oil cakes against mushroom nematode, *Aphelenchoides acchari* and their effect on yield of *Agaricus bisporus*. Indian Journal of Nematology, 21(2): 101–106.

Rosen, C.J., Halbach, T.R. and Mugaas, R. 2000. Composting and mulching: a guide to managing organic yard wastes. University of Minnesota Extension Service, Minnesota.

Ross, R.C. and Harris, P.J. 1982. Some factors involved in phase II of mushroom compost preparation. Scientia Horticulturae, 17(3): 223–229.

Ruan, R., Ding, L., Luo, Y. and Ruan, H. 2011. Cultivation of *Agaricus bisporus* in vineyards using spent pig litter. Acta Edulis Fungi, 18(3): 31–34.

Russ, C.F. and Yanko, W.A. 1981. Factors affecting *Salmonellae* repopulation in composted sludges. Applied Environmental Microbiology, 41: 597–602.

Sanchez, C. 2004. Modern aspects of mushroom culture technology. Applied Microbiology and Biotechnology, 64(6): 756–762.

Sanchez, J.E., Mejia, L. and Royse, D. J. 2008. Pangola grass colonized with *Scytalidium thermophilum* for production of *Agarics bisporus*. Bioresource Technology, 99(3): 655–662.

Sanchez, J. E. and Royse, D. J. 2009. *Scytalidium thermophilum*-colonized grain, corncobs and chopped wheat straw for substrates for the production of A*garicus bisporus.* Bioresource Technology, 100(4): 1670–1674.

Sanchez, J.E. and Royse, D. J. 2001. Adapting substrate formulas used for Shiitake for production of brown *Agaricus bisporus*. Bioresource Technology, 77(1): 65–69.

Sassine, Y.N., Ghora, Y., Kharrant, M., Bohme, M. and Abdel-Mawgood, A.M.R. 2005. Waste paper as an alternative for casing soil in mushroom (*Agaricus bisporus*) production. Journal of Applied Sciences Research, 1(3): 277–284.

Savoie, J.M., Vedie, R., Blanc, F., Minvielle, N., Rousseau, T. and Delgenes, J.P. 2011. Biomethane digestate from horse manure, a new waste usable in compost for growing the button mushroom, *Agaricus bisporus*? Proceedings of the 7th International Conference on Mushroom Biology and Mushroom Products, 176–181.

Shekhar Sharma, H.S. and Kilpatrick, M. 2000. Mushroom (*Agaricus bisporus*) compost quality factors for predicting potential yield of fruiting bodies. Canadian Journal of Microbiology, 46(6): 515–519.

Sithole, S.C., Mugivhisa, L.L., Amoo, S.O. and Olowoyo, J.O. 2017. Pattern and concentrations of trace metals in mushrooms harvested from trace metal-polluted soils in Pretoria, South Africa. South African Journal of Botany, 108: 315–320.

Smith, J.F. and Spencer, D.M. 1977. The use of high energy carbon sources in rapidly prepared mushroom composts. Scientia Horticulturae, 7: 197–205.

Stoknes, K., Beyer, D.M. and Norgaard, E. 2013. Anaerobically digested food waste in compost for *Agaricus bisporus* and *Agaricus subrufescens* and its effect on mushroom productivity. Journal of the Science of Food and Agriculture, 93(9): 2188–2200.

Stoknes, K., Høiland, K., Norgaard, E. and Hammer, J.P. 2008. From food to waste to food—a high yield of mushrooms from food-waste compost. Proceedings of the 17th Congress of the International Society for Mushroom Science, pp. 273–287.

Straatsma, G., Gerrits, J.P.G., Amsing, J.G.M., Van Griensven, L.J.L.D., Thissen, J.T.N.M. and Loeffen, H. 2000. Adjustment of the composting process for mushroom cultivation based on initial substrate composition. Bioresource Technology, 72(1): 67–74.

Tavakoli, H., Mohtasebi, S.S. and Jafari, A. 2008. A comparison of mechanical properties of wheat and barley straw. Agricultural Engineering International: CIGR Journal, 10: 1–9.

Vazquez, J.E.S., Royse, D.J., and Hernandez, G. 2002. Development of non-composted substrates for production of *Agaricus bisporus*. Accessed 12 June 2019. <https://setascultivadas.com/2004articulomayoingles.html>.

Wang, L., Mao, J., Zhao, H., Li, M., Wei, Q., Zhou, Y. and Shao, H. 2016. Comparison of characterization and microbial communities in rice straw- and wheat straw-based compost for *Agaricus bisporus* production. Journal of Industrial Microbiology and Biotechnology: (9), 1249–1260.

Wang, Q., Li, B.B., Li, H. and Han J.R. 2010. Yield, dry matter and polysaccharides content of the mushroom *Agaricus blazei* produced on asparagus straw substrate. Scientia Horticulturae, 125(1): 16–18.

Watson, K. and Weidemann, S.G. 2018. Review of fresh litter supply, management and spent litter utilisation. AgriFutures Chicken Meat, Wagga Wagga.

Watts, P. and McCabe, B. 2015. Feasibility of using feedlot manure for biogas production. Meat & Livestock Australia, Sydney.

Wilkinson, K., Paulin, R., Tee, E. and O'Malley, P. 2002. Grappling with compost quality down under. Proceedings of the International symposium on composting and compost utilization, pp. 527–539. Ohio State University, Columbus Ohio.

Wilkinson, K., Tee, E. and Hood, V. 2000. Does AS4454 adequately benchmark compost quality. Proceedings of the

Compost 2000 Down Under Conference, Melbourne, Vic.

Wright, C.T., Pryfogle, P.A., Stevens, N.A., Steffler, E.D., Hess, J.R. and Ulrich, T.H. 2005. Biomechanics of wheat/barley straw and corn stover. Applied Biochemistry and Biotechnology, 121: 5–19.

Zakaei, M., Bazyar, S., and Khanehbad, M. 2011. Post technology casing soil with the use of vermicompost in mushroom (*Agaricus bisporus* (L.)) Sing.) cultivation. The Quarterly Journal of Animal Physiology and Development, 4(1): 19–26.

Intellectual property, commercialisation and confidentiality

The information in Appendix 1 Attachment B (Stakeholder feedback) should be treated as commercial-in-confidence at the request of some members of the mushroom industry.

Acknowledgements

We would sincerely like to thank the mushroom composters who donated time and expertise on the subject of mushroom composting during the interviews conducted for this research. We have also been in touch with several experts in the field of mushroom research. We would like to acknowledge the invaluable contributions from the following researchers:

- Assoc Prof Michael Kertesz, University of Sydney
- Prof David Beyer, Penn State University
- Dr Ralph Noble, Microbiotech Ltd, United Kingdom
- Dr Kerry Burton, independent consultant, United Kingdom
- Dr Edita Jurak, Groningen University, the Netherlands

Appendices

- Appendix 1 Final Report: Summary of potential alternative carbon sources & feasibility of carbon alternatives *Milestone 190*
- Appendix 1 Attachment A: Potential alternative substrates and viability analysis
- Appendix 1 Attachment B: Stakeholder feedback (provided separately to Hort Innovation as it is commercial-in-confidence)
- Appendix 1 Attachment C: Ready Reckoner — trialing an alternative to wheaten straw for mushroom composting
- Appendix 1 Attachment D: Case studies for the shimeji and oyster mushroom industries

Appendix 1:
Final report:
Summary of potential alternative carbon sources & feasibility of carbon alternatives

Milestone 190

Report written for:

Hort Innovation
Level 5, 606 St Kilda Road
Melbourne
VIC 3004

Report written by:

Dr Kevin Wilkinson, Dr J.F. Jasonsmith, and Dr Jess Drake

Frontier Ag & Environment and Murrang Earth Sciences Pty Ltd

29 November 2019

02 6161 1762

contact@murrang.com.au

www.murrang.com.au

ABN 96 162 928 958

Disclaimer

This report has been prepared for the sole use of Hort Innovation, in accordance with the terms and conditions set out in the contract agreed to between Murrang Earth Sciences and Hort Innovation. The report has been prepared for the purposes outlined in Section 1 of this report. The report must not be relied upon, copied, or duplicated by any other party without written agreement from Murrang Earth Sciences and Murrang Earth Sciences accepts no duty of care to any third party in any way whatsoever.

Due care was exercised in the preparation of this report. Every effort was made to ensure the quality of the information presented. No warranty, express or implied is made in relation to the contents of this report. Murrang Earth Sciences assumes no liability for any loss resulting from errors, omissions, or misrepresentations made by others.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Executive summary

The Australian mushroom industry is worth more than $396 million annually, with over 67,000 tonnes of mushrooms, predominantly *Agaricus bisporus,* produced in the 2016 to 2017 financial year. The availability of the main substrate used to make mushroom compost, wheaten straw, has decreased over recent years as a result of drought affecting the yield and quality of wheat, as well as causing increased competition for wheaten straw from the feedstock industry. The impact of climate change may also affect wheat yields and, therefore, the availability of straw in the future. Changed farming practices have also played a role in reducing wheaten straw availability.

By identifying alternative sources of carbon for mushroom compost production, this project contributes to the broader aim of future-proofing the mushroom industry against the impact of climate change. The use of alternative carbon sources could also be more cost-effective in the long term as supply of wheaten straw becomes constrained.

Hort Innovation funded this project using the mushroom research and development levy and contributions from the Australian Government. Hort Innovation is the grower owned, not-for-profit research and development corporation for Australian horticulture.

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. Sometimes other organic carbon sources are added in small amounts as supplements or activators. Wheaten straw is a good example of a lignocellulose waste stream, i.e. plant residues containing a combination of cellulose, hemicellulose and lignin. Lignocellulosic carbon sources can also be derived from agriculture, forestry or industrial processes (e.g. food processing). Aside from wheaten straw (and other cereal straws), other examples of lignocellulosic carbon sources include crop residues (e.g. sugar bagasse), as well as the biomass of grasses, whole seeds, seed hulls and woody wastes (e.g. sawdust, wood chips and green waste).

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

The production of *A. bisporus* (and other edible mushrooms) in Australia is a well-developed and technically sophisticated process that has evolved over decades of research, development and commercial practice. Wheaten straw is the preferred lignocellulosic substrate in Australia for good reason. It has unique physicochemical properties that are difficult to replicate – it has the right lignocellulosic content, excellent structural properties and excellent water absorbency.

Twenty-four alternative carbon sources or options were identified as potential alternatives to wheaten straw in mushroom composting within internet searches, scientific literature, or as a result of brain-storming by the report's authors. Of these, ten carbon sources were identified as being viable replacements worth further evaluation. This list was then narrowed down using an elimination process as part of a feasibility assessment.

Firstly, the physiochemical properties of the short-listed waste were reviewed for their ability to be utilised in a composting process for *A. bisporus* production. During this process, the authors found that all ten different carbon sources could be used for partial and/or complete substitution of wheaten straw by mushroom composters on an opportunistic basis. The next elimination stage was based on supply and cost. The supply of some of these substrates was found to be unreliable, including from climate change limitations. Many other substrates were found to be subject to price-competition due to their use in other industries — especially the feedstock industry. The majority of carbon sources were eliminated during this stage of the review. For the remaining carbon sources, we then undertook an assessment of hazards, and finally a research and development gap analysis.

Four carbon sources that had appropriate physiochemical properties and were accessible (i.e. had viable costs and availability) included 1) waste paper; 2) forestry waste; 3) corn stover; and 4) sugar bagasse. Use of waste paper (either shredded and soft-mixed) in composting is limited by its physical properties. Waste paper could, however, replace around 20% of wheaten straw in compost without negatively impacting the porosity of the mix. Carbon sources that could be viable as complete substitutes for wheaten straw include forestry residuals such as bark and wood chips (subject to appropriate pre-treatment; sugar and corn stover. A ready supply of these four short-listed carbon sources is available now and is considered likely to persist with the predicted climate change. The physicochemical characteristics of these sources indicates that they could be suitable for mushroom composting. However, while corn stover and sugar both appear to be ideal for use as a substitute for wheaten straw, transport distances could be a logistical hurdle.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

There were no specific hazards for these substrates. General hazard research indicates that unknown yield is the biggest hazard, thus significant investment would be required by industry to ensure confidence in the use of these alternate carbon sources on farms. Therefore further investment in research and development is required to develop new high-performing substrates from any of these alternative carbon sources.

We have concluded that there is a need to approach the problem of alternative carbon sources in an integrated fashion. Therefore, priority should be given to projects involving process optimisation. The mushroom composting process and the cultural practices for growing *A. bisporus* have been optimised for particular commercial mushroom strains growing in a carbon sources based on wheaten straw and poultry manure (as the primary ingredients). Investigating the potential use of other carbon sources should therefore consider how the new production system could be best optimised to ensure ongoing productivity and business viability.

A ready reckoner summarises the findings of this report and is presented as an attachment. This tool was developed to help mushroom growers assess the potential costs and benefits of using short-listed carbon sources. Two case studies for shimeji and oyster mushrooms were also completed as part of this project. They highlight that paper, forestry residuals, and corn stover are already being used by oyster mushroom growers. For shimeji, however, wood logs are generally used in production.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Table of contents

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Figures, tables, and attachments

02 6161 1762

contact@murrang.com.au

www.murrang.com.au

ABN 96 162 928 958

1. Introduction

The Australian mushroom industry is worth more than $396 million annually, with over 67,000 tonnes of mushrooms produced in the 2016/2017 financial year (Hort Innovation 2018). The predominant species, *Agaricus bisporus*, is generally grown in all states of Australia. Major production areas include near Adelaide, metropolitan Melbourne and the Sydney basin.

There is a range of pressures on the mushroom industry, as highlighted in the "*Mushroom Strategic Investment Plan 2017-2021*" (the SIP [Hort Innovation, Date Unknown]). These include food safety requirements, disease and a lack of scientific understanding of the growing process. The need to reduce input costs and consider the risks associated with climate change has been identified in particular, with wheaten straw, the preferred carbon source for compost, predicted to become more difficult to acquire and thus also more expensive. Alternative carbon sources are also needed to reduce carbon source acquisition risks in the future.

The aim of this strategic levy investment project, "*Feasibility of compost substrate alternatives for mushroom production (MU17007)*", was to find alternative sources of carbon for mushroom compost production as a contribution to future-proofing the mushroom industry against the impacts of climate change. Hort Innovation funded this project using the mushroom research and development levy, along with contributions from the Australian Government. Hort Innovation is the grower owned, not-for-profit research and development corporation for Australian horticulture.

Production *of A. bisporus* is the main source of levies to Hort Innovation for the mushroom industry. Therefore, this project largely focused on the needs of *A. bisporus* growers. However, shimeji (multiple spp.) and oyster (*Pleurotus ostreatus*) mushroom growers may also benefit from aspects of this research.

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. Sometimes other organic raw carbon sources are added in small amounts as supplements or activators. Wheaten straw is a good example of a lignocellulose waste stream, i.e. plant residues containing a combination of cellulose, hemicellulose and lignin. Lignocellulosic carbon sources can be derived from agriculture, forestry or industrial processes (e.g. food processing). Aside from wheaten straw (and other cereal straws), other examples of lignocellulosic carbon sources include crop residues (e.g. sugar bagasse), as well as the biomass of grasses, whole seeds, seed hulls and woody wastes (e.g. sawdust, wood chips and green waste).

The production of *A. bisporus* (and other edible mushrooms) in Australia is a well-developed and technically sophisticated process that has evolved over decades of research, development and commercial practice. Wheaten straw is the preferred lignocellulosic substrate in Australia for good reason. It has unique physicochemical properties that are difficult to replicate — it has the right lignocellulosic content, excellent structural properties and excellent water absorbency.

In this report, we highlight possible alternatives for wheaten straw and the feasibility of their use within the industry based on a literature review, knowledge of the physicochemical properties of the carbon sources, access and cost, hazards, as well as stakeholder feedback. We present a thorough gap analysis highlighting research and development needs, as well as a ready reckoner and case studies for oyster and shimeji mushroom producers.

2. Methods

We considered carbon alternatives for their potential as both partial and complete replacements for wheaten straw. Where a carbon material lacks the particular physicochemical characteristics necessary to be viable as a complete substitute for straw, its use as a partial substitute (e.g. by replacing 30% of the straw) could still be worthwhile to reduce reliance on wheat. Although the supply of wheaten straw is predicted to tighten under climate change scenarios, mushroom composters are likely to continue using it to the extent that it is possible. Partial carbon substitutes would therefore be required to fill this gap left over from reduced supply of wheaten straw. Complete replacement is likewise considered in a climate change scenario where wheaten straw is no longer available or cost effective to use. This could be related to climate scenarios predicting the ongoing decline of wheat growing in Australia (Hochman et al. 2017), use by other industries or full retention of straw on farm etc.

As a first step in identifying potential alternative carbon sources for mushroom substrate production, research was conducted to compile a list of potentially viable carbon sources.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

The potential carbon sources were then subjected to a feasibility analysis in a step-wise fashion as outlined in the sections below, followed by a gap analysis and research and development prioritisation.

Although the main focus of this report is *A. bisporus*, we also considered relevant research for *A. blazei* since the cultivation methods for this fungus are very similar to those used for *A. bisporus*. *Agaricus blazei* is a native of Brazil and is also grown for its medicinal properties in Japan, where it is referred to as *Himematsutake.*

2.1 Summary of potential carbon sources for mushroom compost production

In developing our initial list of potential carbon sources, we identified:

1. Alternative carbon sources used in the industry world-wide for mushroom compost production
2. Alternative carbon sources that have been investigated in the scientific literature
3. Other alternative carbon sources available in Australia that have not been previously investigated in research projects or by industry
4. Other approaches to carbon source management, particularly partial substitution of wheaten straw with other carbon sources

These results were summarised in tabular form (Attachment A), identifying where and how these carbon sources are used by industry (if at all), as well as any supporting research associated with them. We then consulted industry stakeholders, as well as Australian and international researchers to capture their experience and opinions on the potential viability of these carbon sources.

The literature search for this review was undertaken using Google searches and library systems at the Australian National University and Deakin University. Search terms "mushroom compost", "mushroom compost substrates", and "*Agaricus bisporus* compost production" were used. We then refined our review of available research and articles using the library and Google with search terms "(substrate type) mushroom compost" or "(substrate type) *A. bisporus*" as appropriate. Some useful research reports were also obtained by directly contacting researchers active in the field.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

A preliminary analysis of the potential carbon sources was then undertaken, considering where and how they are used and whether any supply issues are foreseeable in the future. The various options fell into three categories as follows.

The first category identified carbon sources used in the production of *A. bisporus* compost substrate. These carbon sources may be used in other parts of the world, or else research and development indicate that they are a viable alternative to wheaten straw. These carbon sources proceeded to the next stage of assessment (Section 2.2).

Carbon sources in the second category were those considered to have potential, but are not currently viable without further research and development. These carbon sources also proceeded to the next stage of assessment, the Feasibility study.

Carbon sources in the third category did not proceed to the Feasibility study since barriers to their use were considered to be too substantial. Some of these barriers are discussed in the gap analysis, and research and development sections of this report.

2.2 Feasibility study

Carbon sources short-listed for further investigation were subjected to a three-stage Feasibility study as described below. The feasibility study also acted as an elimination method, whereby each stage of the study eliminated carbon sources that were determined not to be feasible for use in mushroom composting.

The Feasibility study was undertaken in the form of a literature review, and where relevant, feedback from stakeholders was also considered. Where necessary, researchers were also consulted to assist us in clarifying important technical issues.

1. The first stage of the feasibility study was a technical assessment of the physicochemical characteristics of alternative carbon sources and the potential impact of these characteristics on composting. This assessment included:
    a. A comparison of the physicochemical characteristics between alternative carbon sources and wheaten straw, including content of cellulose, hemicellulose and lignin; physical structure (considering particle size, porosity, bulk density etc.); nutrient content; consistency/variability; and, presence/absence of contaminants. Where no published data was available, this was considered within a gap analysis (see item 4 below).

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

b. An assessment of the impact of the proposed carbon alternative on the composting process. Published research was reviewed for information relating to the use of proposed carbon alternatives in mushroom composting. Where research was limited, predictions of possible impacts were made based on the physicochemical characteristics of the material and/or considered in the gap analysis (see item 4 below).
c. An assessment of the potential adverse impacts of the identified carbon sources on mushroom yields.
d. The listing of partial and full replacements based on their physiochemical characteristics. This list was used for the second stage of the feasibility analysis.

2. Procurement costs and the availability of potential carbon sources in mushroom growing regions were reviewed in the second stage of the Feasibility study. The review included:
   a. An assessment of the availability of each short-listed carbon source across Australia, including in major mushroom growing urban environments as well as in rural and regional areas. Volumes of the carbon sources available, location/ease of access, reliability of supply, whether the carbon sources are already being diverted elsewhere, and climate change limitations were considered.
   b. An assessment of costs, including purchasing, transport, and pre-treatment[1].
   c. Making contact with stakeholders from the main mushroom producing regions — that is the Sydney Basin, Melbourne, and Adelaide. An outline of the questions presented to stakeholders is presented in Attachment B.
   d. Each material was qualitatively assessed for viability as an alternative to wheaten straw according to the criteria of cost, volume available, supply reliability, and climate limitations. A material considered to pass viability was one for which the following parameters apply:

      - the **cost** is equal to or cheaper than wheaten straw;
      - the **volume of the material available** is considered to meet potential demand from the mushroom industry. The term low was used to indicate that no quantitative data is availabl,e but information provided in literature or from stakeholders indicates the suppliable volume of the material would be insufficient to meet composter demands;

[1] While an assessment of costs associated with post-treatment disposal (e.g. disposal of waste) was initially planned, such information has not been forthcoming as a result of this research and is therefore not presented.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

- the **supply of the material** is considered to be reliable in the context of market supply and demand, with:
    - those carbon sources which are subject to substantial variation in costs indicated as “*Market dependent*”
    - those for which long-term contracts prohibit supply considered “*Low*”;
    - and those for which supplies can be readily obtained considered “*Reliable”*; and
- **Climate limitations**, either in a general sense of global warming, extreme weather, and drying, or due to one of these specifically, is not projected to impact upon supplies of the material. While *“Irrigation*” is considered related to climate limitations, it is presented as a specific type of limitation, as both surface and groundwater are used for irrigation in Australia, and supplies of such water may or may not be impacted by climate change.

A carbon source that was considered unviable as a substitute to wheaten straw due to cost, volume available, supply reliability or climate limitations failed this assessment.

The costs and availability of potential carbon sources is presented in Section 3.2.2, along with a short-list of potentially viable carbon alternatives to wheaten straw.

3. In the third and final assessment stage, hazards to the adoption of alternative carbon sources were considered. This stage included:
    a. Consultation with the stakeholder groups regarding their experiences and concerns with short-listed carbon sources. Stakeholder feedback on this Final Draft version of the report will be sought and included within the Final Report.
    b. Evaluation of food safety related hazards due to potential contaminants and pathogens, including on-selling of spent mushroom compost, and potential mitigation measures for any unacceptable hazards identified.
    c. Identification of pest and disease hazards to mushroom production from alternative carbon sources and any strategies to mitigate them.
    d. Identification of the legislative requirements and industry Standards for different carbon-alternatives under consideration, including Australian Standards such as AS4419 and AS4454 and state waste reuse regulations.

2.3 Gap analysis and recommendations for research

A gap analysis was undertaken after the Feasability study, to assist in the identification of future research priorities for the development of composted substrates from alternative carbon sources. We identified knowledge gaps and barriers to adoption for the short-listed alternative carbon sources through a review of the literature and also through consultation with industry stakeholders. We also considered the state of knowledge with respect to the biology of *A. bisporus*, and issues associated with substrate utilisation and compost process optimisation as they relate to the development of substrates from alternative carbon sources. From this evaluation, a list of prioritised research and development questions were identified.

2.4 Ready reckoner and case studies

A ready reckoner was developed as a tool to help mushroom farmers assess which carbon sources could be used in their farming operations, and the costs and benefits of these carbon sources (Attachment C). The ready reckoner was created through summarising the findings of this report. Assessment criteria were constrained, and then weighted and ranked based on a qualitative assessment of the properties of the carbon sources and the importance of these properties to the commercial operation of mushroom farms.

Two case studies were developed, two pages long each, focusing on the short-listed carbon sources for the gourmet mushroom industry (Attachment D). This included:

- A summary of relative advantages and disadvantages of the short-listed carbon sources for use in the growing of oyster mushrooms
- A summary of relative advantages and disadvantages of the short-listed carbon sources for use in the growing of shimeji mushrooms

The case studies used literature from this report and additional technical research where required.

3. Results and discussion

A summary of potential carbon alternatives is presented in Section 3.1. The feasibility of using these carbon sources both in terms of their physical and chemical properties, as well as their cost, is then presented in Section 3.2.

3.1 Summary of potential carbon sources mushroom compost production

Twenty-four potential options were identified as potential alternatives to wheaten straw (Attachment A). These alternatives were split into three groups for the purposes of this report as follows (as described above in Section 2.1).

3.1.1 Carbon sources currently in use and those with good research backing

Of the carbon alternatives listed in Attachment A, some are used for mushroom production nationally or internationally, or have been researched as possible alternatives for *A. bisporus* production. Spent bedding or litter from the horse, pig and chicken industries in particular is used in Europe, USA and Asia (Penn State University 2011, 2017; Savoie et al. 2011). Other promising substrates used to produce a range of different mushrooms (including *A. bisporus*) include:

1. Oil seed waste;
2. Sugar bagasse;
3. Spent and fresh grain;
4. Rice straw; and
5. Corn stover.

Many of these substrates are already used within Australian mushroom composts to supplement wheaten straw or horse bedding. However, these carbon sources are not typically used as complete replacements for wheaten straw (e.g. Sanchez and Royse 2009; Kamenik and Marecek 2011). Many carbon sources for which research is available are instead substituted as blends or are wastes that are high in carbon and nitrogen, such as spent oil seed waste (e.g. Mammiro and Royce 2008; Matute 2011; Krupodorova and Barshteyn 2015). Rice and corn straw are used in the production of mushroom compost in many regions where these crops are more prevalent, such as within Asia and the USA (e.g. Sanchez and Royse 2009; Amin et al. 2010; Kumar et al. 2011; Adjapong et al. 2015).

3.1.2 Carbon substrates with limited or unknown potential

There are several substrates listed in Attachment A for which our research indicates limited viability as an alternative source of carbon for *A. bisporus* compost production.

The use of spent coffee grounds has been largely investigated for the production of oyster mushrooms (e.g. Vazquez et al. 2002). We found only one article (not peer reviewed) examining the use of spent coffee grounds within compost used to grow *A. bisporus*. Based on this, and feedback from stakeholders which indicates that spent coffee grounds present a high disease risk, we do not suggest that coffee grounds continues to be explored.

Research on paper and cardboard waste focuses on its use as *A. bisporus* casing (e.g. Sassine et al. 2005, Owaid et al. 2015), although this material is also currently used to cultivate oyster mushrooms. Owaid et al. (2015) have suggested that paper and cardboard are an alternative to other cellulosic waste such as wheaten straw.

Sawdust is already commonly used for shimeji and oyster mushrooms, and may also be blended with seed hulls and oil waste (e.g. Kyung et al. 2010). In addition, we found two papers exploring the use of wood or forestry waste products (wood chips, bark and sawdust) in mushroom compost mixes from Norway (Stoknes et al. 2008; Stoknes et al. 2013). These carbon sources were composted with food waste with some success (see below). The authors suggested that their work showed that there is "*no unambiguous need for straw when preparing a mushroom compost*" and that "*spruce bark can be a substitute*" (Stoknes et al. 2008). They hypothesised that the bark provided the structural requirements of the mix, while the food waste provided all the necessary nutrients for the growth of mushrooms.

There was little peer-reviewed research on the use of municipal green waste in mushroom production. However, the Horticultural Development Council in the UK has funded some work evaluating substitution of wheaten straw and poultry manure with green waste, as well as other carbon sources (Noble 2008). Not a lot of detail was provided in the report about the composition of that green waste, but we suspect that it contained a high-grass content[2]. Substituting green waste for around 29% of the straw and 11% of poultry manure resulted in a significant reduction in mushroom yields. There has also been some research

[2] Based on the reported nitrogen and ash contents of 1.67% and 55.4%, respectively.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

conducted in the Netherlands on the use of composted green waste as a component in mushroom compost (Gerrits 1991). This research showed that there was a strong correlation between percent substitution of conventional substrate with composted green waste and mushroom yields[3].

Focusing on single-origin or supplier sourced green waste may be more promising. Single-source grasses like Pangola grass and Lantana could be used as substrates for *A. bisporus* compost production (e.g. Sanchez et al. 2008, Owiad et al. 2017b, Bisht and Harsh 1985). There were also a number of papers on the use of substrates inoculated with thermophilic fungus (*Scytalidium thermophilum)* to promote the growth of *A. bisporus* production through providing a more bioavailable carbon source (e.g. Sanchez et al. 2008, 2009). One example of this particular process was the use of pre-colonised Pangola grass for *A. bisporus* production (Sanchez et al. 2008).

Green waste was investigated in more detail at the specific request of Hort Innovation (Section 3.2). There has been some interesting work from Norway using source separated[4] food waste in compost mixes for the production of mushroom substrate (Stoknes et al. 2008; Stoknes et al. 2013). This work showed that source-separated food waste composted with spruce bark had good potential as a mushroom substrate. Yields for *A. bisporus* in this substrate were almost as high as a commercial mix (comprising wheat straw, poultry manure and gypsum), while those for *A. brasiliensis* were much higher (Stoknes et al. 2008). The use of post consumer food waste in mushroom composting is not yet viable in Australia. Significant investment in infrastructure and education by local government would be required should such utilisation be desired, with food waste recycling undermined by heavy plastic, glass and metals' contamination. There is interest from local government and the

[3] This work involved the replacement of mushroom substrate with composted green waste (not the raw materials). This compost was obtained from a commercial green waste composting facility.

[4] Source separated food waste usually means the collection of household food waste in which contaminants are separated out by the householder, i.e. before collection rather than after collection.

community in the separate collection of household food waste, but few programs have been rolled out.[5]

There are potential sources of pre-consumer food waste that are unlikely to have the same contamination problems as post-consumer sources. In the UK, Noble (2008) found that mushroom yields in composted substrates were unaffected by substituting 19 to 28% (by weight) of wheat straw with vegetable waste (root vegetables, brassica leaves and tomato stems). Due to its nitrogen content, vegetable waste also replaced 11 to 12% of the poultry manure in the compost mix. Furthermore, waste tea leaves are actively used as a mushroom compost substrate in India and Asia (Owaid et al. 2017a; Barman et al. 2017). Some researchers have also investigated food as a partial casing and supplement to compost substrates where the waste has first been processed by vermicomposting (Matute and Curvetto 2010; Zakaei et al. 2011; Barman et al. 2017).

3.1.3 Carbon substrates that are unfeasible for mushroom compost production

Some potential carbon alternatives were easily discounted from further consideration due to significant issues or risks. Some of them, for example, have been the subject of research but have been found to be not appropriate or are unlikely to be feasible in the short to medium term in Australia.

By-products of the meat and dairy industry, namely paunch and whey, were not considered to be viable due to lack of research backing (e.g. Nell and Krige 1971; Smith and Spencer 1977). Peat is generally not produced in Australia. Coal has been previously trialled as an alternative casing material to peat, however, we consider the chemical risks presented by coal to be too substantial (Noble et al. 2003; Noble and Dobrovin-Pennington 2005). Using the described searches, there was no research found on biosolids (i.e. processed human sewage). Australia also does not have a viable coconut industry and so no coconut waste is currently generated. Vermicompost has the same limitations as food waste, as described

[5]Examples of successful food waste collection in Australia are available, though they are rare. The shires of Wodonga and Indigo in Victoria and Albury in NSW have co-operated together to implement a successful food waste collection system. The system collects both food and green waste from households. Another good example of food waste collection comes from Penrith Council in Sydney.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

above. In summary, the list of unviable carbon sources considered in this report includes (with the reasons they were considered unviable presented within parentheses):

1. Peat (limited peat production in Australia);
2. Biosolids (chemical risks considered too substantial);
3. Coal and brown coal (chemical risks considered too substantial);
4. Coconut coir (no coconut industry within Australia);
5. Vermicompost (an unviably small industry in Australia);
6. Paunch (limited research backing and volumes available); and
7. Dairy by-products (limited research backing; high moisture content indicates it is not a carbon source).

3.1.4 Summary of viable or possibly viable carbon alternatives

As a result of the initital screening process presented in Sections 3.1.1. and 3.1.3, we prodiced a short-list of 10 substrates that may be viable as alternatives to wheaten straw in mushroom compost (see Appendix A for references and details). Some of these are broad groupings that, with further evaluation, were more narrowly defined through the feasibility assessment process. Green waste is included in the list at the request of Hort Innovation Australia, since it is a significant municipal lignocellulosic waste stream that is expected to grow in volume over time and is also under-utilised in many parts of Australia. The short-listed substrates are:

1. Green waste
2. Bedding or litter from the intensive animal industries (e.g. horse, pig and chicken)
3. Paper and cardboard
4. Spent or fresh grain
5. Seed hulls
6. Oil seed waste
7. Corn stover
8. Other straws and crop waste (e.g. rice, cotton, canola, and hay)
9. Sugar bagasse
10. Forestry residuals (e.g. wood waste, woodchips, bark and sawdust

Food waste is not included in this list because there are too many uncertainties at the present time with respect to composition, origin and volumes available. These issues are discussed in the Gap analysis and Research and development sections below (Section 3.2.4 and Section 4).

3.2 Feasibility study of carbon alternatives for mushroom compost production

As presented in Section 2.2, there were three stages to assessing the feasibility of using the short-listed carbon sources in commercial mushroom composts. These were a technical stage, where critical technical issues associated with substrate selection and compost quality were considered. A stage where the costs and logistics of attaining these carbon sources were assessed. And a final stage, where the hazards presented by these carbon sources was considered.

3.2.1 Stage one: technical assessment

The growing substrate for *A. bisporus* is traditionally manufactured from a carbon-rich base material, such as wheaten straw, combined together with gypsum and a source of nitrogen. Sometimes other organic raw carbon sources are added in small amounts as supplements or activators. The carbon-rich base sources are most commonly comprised of lignocellulose — plant residues containing a combination of cellulose, hemicellulose and lignin. These lignocellulosic carbon sources can be derived from agriculture, forestry or industrial processes such as food processing. Aside from wheaten straw (and other cereal straws), other examples of lignocellulosic carbon sources include crop residues (e.g. sugar bagasse), as well as the biomass of grasses, whole seeds, seed hulls and woody wastes including sawdust, wood chips and green waste.

Substrate quality is known to affect the growth of edible fungi and the subsequent yield of their fruiting bodies — i.e. their mushrooms (Shekhar Sharma and Kilpatrick 2000). There are, therefore, a number of technical issues to consider in examining the potential suitability of lignocellulosic carbon sources for use as a mushroom compost substrate. In this literature review, we first touch on the fundamentals of lignocellulosic bioconversion by edible fungi, with a particular focus on *A. bisporus.* Secondly, we examine the mushroom composting process and the unique role played by wheaten straw in it. With this as background, we then move into the physicochemical properties of different lignocellulosic carbon sources as alternatives to wheaten straw. The physicochemical properties of carbon sources can directly affect the efficiency of bioconversion (e.g. mushroom yield per square metre of floor space) as well as the compost process that is used to manufacture the substrate. This is an important consideration since compost process management can affect both substrate quality and the environmental impacts of mushroom composting (e.g. from odour generation).

A summarised technical assessment of the potential carbon sources listed in Section 3.1.4 is presented at the end of this section.

3.2.1.1 Bioconversion of lignocellulosic carbon sources by edible fungi

Cultivated edible mushrooms are the fruiting bodies of basidiomycetes, all of which can be divided into primary, secondary and tertiary decomposers. Each type of edible mushroom degrades different forms of organic matter, and thus has different substrate requirements for their cultivation.

Primary decomposers such as the oyster mushrooms (*Pleurotus* spp.) and shiitake (*Lentinula edodes*) degrade cellulose, hemicellulose, lignin, and other components of plant material (Grimm and Wösten 2018). Unlike secondary and tertiary decomposers, primary decomposers do not depend on other organisms and their metabolites for their growth and fructification. Primary decomposers can theoretically degrade a wide range of lignocellulosic residues, such as wheat straw, cotton wastes, coffee pulp, corn cobs, sunflower seed hulls, wood chips and sawdust, peanut shells, vine prunings and others into mushroom protein (Philippoussis 2009). These organisms produce a plethora of enzymes to facilitate the degradation of lignocellulosic substrates, including lignin-degrading enzymes (laccase, lignin peroxidase, manganese peroxidase, aryl alcohol oxidase, aryl-alcohol dehydrogenase or quinone reductase), and hemicellulose and cellulose-degrading enzymes such as xylanase, cellulase or cellobiose dehydrogenase (Carrasco et al. 2018).

Secondary decomposers such as *A. bisporus* typically colonise partly decomposed carbon sources like compost, while tertiary fungal decomposers such as *Agrocybe* spp. are generally associated with soils and plant litter (Grimm and Wösten 2018).

The primary, secondary and tertiary decomposer groupings for edible mushrooms are not discrete categories since secondary decomposers, such as *A. bisporus,* have some capacity to degrade lignin. For example, *A. bisporus* produces at least two lignolytic enzymes, laccase and manganese peroxidase, but these fungi are not as effective at degrading lignin compared to the primary decomposers, such as white-rot fungi (Philippoussis 2009). For example, Chen et al. (2000) showed that *A. bisporus* mainly utilised the polysaccharide component of compost substrate, although some alteration of lignin was observed through partial degradation of its chemical structure.

Some researchers have proposed that the lignin-degrading capacity of *A. bisporus* is considerable enough to make the development of non-composted substrates a research priority. Colmenaris-Cruz et al. (2017) reported on the early work of Till (1962) showing that *A. bisporus* could be cultivated on a non-composted substrate, like autoclaved sawdust. Cultivation of *A. bisporus* on sterilised or pasteurised substrates was explored quite extensively in the mid to late 2000s by research groups such as Penn State University, but these novel approaches do not appear to have been commercially adopted. Although the main focus of this project was to identify alternatives to wheaten straw for manufacturing substrates for *A. bisporus* through composting, other solutions could be developed, including new production systems based on non-composted substrates and/or hydroponics, for example. However, this aspect is beyond the scope of this project.

3.2.1.2 Review of mushroom composting processes and the role of wheaten straw

In this section, we will briefly review the mushroom composting process for *A. bisporus* and discuss the unique function provided by wheaten straw in the process.

In the Australian mushroom industry, the typical compost mix is based on wheaten straw, poultry manure, gypsum and nitrogenous fertiliser (e.g. urea). This is often called synthetic compost since the nitrogen content of the mix is supplemented with urea. In contrast, mushroom compost mixes in North America and Europe are not usually supplemented with nitrogen fertiliser because they are based on stable (horse) manure; they are, therefore, referred to as non-synthetic compost.

Prior to composting, wheat straw is pre-conditioned for a few days prior by soaking with water. This softens the straw, making it more receptive to water. There are two phases of composting — that is phase I and phase II — that are completed prior to inoculation of the finished substrate with the spawn of *A. bisporus*, with spawning sometimes described as phase III.

Phase I composting usually begins by combining the raw carbon sources into rectangular piles (ricks) with vertical sides by the use of a specialised windrow-turner. These piles are

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

formed on a concrete stand with forced aeration and under a roof with open sides. Phase II composting involves pasteurisation and conditioning indoors under controlled conditions for an additional seven to 10 days. More recent developments include the completion of the entire composting process (phase I and phase II) in completely enclosed bunkers or tunnel systems to minimise odorous emissions (principally from ammonia, NH_3).

Phase I is characterised by rapid decomposition of the raw carbon sources under aerobic and thermophilic conditions over a period of seven to 14 days. Peak temperatures in excess of >70°C are common during this period. High temperatures of around 75 to 80°C have been traditionally viewed as necessary to induce Maillard reactions[6] and the fixing of free ammonia through reaction with carbohydrates and lignatious polymers (Miller et al. 1990). The target carbon:nitrogen ratio at the start of phase I is typically around 25 to 30:1, with a total nitrogen content of 1.7 to 1.8%, and moisture content of up to about 75%. The high moisture content is a distinguishing feature of mushroom composting systems compared to urban waste composting. The optimum moisture content in urban waste composting is typically thought to be around 50% (Haug 1993; Epstein 1997).

In phase II, the composting process is tightly managed to create a substrate with the conditions necessary for the growth of the *Agaricus* fungus after spawning[7]. This substrate is selective for *A. bisporus* because it suppresses the growth of weed moulds and disease causing organisms, which would otherwise overwhelm the *A. bisporus*. Miller et al. (1990) provide evidence that this selectivity is based on reducing certain very available carbon compounds during phase II composting and fostering the proliferation of a large and stable microbial community, especially *Scytalidium thermophilum.* This thermophilic fungus colonises phase II compost (seen as firefang), suppressing weed moulds and diseases through ecological competition and antagonism. After spawning, the *A. bisporus* fungus uses this microbial community as a food source.

Phase II has two steps. Pasteurisation at 55 to 60°C for six to eight hours, followed by conditioning at lower temperatures of around 45 to 50°C until ammonia is cleared. A step-wise conditioning process, with a gradual, controlled reduction in temperature, is

[6] Browning reactions of carbohydrates, often referred to as caramelisation.
[7] Spawn of *A. bisporus* is added to the substrate at the end of phase II.

typically followed to convert free ammonia into microbial biomass for the *Agaricus* mycelium to utilise as a food source.

Physical properties of compost substrates

Here we will briefly discuss the important physical (structural) properties associated with compost mixes, which are in turn influenced by the nature of the raw carbon sources. As we shall see later, wheaten straw has unique physical attributes that must be matched if an alternative carbon source is to be viable as a complete substitute in mushroom composting.

Organic matter decomposition takes place in the biofilm surrounding compost particles (Figure 1). This biofilm consists of a thin layer of water within which compost microorganisms do their work (Cao et al. 2013). The moisture content must be in balance, with free air space in the compost matrix to ensure that aerobic bacteria[8] can thrive and do their work. When the moisture content is too high (60% for urban waste composting, greater than 75% for mushroom composting), the pore space between and within particles is filled with water, oxygen diffusion is impeded and anaerobic microorganisms begin to dominate (Haug 1993; Epstein 1997). Anaerobic conditions exacerbate the risk of odorous gases forming in composting systems. Furthermore, the maintenance of aerobic conditions during composting (i.e. at least 5% oxygen content) is generally considered essential for the production of quality mushroom substrate (Miller et al., 1990; Noble and Gaze, 1996). We will explore further below how the unique physical properties of wheaten straw enables mushroom composting mixes to be aerobic even at moisture contents above 70%. Aerobic conditions are not usually possible at such high moisture contents when other Carbon sources are used, even under forced aeration systems.

[8] It is the aerobic bacteria that are largely responsible for the rapid increase in temperature during the initial stages of composting. They degrade the readily available carbohydrates and set the stage for the succession of actinomycetes and thermophilic fungi that follow.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

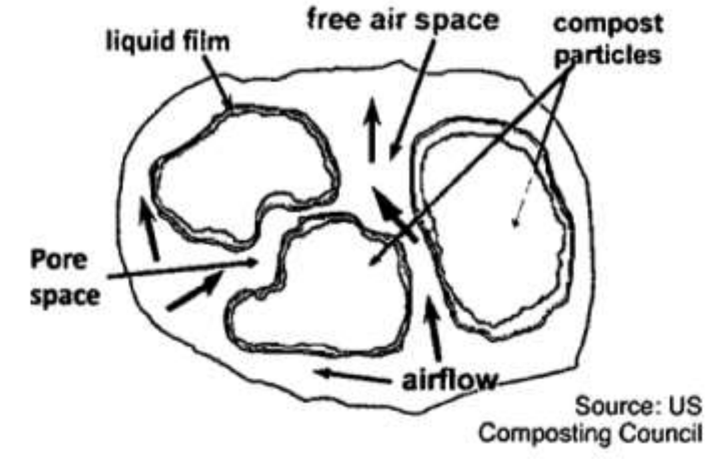

Figure 1. Relationship between water and free air space surrounding composting particles

This brings us to another important issue to consider — the porosity of the mix. Air-filled porosity is the volume of free air space in a mix. Air-filled porosity should be maintained above 40% (volume per volume), and ideally in the 55 to 65% range to ensure that a compost pile is maintained in an aerobic condition (Coker 2012; Rosen et al. 2000). Whilst it is possible to measure air-filled porosity simply with a bucket and scales (Rosen et al. 2000), bulk density (in kg/m^3) is typically used as a surrogate. This is because a linear relationship exists between air-filled porosity and bulk density (Agnew et al. 2003). Bulk density at the start of composting should be below about 650 kg/m^3 (Coker 2012). While mushroom composters desire a dense substrate to maximise its productive capacity, excessively dense compost will be anaerobic and of poor quality (Miller et al. 1990).

The particle size and/or pore size distribution, or the structure, of a compost mix plays a major role in providing the balance between the minimum structural integrity of a pile (to avoid slumping), and adequate porosity. There must be a good combination of finer compost particles that provide energy for the microbes, and larger particles that provide structural support. A pile that is too coarse will not heat up or retain sufficient water. A pile that is too fine rapidly becomes anaerobic because water cannot drain away and diffusion of oxygen into the pile is impeded. Therefore, structure of carbon sources used in compost is essential in composting, and so the structure of wheaten straw is just as important as its chemical components.

Wheaten straw provides both the structural support required for effective composting as well as the food base for the compost microflora.

In urban waste composting, the principle structural component of the mix is often described as the bulking agent, which is usually screened out at the end of the composting process and reintroduced again to prepare fresh mixes. A bulking agent is usually the coarse, woody component of a compost mix.

A bulking agent is generally not used in mushroom composting because it reduces the yield of compost available for growing mushrooms. Screenings can be reintroduced as inoculum in fresh mixes, and can act as a partial substitute for wheaten straw.

Aerobic conditions in mushroom composting are also made possible through the incorporation of gypsum into the mix. In fact, gypsum provides calcium contribution, precipitates suspended colloids and makes the compost less greasy (Lyons et al. 2006). A mushroom compost mix is often described as greasy when weak wheaten straw[9] is used since it has insufficient structural support.

The macromolecular structure of wheaten straw is unique, enabling it to simultaneously provide three important functions: it acts as the principal carbon source for composting; absorbs a large amount of water without compromising air-filled porosity; and provides the structural strength to support the weight of the pile.

Wheaten straw is hollow in the centre (the lumen) with vascular bundles of various pore sizes in the parenchyma (Liu et al. 2005) contributing overall to a highly porous structure (Figure 2). Bouasker et al. (2014) showed that the porosity of dried ground cereal straw exceeded 96%. As a result, the bulk density of these straws was also very low (25 to 47 kg/m^3). Compared to other vegetable fibres, cereal straws are highly absorbent of water. At 20 °C, wheaten straw was found to absorb a quantity of water three times its own weight (Bouasker et al. 2014).

[9] Weak wheaten straw is too soft and collapses too easily under weight.

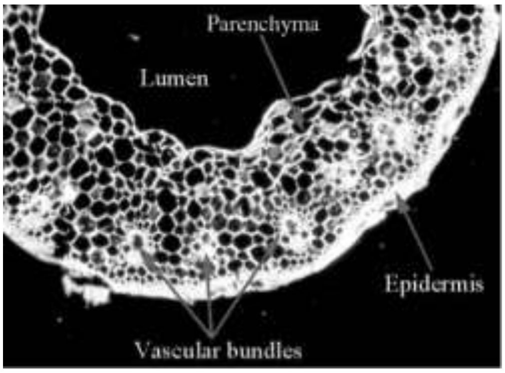

Figure 2. A polarized optical microscopy (POM) image of a cross-section of wheaten straw (Liu et al. 2005)

Bousaker et al. (2014) found that barley straw[10] had even higher water absorbency than wheaten straw varieties (Figure 3). However, barley straw is typically weaker than wheaten straw, so although it can hold a lot of water, it will not support the compost pile when wet.

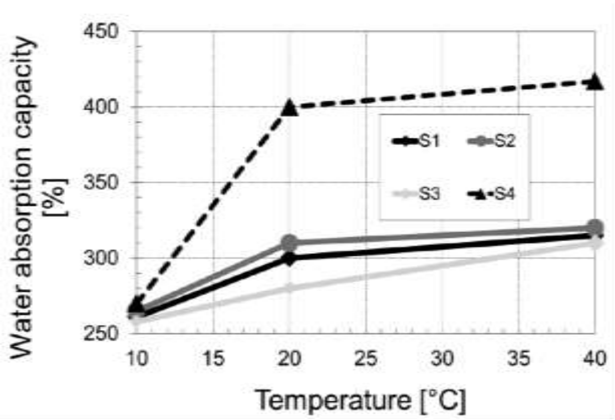

Figure 3. Water absorbency of ground cereal straw. The text S1 to S3 indicates varieties of wheat and S4 a barley variety. Source: Bouasker et al. (2014)

[10] Only one variety of barley was tested.

The strength of wheaten straw is an agronomic feature that has been bred into the wheat plant in order to overcome the problem of lodging[11]. Every experienced mushroom composter knows that there is a great difference between the strength of different lignocellulosic carbon sources — even between different cereal straws or the same type of straw grown in different conditions. The strength of different types of straw can be measured, with Tavakoli et al. (2008) showing that shear strength, bending stress and other mechanical properties were significantly different between wheat and barley straw. The mechanical strength of wheat was between 1.5 and 2.5 times that of barley (depending on the test), and the results depended on the position along the length of the stem being tested. Data which pcompares the bending stress of wheaten and barley straw is shown in Figure 4.

Differences in the mechanical strength between straws is dependent on the chemical composition of the plant carbon sources — that is the relative composition of cellulose, hemicellulose and lignin — the size of the cell structures and vascular bundles (i.e. their number and diameter), and in the case of corn, the thickness of the rind region (Wright et al. 2005).

The balance between moisture content and porosity in any composting system is feedstock and process-dependent[12]. It is unclear to us whether high moisture contents are a necessary feature of every mushroom composting system. We know, for example, that mushroom composters use different approaches to introduce water with some saturating the mix at the start of phase I, whereas others will introduce water more gradually. If an alternative to wheaten straw were trialled, it would have to be composted at its optimum moisture content and porosity, since it is unlikely that the porosity of such mixes would be adequate at the same moisture level that is optimum for straw. In other words, we do not know if it is necessary or not to match the moisture-porosity characteristics of the straw-based pile with an alternative compost mix based on another carbon source to produce quality mushroom substrate.

[11] Lodging is the problem associated with cereals falling over in heavy wind or rainfall. Lodging interferes with efficient mechanical harvesting.
[12] Feedstock is a general term for the raw material used to make a compost pile.

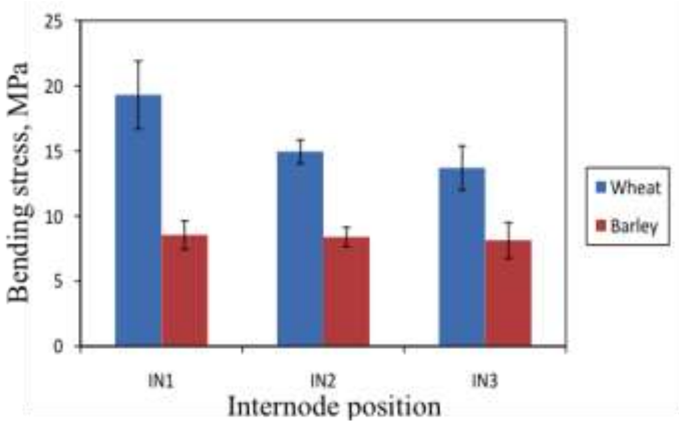

Figure 4. Bending stress for wheat and barley straws at different internode positions (i.e. the position along the length of the stem). Source: Tavakoli et al. (2008)

As we have discussed, the physicochemical composition of the substrate is known to affect mycelium growth, mushroom quality and crop yield (Shekhar Sharma and Kilpatrick, 2000). In fact, the consistency of substrate is critical to mushroom farm productivity. Achieving this consistency of compost is an ongoing issue for the industry in Australia with problems arising due to fluctuations in availability, quality and cost of both of the main components, wheaten straw and chicken manure (Seymour, 2019). We will, therefore, review the physicochemical characteristics of the feedstock used in the manufacture of mushroom substrates.

3.2.1.3 Physicochemical properties of carbon sources

The principal components of mushroom substrates are solid agro-industrial residues, all of which have a common macro-molecular structure of cellulose, hemicellulose and lignin (i.e. lignocellulose). Lignocellulosic carbon sources are also an attractive renewable raw material being considered for the development of other biotechnological processes including ethanol, biogas and syngas production. Competition for lignocellulosic carbon sources may, therefore, increase when and if these developing biotechnological processes are commercialised. This will be discussed further in the Section 3.2.2 below.

Cellulose is the main polymeric component of the plant cell wall and the most abundant polysaccharide on Earth (Baldrian and Valaskova 2008). It consists of a linear chain of several hundred to >10,000 β-1,4 linked D-glucose units. Although it is chemically simple, the intermolecular bonding pattern can make cellulose a very complex structure. In contrast to cellulose, hemicelluloses contain a number of different sugar monomers, not just glucose. Hemicellulose is comprised of shorter chains, which can be branched or unbranched, meaning it is a heteropolymer. The different sugars in hemicellulose are divided into three main groups: hemicelluloses, mannans and galactans. Compared to cellulose, hemicellulose is less resistant to hydrolysis.

After cellulose, lignin is the second most abundant renewable biopolymer in nature. Lignin, representing between 26 to 29% of lignocellulose, is strongly bonded to cellulose and hemicellulose, imparting rigidity and protecting the more easily degradable components from hydrolysis (Philippoussis 2009). Lignin is an aromatic polyphenol macromolecule, 3-dimensional and amorphous in structure.

The proportions of cellulose, hemicellulose and lignin in various agro-industrial residues, along with nitrogen content and carbon to nitrogen ratios, as well as an assessment of their physical properties are shown in Table 1.

A brief review of Table 1 shows that there is considerable variation in the chemical composition of lignocellulosic carbon sources derived from agro-industrial residues. Within this, there is even considerable variation in composition of residues derived from the same species. For example, the lignin content of wheat species reported in Philippoussis (2009) varies from 5.6 to 15% (of dry matter). The Australian Mushroom Industry also reports variability of wheaten straw quality as a result of geographic and production sources (e.g. irrigated vs non irrigated straw), different seasons (year to year variation depending on yield) and the age of the straw in storage (early season straw is too strong, old straw too weak)[13].

On the other hand, Table 1 also demonstrates that there is theoretically a wide range of potential lignocellulosic carbon sources that could be used as ingredients for mushroom compost production. Many different carbon sources have similar lignocellulosic content to wheaten straw, but few of these also match its physical characteristics. The two potential carbon sources that appear to be the closest match for wheaten straw are corn stover and rice straw (Table 1). Sugar bagasse is also a reasonable match, although it contains

[13] A finding derived from discussions with mushroom composters, industry consultants and researchers.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Table 1. Physicochemical properties of various lignocellulosic carbon sources for mushroom composting[1]

Group	Residue	% Cellulose	% Hemicellulose	% Lignin	Cellulose/ lignin	% Ash	% N	C/N	Structure[2]
Wheat	Straw	32–40	21–29	6–15	2.2–5.3	5.6–8	0.4–0.8	49–60	Good
Green waste	Mixed green	25–45	13–30	10–25	2.0–4.0	1.0–4.0	0.5–2.0	28–150	Good-fair
	Grass residues	25–40	13–38	6–18	2.4–3.9	4.2–6.2	1.3–2.5	28–42	Fair-poor
Paper, cardboard	Paper	54–70	12–25	11–30	3.0–6.0	NA	NA	NA	Poor
Spent grain	Brewer's grains	16–18	26–30	27–28	0.6–0.8	4.6–5.0	4.1–4.5	11–12	Poor
Corn stover	Leaves, straw,	36–40	25–29	13–21	2.1–2.3	3.6–.07	0.6–0.9	56–73	Good
	cobs	28–45	35–43	11–17	2.5–2.7	4.4–4.8	0.4–1.1	64–72	Fair
Seed hulls	Rice straw,	23–38	18–29	6–18	3.6–5.9	8.3–18	0.5–1.1	51–58	Fair
	rice husks,	28–43	18–21	22–23	1.3–1.9	17–21	0.3–0.4	100–136	Fair-poor
	sunflower husks	31–43	24–25	23–29	1.1–1.8	3.0–3.3	0.6–0.9	60–72	Poor
Other crops	Cotton trash	52–90	5–20	4–12	5.0–11.0	2.6–8.4	0.3–1.4	40–59	Good-fair
Sugar	Bagasse	27–40	19–30	19–23	1.4–2.2	1.5–5.0	0.2–0.8	120–190	Good
Forestry	Woodchips, sawdust (softwood)	38–50	11–25	26–30	1.4–1.7	0.4–0.5	0.1	310–510	Good-fair
	Woodchips, sawdust (hardwood)	43–45	22–33	24–26	1.7–2.0	0.2–0.3	0.1–0.2	150–450	Good-fair

1. Chemical compositions estimated from the published data compiled by Philippoussis (2009), except for green waste, which was estimated based on the assumption that different sources of green waste can either be grass/leaves dominant (with some wood), very woody (with some grass/leaves), or anywhere in between these extremes
2. Structure grading based on what we know of the physical characteristics of the carbon sources: Good = ideal particle size distribution or porosity for composting. This material will provide good structural support and water holding properties in compost mixes; Poor = carbon sources either too fine or too coarse for use as main structural component during composting; Fair = structural properties between good and poor. This assessment is based on the general relationship between particle size distribution, porosity and water holding capacity. Piles with too many fine particles can be dense and anaerobic, whereas piles that are too coarse can be dry and may not heat up.

more lignin than straw and, therefore, might take longer to break down during composting. Cotton trash and paper contain significantly more cellulose than straw, and brewer's grains much less (Table 1). However, the high nitrogen content and poor structural properties of brewer's grains indicate that it is probably better suited to being a supplementary source of N rather than as a source of carbon.

Corncobs have a relatively high hemicellulose content and moderate lignin content making them potentially easily degradable, but they would need to be ground up to facilitate decomposition. An additional pre-treatment step of size reduction (e.g. with a tub grinder) and screening would assist in the biodegradation of carbon sources derived from wood products.

The ratio between lignin and other more readily degradable carbon compounds (e.g. hemicellulose, cellulose and simple sugars) in lignocellulosic carbon sources is an indication of their biodegradability (Melillo et al. 1989). In Table 1 we see this represented as the cellulose/lignin ratio, with higher numbers indicating higher potential biodegradability. It is notable that, in general, the field-based residues such as wheaten straw, green waste, corn, grass and rice residues have higher cellulose/lignin ratios than processing residues such as grains, seed hulls/husks, bagasse and sawdust. Notable exceptions to this rule are cotton processing waste and waste paper.

Woodchips/sawdust also have very high carbon:nitrogen ratios. High carbon:nitrogen ratios can be adjusted by adding additional nitrogen. Whilst the particle size of sawdust is too fine to enable large compost piles to be constructed, woodchips can be too coarse to hold sufficient water. However, bark is superior to woodchips in this regard. Pine bark, for example, is highly porous with a total porosity of around 80%, high aeration capacity and a good capacity for water retention in its micropores (Castillo 2004).

Bagasse is also in this category (high carbon:nitrogen ratio), although its structural properties are generally considered good for composting (Meunchang et al. 2005). A consideration for bagasse is that it generally has a low pH (around 4-5), and its inclusion in a composting mix has been shown to conserve nitrogen (Meunchang et al. 2005). This could be advantageous for mushroom composting since one objective of phase II is to conserve available forms of nitrogen (ammonium and ammonia) in the biomass of microbes. However, bagasse also has a lower cellulose/lignin ratio than wheaten straw (Table 1), meaning that it is potentially less biodegradable.

Waste paper has a high cellulose content and good potential biodegradability but its structural properties compared to wheaten straw are inferior (Table 1). Cotton trash also has a high cellulose content and potential biodegradability. Costa et al. (2017) report that its nutrient content is high and compost manufactured from it may have high electrical conductivity (EC, a measure of soluble salts)[14].

An additional consideration is ash content, which can vary widely between and within raw carbon sources (Table 1). Ash is a measure of the mineral (non-organic) content of raw carbon sources or compost. Although it is frequently measured to monitor the progress of decomposition, ash does not contribute much to substrate quality per se[15]. For this reason, an ash content of over 20-25% in compost is generally thought to be the upper limit[16]. The high initial ash content of some carbon sources (e.g. rice hulls) may be a factor limiting their inclusion in a compost mix.

Although direct substitution of any proposed alternative for wheaten straw may be possible, the variability of the material is a separate issue that needs consideration. Variability in the physicochemical properties of raw carbon sources can affect the composting process and compost quality, which in turn influences mushroom production. To some extent, variability of compost raw carbon sources is unavoidable, and compost producers are accustomed to managing it by varying the blend, or by using organic and/or inorganic nutrient supplements. For such management to be feasible, composters need to have a sound understanding of the physicochemical characteristics of the various components of the mix, and how these vary over time and between sources. Successful composting always starts with getting the mix right in the first instance, but this pre-supposes that the physicochemical properties of each component of a mix are known. Once a mix is prepared

[14] Costa et al. (2017) found that the potassium content of cotton trash was relatively high. High EC in mushroom substrates can sometimes be an impediment to yield. The industry reported that EC also restricts the reuse of spent mushroom substrate in fresh compost mixes.

[15] As organic matter is broken down in the compost mix, the concentration of the mineral component (i.e. ash content) increases. Raw carbon sources that are high in ash content will result in composts that have higher ash content than raw carbon sources with low ash content. The principal food source in substrate for *A. bisporus* is the organic matter content, not the ash content.

[16] Personal communication with mushroom composter.

and composting begins, it is usually impractical to make significant in-process changes to correct for poor compost quality (Straatsma et al. 2000).

The extent of variation in the physicochemical properties of carbon sources differs between types, seasons and sources. One example is municipal green waste. Green waste is a term used for plant carbon sources collected from various sources — from woody roadside vegetation to kerbside bins containing a high proportion of grass clippings and soft greens. A survey conducted in Melbourne showed that the major influence on variability of green waste was associated with seasonal fluctuations in grass clippings (Wilkinson et al. 2000). As a result, carbon:nitrogen ratio of composted products manufactured from green waste in Melbourne can vary anywhere between 18:1 to 134:1 (Wilkinson et al. 2002). In some suburban areas in Melbourne, the autumn leaf fall is also a significant event, as it is in North America and Europe (Finstein and Hogan 1992; Norsdedt et al. 1993). Use of such alternative carbon sources (green waste), would require that the specific exact source (e.g. kerbside bins, roadside) and composition (e.g. soft greens or woodier fraction) be considered, as its use in mushroom compost has the potential to create great variability in compost quality and uncertainty with respect to mushroom quality and yields[17].

Whilst some published tables of the characteristics of various carbon sources are available (like the one in Table 1), they can only be used as a starting point in any investigation of potential lignocellulosic carbon sources for substrate production. Samples of any proposed alternative carbon source should be sent to a laboratory for analysis well in advance of it being used. The hard data from the laboratory analysis can then be used to calculate an ideal ratio of the material in a mix, with respect to ratio of carbon:nitrogen, moisture content, pH, porosity and bulk density for composting. This will ensure that compost production can be managed without any adverse effects and gives the best opportunity to produce a substrate of consistent quality.

[17] The industry also has concerns about the physical properties of green waste, though these could possibly be overcome through appropriate pre-treatment such as grinding and screening. The quality of green waste is often badly affected by impurities such as plastic, glass and metals.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

3.2.1.4 Summary of the technical review

We have seen that there are many carbon sources with similar chemical characteristics to wheaten straw, most of which could feasibly be used as partial substitutes in the composting process. Complete substitution is a more difficult prospect to consider, given the unique macromolecular structure that wheaten straw brings to a composting mix — that is its ability to act as the principal carbon source for composting, absorb a large amount of water without compromising air-filled porosity, and provide the structural strength to support the weight of the compost pile.

It should also be emphasised that this review has focused largely on finding alternatives to straw for inclusion in the mushroom composting process, which is the traditional approach used for substrate preparation for *A. bisporus*. There could be merit in exploring potential systems for straw-free substrate preparation that do not involve composting. Many alternative carbon sources may have limited usefulness in a compost mix because of their fine structure for example, but they may be considered as an option if/when non-composted substrates are developed.

In Section 3.1.4, we identified 10 substrates as worthy of assessment in this technical feasibility of carbon alternatives to wheaten straw. Within these 10 substrates, we looked at specific streams. Terms likeseed hulls are too broad to be ultimately useful, so we reviewed specific types of seed hulls. The final specific list was determined both by the technical feasibility of their use as a substitute for wheaten straw, and is shown in Table 2.

We assessed the physicochemical properties of these carbon sources by consulting Table 1, other published sources and feedback from industry. Where possible, we identified limiting factors associated with them and from that concluded whether each material was suitable as either a partial or complete substitute for wheaten straw (Table 2). There is some uncertainty in many of the results since it is greatly dependent on the quality of the carbon sources available, which may vary considerably between sources and from batch to batch within a source. Furthermore, few definitive conclusions can be drawn without having conducted composting and mushroom production trials. For this reason, qualitative ratings were given, where "*+++*" means it is highly suitable, for example, and "-" not so suitable.

Table 2. Technical feasibility of various carbon sources as partial or complete replacements for wheaten straw on a scale of highly unfeasible (---) to highly feasible (+++)

Type	Physicochemical properties		Limiting factors	Potential substitution for wheaten straw		Comments
	Chemistry	Physics		Partial	Complete	
Green waste	+++	+++	Variability, contaminants	+	?	Various streams of green waste; requires significant pre-treatment, screening etc
Stable (horse) bedding	+++	++	Variability	+++	++	Ideal with straw as bedding but not sawdust
Paper	+++	-	Structure	++	-	Trichoderma risk according to industry
Cardboard	+++	+	Structure	++	-	Trichoderma risk
Spent grain	++	-	Structure, N content	++	-	NA
Corn cobs	+++	+	Structure (bulky)	++	-	May require pre-treatment, screening
Corn stover	+++	+++	May require pre-treatment	+++	+++	Excellent potential alternative
Almond hulls	+++	-	Structure	+	-	NA
Canola straw	+++	+++	?	+++	++	Risk of pesticide contamination
Oil seed meals	++	-	High N content	++	-	NA
Olive & grape marc	++	+	?	++	-	NA

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Table 2 (continued). Technical feasibility of various carbon sources as partial or complete replacements for wheaten straw on a scale of highly unfeasible (---) to highly feasible (+++)

Type	Physicochemical properties		Limiting factors	Potential substitution for wheaten straw		Comments
	Chemistry	Physics		Partial	Complete	
Hay (wheat)	+++	+++	Quality	+++	?	Aged or spoiled hay not as strong as straw. Likely to be mouldy
Cotton trash	+++	++	Pesticides?	+++	+	Less degradable than straw
Rice hulls	+++	-	Structure	++	-	Dry and dusty
Sugar bagasse	+++	+++		+++	+++	Excellent potential alternative
Wood chips	++	++	Woody, bulky	++	+	Both bark and woodchips would require pre-treatment. They are less degradable than straw
Bark	++	+++	Woody, bulky	+++	++	
Sawdust	+++	+	Structure	+++	-	Less degradable than straw
Recycled pallets	+++	++	Metal contamination?	+++	++	Particle size dependent (pre-treatment required). Less degradable than straw. Contamination with nails?

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

All substrates in Table 2, the same 10 substrates as listed Section 3.1.4, are technically feasible for use as a partial substitute for wheaten straw. These include:

1. Green waste
2. Bedding or litter from the intensive animal industries (e.g. horse, pig and chicken)
3. Paper and cardboard
4. Spent or fresh grain
5. Corn stover
6. Seed hulls (e.g. almond and rice hulls)
7. Oil seed waste (e.g. oil seed meals, olive and grape marc)
8. Other straws and crop waste (e.g. canola, cotton, hay)
9. Sugar bagasse
10. Forestry residuals (e.g. wood waste, bark, woodchips and sawdust)

We have included these sources as they can theoretically be composted along with wheaten straw when included at between 5 to 30% of the mix. The most common issue limiting the percentage inclusion in a mix is the potential negative impact of the substrate on the moisture content-porosity relationship in a compost pile.

Five of the carbon sources listed in Table 2 are technically feasible as complete alternatives for straw, subject to quality criteria and variability. These are:

1. Stable (horse) bedding — based on the fact that this type of material is already widely used throughout the world for mushroom composting. There is less certainty, however, about the suitability of stable bedding based on sawdust-manure rather than straw-manure.
2. Corn stover — may be suitable based on physicochemical properties. Cobs ideally should be ground up to smaller particles.
3. Other straws and crop waste, specifically cotton trash and canola straw — may be suitable based on physicochemical properties.
4. Sugar bagasse — based on its excellent physicochemical properties
5. Forestry residuals, wood waste, wood chips and bark — subject to appropriate pre-treatment such as grinding and screening.

We have included canola straw in this list based on research conducted in the UK (Noble et al. 2002). They found that compost based on canola straw could be as productive as wheaten straw. Canola straw also reduced odorous emissions since it maintained its structure and porosity better than wheat straw. There is some uncertainty about whether

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

this is applicable to Australian canola since one mushroom composter described canola straw as weaker than wheaten straw.

We could not come to any definitive conclusion on the suitability of green waste and hay (Table 2). As discussed previously, green waste is a catch-all phrase for many different urban plant waste streams. It *could* be possible to use clean, single source green waste streams as discussed in Section 3.1.3, but these would then need to be ground-up and screened/blended to create a mix of suitable particle size for mushroom composting. Any hay that is used for mushroom composting is likely to only be available when it is not suitable for feeding to livestock (spoiled hay). It may still have suitable strength but this is doubtful, and it may also be mouldy.

To sum up, it is theoretically feasible to grow *A. bisporus* in a wide range of lignocellulosic compost substrates. However, theoretically feasible is not the same as commercially viable. Further research and development will need to be undertaken to determine the commercial applicability of different substrate alternatives. This will be discussed in further detail in sections below.

3.2.2 Stage two: Procurement costs and availability

A review of procurement costs of potential carbon alternatives and the availability of potential carbon sources in mushroom growing regions is presented in this section, with only those carbon sources short-listed in Section 3.1.4 considered below. These are:

1. Green waste
2. Bedding (horse)
3. Paper and cardboard
4. Spent or fresh grain
5. Corn stover
6. Seed hulls (e.g. almond and rice hulls)
7. Oil seed waste(e.g. oil seed meals, olive and grape marc)
8. Other straws and crop waste (e.g. cotton, canola, and hay)
9. Sugar bagasse
10. Forestry residuals - wood waste, wood chips, sawdust and bark

This procurement assessment was undertaken as part of the feasibility study, as potential alternative carbon sources may be technically feasible, but can also be too costly or have limited availability. Different forms of substitution or reuse of spent substrates or compost are not discussed in this section, due to the feasibility of these options being related to physical and chemical constraints, rather than procurement. Finally, we interviewed stakeholders — either by phone or by email, asking them about their experience with and thoughts on the carbon sources listed above. This stakeholder feedback is presented in Attachment B.

Note that the costs presented in this section may or may not include transport, as detailed below, and are only representative of costs at the time of this report's writing. A summary of this assessment is presented at the end of this section.

1. Green waste

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Green waste	-ve to 190[c]	1.9 Mt	Low[1]	None	Fail[1]

1 In most metropolitan regions, supply and processing contracts are already in place. There are, however, fewer contracts in place for green waste in regional areas
a Includes transport costs to Canberra as a proxy
b Includes limited transportation costs
c Includes no transportation costs
-ve indicates potential for payment to contractors who remove green waste for processing

A 2011/2012 survey of organics processing facilities, excluding those operated by local councils, was conducted by the Department of Sustainability, Environment, Water, Population and Communities and found that 1.9 Mt of green waste was disposed of across Australia annually (Campbell 2012). New South Wales, Victoria and Queensland were the largest producers of this waste, generating 600,000 t, 480,000 t, and 410,000 t respectively. Around 200,000 t was produced in South Australia.

A number of different waste collection companies as well as municipal waste collection facilities or information lines were contacted for the purposes of this report. The availability of green waste is greatly limited in the metropolitan regions due to long-term supply contracts being in place between local governments and processing companies. In Sydney, the City of Sydney Council pays companies to collect and/or remove green waste. As such, if mushroom contractors were to win these contracts, they would potentially generate income through the use of green waste for mushroom composting. This is not the case in South Australia, however, with green waste delivered to the City of Adelaide's facilities where it is processed, turned into mulch, and sold for approximately $62.5 to $190 per tonne. Green waste is composted in most metropolitan areas and turned into soil conditioners and mulches. Mushroom composters could compete for these contracts, but this would be a high-risk strategy based on uncertainty around the quality and variability of the material.

MURRANG
earth sciences ™

✘ Green waste: unviable

- Inappropriate physical properties
- High uncertainty of quality
- Cheap purchase cost
- Abundant supply
- Development potential

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

2. Bedding from intensive animal industries

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Animal bedding	12.50[c]–22.50[b]	NA	Unknown	None	Fail[1]

1 Stakeholder feedback indicates limited viability due to physical properties
a Includes transport costs to Canberra as a proxy
b Includes limited transportation costs
c Includes no transportation costs

Approximately 9.8 Mt of animal manure was produced in Australia in the 2016 to 2017 year (Pickin et al. 2018), with a substantial proportion of this generated by feedlots in grain-growing regions (Watts and McCabe 2015). Tens of thousands of tonnes of manure are diverted for composting, with 451,000 t processed in the 2011/2012 year by organics recycling facilities across Australia (Campbell 2012).

A study conducted by Blue Environment found that 16,000 m^3 of stable (horse) was generated by 2,960 horses on 25 properties per annum, within two shires in Victoria (Grant 2012). An estimated total of 50,000 tonnes per year was established in the area of Strathbogie, however, it was specifically noted that this material had lower value for mushroom composters than had previously been the case due to sawdust replacing wheaten straw as the preferred bedding substrate. Based on the value of stable bedding to local home gardeners, the cost of transport to purchasers within 10 km, and handling, the horse bedding was estimated to have a value of $12.50 to $22.50 per tonne.

Stakeholder feedback indicates horse manure on straw bedding was once a popular source of carbon for mushroom farmers (Attachment B). This is consistent with the findings of our literature review (Section 3.2.1). As straw has become increasingly expensive, however, stables have moved to the use of sawdust bedding, and the supply of horse manure to mushroom composters is now sporadic and its quality described as inconsistent.

Based on the information in this section, stable bedding is considered to not be a viable complete substitute to wheaten straw, due to the use of sawdust as bedding substrate.

Feedback from stakeholders in the Australian mushrooming industry finds that this sawdust based manure is an inadequate as a complete substitute for wheaten straw. However, it may be appropriate as a partial substitution in cases where it is not already being used by composters.

✘ Stable bedding (sawdust): unviable

- Inappropriate physical and chemical properties
- Limited supply

3. Paper and cardboard

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Shredded	90[c]	*5.6 Mt	Unknown	NA	Pass?[1]
Cardboard	120–240[c]	*5.6 Mt	Market dependent	NA	Fail[2]
Soft-mixed	50–60[c]	*5.6 Mt	Reliable	NA	Pass?[1]

**Total paper and cardboard waste produced in Australia annually*
1 Viability limited by physical constraints
2 Viability limited by cost
a Includes transport costs to Canberra as a proxy
c Includes no transportation costs

Australia produced 5.6 Mt of paper and cardboard in the 2016 to 2017 year (Pickin 2018), with paper including soft-mixed and shredded paper types. Sixty percent of the paper and cardboard produced in the 2016 to 2017 year was recycled, and 43% of this was recycled overseas. While generation of paper and cardboard waste is decreasing substantially (15% per annum) on a per capita basis, it is increasing at a rate of 1% overall. Importantly, the main areas that generate these wastes are the urban centres, indicating that sources of paper are nearby mushroom composters, with Visy the main processor of cardboard and paper waste in Australia. Visy supplies soft-mixed paper at a rate of $50 to $60 per tonne. The cost of cardboard[18] is far higher and fluctuates based on international demand, with approximate costs of $120 to $240 per one tonne pallet. The use of shredded paper for use by the chicken industry as litter has been costed at $90 per tonne (Watson and Wiedemann 2018).

Stakeholder feedback indicates that paper and cardboard could be used in partial substitution, however, not at rates of greater than 10% due to their effects on porosity. There were also concerns by composters that the fungus *Trichoderma* may increase in association with the paper, with substantial negative impacts to mushroom productivity as a result. No stakeholders engaged for this report had used cardboard or paper previously.

Based on the information in this Section, cardboard is not viable as an alternative to wheaten straw due to unreliable supply. Paper in general is considered unviable due to its physical properties, which decrease the porosity needed within mushroom compost. It is considered to only be viable in the form of a partial substitute for wheaten straw as a result of these limitations. Due to its cheap cost, chemistry and reuse opportunities, paper may be developed into a potentially viable substrate with further research. This is discussed in more detail later in the report

? Paper and cardboard: potentially viable

- Inappropriate physical properties
- Cheap purchase cost
- Abundant supply
- Development potential

[18] Soft mixed paper: sourced from curbside recycling including newsprint, cardboard, and white paper.

4. Spent grain

Type	Cost ($/t)	Volume available (t)	Reliability of supply	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Spent grain	*85[b]*	Low	Low	Unlimited	Fail[3]

a Includes transport costs to Canberra as a proxy
b Includes limited transportation costs
3 Viability limited by cost & supply

Indicative costs for spent grain are approximately $85 a tonne from feedstock supplier Castlegate James, one of Australia's largest feedstock suppliers. Breweries such as Coopers in South Australia have had contracts with Castlegate James for more than 20 years, and as such it is unlikely feedstock can be purchased from breweries outside these contracts. Castlegate James stated that spent brewer's grain had a dry matter content of 23%, with the delivery cost of $85 per tonne applying to facilities within 100 km of their depot. Supplies of spent grain are limited, however, with many contracts for supply being long term (i.e. five-years). While some spent grain is low in nitrogen, due to a filter mash being used in beer processing, this is not the case for most breweries, and spent grain is, therefore, high in nitrogen. Further information from mushroom composters shows that the unreliable supply makes spent grain an unviable alternative to wheaten straw.

✘ Spent grain: unviable

- Appropriate physical and chemical properties
- Unreliable supply
- Potentially unviable cost

5. Corn stover

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Corn stover	NA	Up to 960,000	Moderate	Irrigation limited	Pass[3]

a Includes transport costs to Canberra as a proxy
3 Viability limited by cost & supply

Just over half the corn in Australia is grown in New South Wales, with the remaining production occurring in Victoria (Beckingham 2007). Stakeholder feedback indicates this production occurs under irrigation in New South Wales' Riverina district. Of the corn produced in Australia, 80% goes to the food-processing sector. This means that there is significant concentration of corn waste by-products for potential distribution to the mushroom composting industry. Simplot Pty Ltd, located in Bathurst (within the Sydney Basin) is the only corn processor in New South Wales (NSW DPI 2007). Simplot's harvest begins in November and finishes in June, although corn harvest in New South Wales generally occurs between March and April. All of Simplot's corn stover, which includes both maize straw and the processed corn cobs, are currently sold to the feedstock industry for an undisclosed sum. Substantial volumes are available, however, with 3,000 to 4,000 t a day collected during the harvest period. If the eight months of harvest is estimated to last 240 days, this means 960,000 t of corn stover is produced per year.

Corn stover has been trialled by the mushroom composting industry before and was considered by some composters to be a highly viable alternative to wheaten straw due to its physicochemical properties. Despite this, corn stover is not widely used due to cost limitations for transport from the irrigated land in the Riverina to the major cities. As a result the mushroom industry (through stakeholder feedback) consider corn stover less viable.

? Corn stover: potentially viable

- Desirable physical and chemical properties
- Reliable supply
- Potentially unviable cost – requires negotiation
- Transport limitations

6. Seed hulls

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	***230[c]–375[a]***	***Limited***	***Market dependent***	***Climate limited***	***NA***
Almond	Unknown	Unknown	Market dependent	Rainfall/irrigation	Fail[3]
Rice	NA	Zero during drought years	Market dependent	Rainfall/irrigation, climate limited	Fail[3]
All	Unknown	87,000	Market dependent	Rainfall/irrigation	Fail[3]

a Includes transport costs to Canberra as a proxy
c Includes no transportation costs
3 Viability limited by cost & supply

87,000 tonnes of nut waste was generated within Australian in the 2016 to 2017 financial year, with 90% of this sent to compost (Arcadis 2019). While data for this waste was not found within the timeframes available for this report, feedback from stakeholders indicates that most almond hulls are being used by the livestock industry as fodder. Nut hulls have been considered for use as chicken litter, with an estimated cost of $117 per tonne for almond hulls specifically (Watson and Wiedemann 2018).

Seed hulls, such as cotton and rice, are already used in mushroom composting due to their use in chicken bedding. Chicken bedding is a widely used source of manure for mushroom composters. It can only be used in limited amounts, however, as the sawdust and/or paper on which it is based negatively impacts the porosity of mushroom compost. Cotton hulls can also negatively impact equipment, as they are easily mobilised in the wind and get caught in, and damage, machinery.

A number of organisations were contacted regarding the supply of rice hulls. While some were able to supply small volumes (i.e. by the bale), there has not been a bulk supply of rice hulls over the three years prior to this report due to drought conditions. Rice straw is used successfully by mushroom composters in other parts of the world.

Based on the information presented in this section, seed hulls are an unviable alternative to wheaten straw due to their limited supply. When available, they could be used as a partial substitute for wheaten straw.

✘ Seed hulls: unviable

- Physical limitations
- Unreliable supply
- Potentially unviable cost

7. Oil seed waste

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Canola meal	300–400[c]	Unknown	Feedstock competition	Rainfall limited	Fail[3]
Olive marc	50[c]	62,500*	Low	Rainfall/irrigation	Fail[3]

**Based on 2008 data*
a Includes transport costs to Canberra as a proxy
c Includes no transportation costs
3 Viability limited by cost & supply

Canola has grown to become the third largest crop in Australia, with a record 4 million tonnes produced in the 2012 to 2013 year (AgriFutures 2017c). New South Wales, Victoria and South Australia are the second, third and fourth biggest producers of canola in Australia respectively (Western Australia is the largest producer). Canola seed is harvested and crushed for oil, with the waste product termed meal. This meal is a high-protein feed for intensive livestock operations including cattle, poultry, and dairy, with the proportion of meal used depending on pricing and availability of oilseed meal as well as other grains. The Australian Oilseeds Federation supplies information regarding oilseed. Oilseed costs vary daily and are driven not just by Australian factors but also by global demand and international drivers. Approximate price ranges are $300 to $400 per tonne, with this pegged against soybean meal, which is sold at a rate of $300 to $600 per tonne.

Oil seed waste, and specifically canola waste, is considered to be a highly viable source of carbon for mushroom composters, except for its very substantial cost limitations. If it were to be available and could be supplied at an appropriate price, mushroom composters would use it.

Approximately 62,500 t of olive marc was produced in Australia in 2008 (Nair and Narkham 2008), with information presented in Section 3.1 indicating that these have some physical and chemical properties that would be beneficial to mushroom compost. While procurement costs of this solid waste were estimated at $50 per tonne, this estimate was based on free supply of olive waste generated by olive groves rather than supply to external consumers.

Based on the information presented in this section, oil seed waste is an unviable alternative to wheaten straw, due to the limited supply available.

✘ Oil seed waste: unviable

- Appropriate physical and chemical properties
- Unreliable supply
- Unviable cost

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

8. Crop waste (e.g. canola and cotton straw, and wheaten hay)

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	***230[c]–375[a]***	***Limited***	***Market dependent***	***Climate limited***	***NA***
Total hay	100–400[a,c]	3.5 Mt†	Feedstock competition	Rainfall/climate limited	Pass[3]
Cotton trash	0[c]	500,000**	Market dependent	Rainfall/irrigation, climate limited	Pass[4,5]

†Based on 2013-2014 data
***Based on volumes available from single supplier per annum*
a Includes transport costs to Canberra as a proxy
c Includes no transportation costs
3 Viability limited by cost & supply
4 Viability limited by transportation distance
5 Viability limited by potential climate impacts

The main grain growing regions in Australia are the Northern region, encompassing northern New South Wales and Queensland; the Southern region, encompassing Victoria, Tasmania, and South Australia; and the Western region, being Western Australia (GRDC 2019). Of these regions, it is the Southern region that is relevant to this report, due to the main mushroom growing centres (i.e. the Sydney Basin, metropolitan Melbourne, and Adelaide) being located nearby.

While hay is traditionally made from dried, flowering grasses, in Australia it is also made from lucerne and canola. Victoria and south-eastern South Australia are the highest hay production regions in Australia, with 40% of Australia's total hay and silage production occurring in Victoria (Peace 2017). Only 40% of the hay produced is sold each year with the total hay and silage production being approximately 3.5 Mt in 2013 to 2014. Just over 0.9 Mt of this hay and silage was exported overseas. In dry years, where crops fail and are harvested early for resale as hay, production can increase to 4.5 Mt per annum (Peace 2019). It is assumed that production of wheaten straw is included in this statistic.

Wheat is the largest crop in the Southern region, with 1,550 ha projected to be harvested in in Victoria, 2,000 in South Australia, and 2,500 in New South Wales in the 2019 to 2020 year (ABARES 2019). Barley and canola are the other main crops grown in these areas. The area under these crops in Victoria, South Australia, and New South Wales is less than half that under wheat. Barley and canola harvests had a combined total of 13 Mt in the 2017 to 2018 year compared to wheat with a harvest of 21 Mt (ABS 2019). The sum of all alternatives to wheat (i.e. barley, canola, sorghum, oats and cotton) was 16 Mt, 5 Mt less than wheat alone in 2017 to 2018. This indicates a more limited supply of by-products from these crops than is currently available from wheat. While sorghum is the most significant grain crop in Australia, it is limited to the Northern (i.e. Queensland and northern NSW) region (AgriFutures 2017a).

Price increases or hay are correlated to increasing hay production. This is due to the demands that drought places on livestock fodder. Hay prices fluctuate from $100 per tonne in a low-demand year when growing conditions are good and less hay is needed to $400 a tonne in years such as 2018, when demand is high and supply of hay increases due to the harvest of failed crops as hay. Costs for supply of cereal crop residue to the chicken meat industry for litter were estimated to be $170 per tonne (Watson and Wiedemann 2018). The increase in cost of cereal crop residue impacts mushroom composters, with one grower in South Australia seeing a doubling in production costs (Forbes 2019). Based on this information, replacing wheaten straw with hay is undesirable as it has the potential to substantially increase production costs.

Cotton trash is comprised of the sticks and leaves incorporated with the cotton that comes into gins for processing. The supply of cotton trash is strongly season dependent, with demand for the trash outstripping supply in some years — by July 2019 the supply of cotton trash from Southern Cotton, in Whitton, for example, was 100% allocated for the 2020 year. The cotton processor Southern Cotton, can produce up to 500,000 t of cotton trash, depending on the year, and charges only a nominal loading fee of $6, otherwise giving it away for free. Haulage of cotton trash was considered a major limitation for mushroom composters, with cotton trash otherwise considered a good alternative to wheaten straw by some — although not all.

Based on the information presented in this section, crop waste could be considered a potentially viable alternative to wheaten straw if transport costs can be overcome. Other crops also have potential to be limited by climate change scenarios, however, similar to that of wheat.

? Crop waste: potentially viable

- Appropriate physical and chemical properties
- Unreliable supply
- Climate limitations
- Transport limitations

9. Sugar bagasse

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Sugar bagasse	9[c]	Unlimited	Moderate	Moderate	Pass?[4]

a Includes transport costs to Canberra as a proxy
c Includes no transportation costs
4 Viability limited by transportation distance

Supply of sugar is limited to the Northern region of Australia — that is northern New South Wales and Queensland (Agrifutures 2017b; Watson and Wiedemann 2018). Therefore, the transport of sugar bagasse to the main mushroom growing centres in the southern states makes this otherwise potentially highly desirable waste stream a sub-optimal alternative to wheaten straw.

Information provided by the Australian Sugar Milling Council indicates that supply of bagasse outstrips demand, with its value based on its use by the sugar mills themselves as a fuel. Based on this use, it has a nominal value of $9 per tonne. As with cotton, however, it is haulage that has limited the use of sugar bagasse in the mushroom composting industry. Stakeholder feedback suggests sugar bagasse is the best alternative, or an even better alternative, to wheaten straw. It is noted that recent research indicates that climate change will have negative impacts on the sugar industry, largely as a result of changing rainfall seasonality (Linnenkuecke 2019). This may also limit the usefulness of sugar bagasse.

Based on this information, the distance and cost of transport of sugar bagasse to mushroom composters is the main factor limiting the use of this material as a viable alternative to wheaten straw. Feedback from mushroom composters indicates this substrate could otherwise be a highly valuable ingredient in mushroom compost.

? Sugar bagasse: Potentially viable

- Appropriate physical and chemical properties
- Successfully trialled
- Cheap purchase cost
- Abundant supply
- Transport limitations

Figure 5. Sugar bagasse. Sourced from Creative Commons: "*Bagasse*" by Tele Jane is licensed under CC BY 2.0

10. Forestry residuals (wood waste, bark, woodchips and sawdust)

Type	Cost ($/t)	Volume available (t)	Supply reliability	Climate limitations	Viability
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Woodchips and bark	Negotiable	15,000-20,000****	Market dependent	NA	Potentially[1]
Sawdust	Unknown	500,000	Strongly market dependent	NA	Fail[1,3]
Reused sawdust	24[c]	Unknown	Market dependent	NA	Fail[1]
Recycled pallets	125[c]	48***	Market dependent	NA	Fail[1]

**Based on 2013-2014 data*
****Based on volumes available from single supplier per day*
*****Based on volumes available from single supplier per annum per plant*
1 Stakeholder feedback indicates limited viability due to physical properties
3 Viability limited by cost & supply
a Includes transport costs to Canberra as a proxy
c Includes no transportation costs

The chicken industry is an important consumer of organic waste products, with wheaten straw, woodchips and sawdust the primary forms of litter used in chicken production. Decreasing supply of these carbon sources has also impacted the chicken industry. Sawdust has increased in cost above the consumer price index, costing $18 to $30 per m^3 — equivalent to $90 to $150 per tonne (Watson and Wiedemann 2018).

Recycled pallets are used in the chicken litter industry as an alternative to wheaten straw, sawdust and woodchip, at an average cost of between $15 and $25 m^3 (Watson and Wiedemann 2018). This is in comparison to reused litter based on sawdust, which has an estimated production cost of $24 per tonne to the chicken farming industry. Sawdust generated from recycled pallets is supplied in Sydney by Direct Pallets, who were contacted as part of this research. This company quoted the cost of Biobedding, the recycled pallet sawdust product for the chicken industry, at a rate of approximately $25 per m^3 ($125 per tonne), with up to 240 m^3 deliverable per day.

Demand for sawdust is strong with specialist suppliers such as Pollards stating they would be unable to supply in amounts of hundreds to thousands of tonnes per annum.

Midway, Australia's largest woodfibre processor and exporter, consistently produces 15,000 to 20,000 t of material comprised of a mix of wood chips and bark at both its Portland and Geelong mills. No consistent market for this product has been created by Midway, with the price negotiable.

While larger mushroom composters contacted for this research have the capacity to break down woodchip and sawdust, some producers considered these products to be unviable due to the composting time required to do so (Section 3.2.1). Some larger producers were also dubious of using woodchips and sawdust despite their capacity to break it down. This is because mushroom composters internationally are not using it, despite the substantial investment in some parts of the world into different mushroom substrates. Based on this information, we consider it likely that sawdust and woodchips could be viable for use in mushroom compost, but this use has not been successfully adopted as a full replacement for wheaten straw at a commercial scale and requires development.

Sawdust is known to negatively impact the density of mushroom compost, resulting in a poorer substrate mix for composting processes. The use of an alternative substrate such as woodchips or sawdust would require a substantial change in composting systems, as none of the current composting infrastructure is designed to work with this type of substrate. Further research and development in this area would be required.

Based on this information, sawdust is probably not viable as a complete replacement for wheaten straw in mushroom compost due to its impact on compost structure and inappropriate chemical properties. Woodchips and bark have the potential to be used in mushroom compost, however, and would require processing, research and development to form an appropriate growth substrate.

? Forestry residuals: Potentially viable

- Sawdust unviable due to physical properties
- Woodchips and other forestry residuals are potentially viable
- Chemical limitations
- Available supply
- Requires development

3.2.2.1 Summary: Procurement costs and availability

This analysis shows that many of the potential carbon alternatives to wheaten straw are limited by supply and cost issues (see Table 3 for a summary). Many agricultural residues are already in demand by the livestock industry as stockfeed, however, some of these may be available on an opportunistic basis. They would be incorporated in a mushroom composting operation only when available, so it is unlikely that they would be used as complete substitutes for wheaten straw. Developing new substrates without wheaten straw would not be feasible without security of supply.

Sugar bagasse, corn stover and woodchips/bark appear to be abundantly available and they are also technically feasible for use a complete replacements for wheaten straw (Table 3). In addition to this, some waste paper streams are abundantly available and could be used as a regular partial replacement for wheaten straw (Table 3).

We consider that a mix of wood chips and bark, similar to that available from Midway sawmills (see previous section) could be developed into a suitable substrate for composting subject to investment in research and development. This is dependent on a number of factors including the species of wood or bark being used and pre-treatment processes (e.g. grinding and screening). The bark from some plant species is highly porous in structure, and there is a precedent for the use of pine bark in composting. It is routinely used to manufacture potting media via a tightly controlled composting process (Castillo 2004). Some of these technical challenges are explored further in the following sections.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Table 3. Feasibility of carbon alternatives for use in mushroom compost

Material	Cost ($/t)	Volume available (t)	Supply reliability	Climate change limitations	Viable
Wheaten straw	*230[c]–375[a]*	*Limited*	*Market dependent*	*Climate limited*	*NA*
Green waste	-ve to 190[c]	1.9 Mt	Market dependent	None	Fail[1]
Bedding or litter from intensive animal industries					
Stable bedding	12.50–22.50[b]	NA	Unknown	NA	Fail[1]
Paper and cardboard		5.6 Mt*			
Shredded paper	90[c]	-	Unknown	NA	Potentially[1]
Cardboard pallet	120–240[c]	-	Market dependent	NA	Fail[2]
Soft-mixed paper	50–60[c]	-	Reliable	NA	Potentially[1]
Spent or fresh grain	85[b]	NA	Low	Unlimited	Fail[3]
Corn stover	NA	Up to 960,000	High	Irrigation limited	Yes[3]
Seed hulls	Unknown	Low	Moderate	Rainfall/irrigation limited	Fail[3]
Almond	Unknown	87,000	Market dependent	Rainfall/irrigation limited	Fail[3]
Rice hulls	NA	Zero during drought years	Market dependent	Rainfall/irrigation, climate limited	Fail[3]
Oil seed waste			Market dependent	Rainfall limited	Fail[3]
Canola meal	300–400[c]	Unknown	Strongly Market dependent	Rainfall limited	Fail[3]
Olive marc	50[c]	62,500 t per annum*	Low	Rainfall/irrigation limited	Fail[3]
Crop waste (failing-wheat) including canola, rice and cotton	100–400[a,c]	3.5 Mt†	Market dependent	Rainfall limited, climate limited	Fail[4,5]
Total hay	100–400[a,c]	3.5 Mt†	Feedstock competition	Rainfall/climate limited	Fail[3]
Cotton trash	0	Up to 500,000***	Market dependent	Rainfall limited, climate limited	Fail[4,5]
Soybean meal	300–600	Unknown	Strongly Market dependent	Rainfall limited	Fail[3]

a Includes transport costs to Canberra as a proxy
b Includes limited transportation costs
c Includes no transportation costs
**Total paper and cardboard waste produced in Australia annually*
***Based on 2008 figures (Nair and Markham 2008)*
****Number based on figures for single supplier*

1 Viability limited by physical constraints
2 Viability limited by cost
3 Viability limited by cost & supply
4 Viability limited by transportation distance
5 Viability limited by potential climate impacts
-ve indicates potential for payment to contractors who remove green waste for processing

†Based on 2013-2014 data

Table 3 (continued). Feasibility of carbon alternatives for use in mushroom compost

Material	Cost ($/t)	Volume available	Supply reliability	Climate change limitations	Viable
Wheaten straw	***375[a]***	*Limited*	*Market dependent*	*Climate limited*	*NA*
Sugar bagasse	9[c]	Unlimited	Moderate	Moderate	Potentially[4]
Forestry residuals					
Woodchips and bark mix	Negotiable	15,000-20,000****	Market dependent	NA	Potentially[1]
Sawdust	NA–24	Unviably limited	Strongly market dependent	NA	Fail[1,3]
Recycled sawdust	24[c]	Unknown	Market dependent	NA	Fail[1]
Recycled pallets	125[c]	48***	Market dependent	NA	Fail[1]

a Includes transport costs to Canberra as a proxy
b Includes limited transportation costs
c Includes no transportation costs
**Total paper and cardboard waste produced in Australia annually*
**Based on 2008 figures (Nair and Markham 2008)*
***Number based on figures for single supplier*
****Based on volumes available from single supplier per day*
*****Based on volumes available from single supplier per annum per plant*

1 Viability limited by physical constraints
2 Viability limited by cost
3 Viability limited by cost & supply
4 Viability limited by transportation distance
5 Viability limited by potential climate impacts
†Based on 2013-2014 data

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

3.2.3 Stage three: Hazard analysis

In this section, we explore the potential hazards associated with the use of alternative carbon sources. These hazards fall into the following general categories:

1. Mushroom-farm worker health and safety
2. Hazards to the health of mushroom consumers
3. Environmental compliance, food safety requirements (e.g. MRLs, HACCP) and other standards (e.g. AS4454)
4. Process management and productivity (e.g. process control of composting and hazards to mushroom productivity)

We will first consider any hazards associated with the four short-listed carbon alternatives, and then discuss hazards that could be triggered by any abrupt change in practice.

3.2.3.1 Hazards associated with short-listed alternative carbon sources

Information on specific hazards presented by the short-listed alternative carbon sources (paper, sugar bagasse, corn stover and forestry residuals) to mushroom composting and yields is not detailed in scientific literature. This is probably because few papers have examined these carbon sources for mushroom farming, and so a comprehensive coverage of specific hazards is just not available.

We held discussions with industry stakeholders about their thoughts and experience with alternative carbon sources (Attachment B). A frequent theme running through these discussions was that, if a substitute for wheaten straw were available, then the industry would have already found it. Very few specific hazards were identified from these interviews, with most people doubtful of the mushroom yields that could be obtained from alternative substrates. Other concerns relate to how well any alternative carbon source fits into current production systems, noting that the equipment in use (e.g. compost turners) is designed to work with wheaten straw. Some stakeholders viewed sugar bagasse and corn stover as potentially favourable, provided that procurement costs were reasonable. Paper was thought to be potentially hazardous due to increased risk of infection by *Trichoderma* species. The reasoning for this concern is uncertain but it is probably because paper could potentially add to the quantity of readily available carbohydrates in a mix. Storage could also be a factor. Forestry residuals were almost universally disregarded for three reasons: 1)

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

it was thought that they would take too long to break down given that some composters are working on a short, three-week cycle; 2) there were concerns that the resultant substrate would have the wrong microflora (i.e. the substrate would not be selective for *A. bisporus*); and 3) risks associated with infections by *Trichoderma spp.*

We know that pine bark potting media can support the growth of *Trichoderma spp*. under some conditions (Hoitink and Fahy 1986). In fact, inoculation of *Trichoderma spp*. has often been proposed as a means to control plant pathogens in pine-bark potting media. A second potential hazard is the anti-microbial effects of phenols (especially the tannins) that are present at high levels in some barks. High residue levels of tannins could affect mushroom yield. Nevertheless, the tannin content of pine bark reduces rapidly during composting provided that thermophilic conditions[19] are quickly attained. Tannins are water-soluble compounds that are quickly denatured by heat, but they can persist in composted pine bark when the compost mix fails to heat up (Mupondi et al. 2006).

A major concern for all mushroom farmers is the need to control chemical residues. Chemical residues include herbicides, pesticides and fungicides. Chemical hazards apply to all agricultural residues, including the already utilised wheaten straw, or alternatives such as sugar bagasse or corn stover. Chemical residues can impact compost processes by impacting compost microflora, as well as having a catastrophic effect on the growth of the *A. bisporus*. The specific hazard these chemicals present to composters is dependent upon chemical concentration, type, and use, and must therefore be assessed on a case-by-case basis. To mitigate the chemical hazards presented by crop wastes, mushroom composters should use the same methods already used to restrict chemical hazards associated with wheaten straw. Where no measures are in place, we suggest that strict quality assurance measures are adhered to. The details of chemicals used on the crop by substrate suppliers should be collected, as well as safety data sheets.

3.2.3.2 Main hazards of concern and their management

Since information on the specific hazards associated with the four short-listed is limited, we will now discuss issues to consider when any new carbon source is brought onto a

[19] Thermophilic conditions usually refers to temperatures above 45°C.

mushroom farm. These are summarised in Table 4. This analysis is not an exhaustive coverage but could be used to form the basis for completing detailed risk assessments when facility operators consider any new carbon sources.

Mushroom-farm worker health and safety could potentially be put at risk with the introduction of new raw carbon sources used in the production of compost substrate. The main hazards we can identify are sharps (e.g. glass, metal shards and needles) or ingestion/inhalation of pathogens and bio-aerosols. The most significant of these hazards with respect to new carbon sources is probably sharps, most likely for organic waste streams derived from municipal sources (e.g. green waste and food waste). Ingestion/inhalation of pathogens and bio-aerosols could be hazards in cases where there are changes made to waste handling and storage. But pathogen and bio-aerosol hazards are unlikely to be exacerbated with new carbon sources over and above the risks already associated with the use of products like poultry litter. Where manures or wastes that are wet or high in nutrients are used, these should be incorporated into composting operations as quickly as possible upon receival.

Hazards to consumers of mushrooms could be associated with chemical residues (e.g. heavy metals and organic contaminants) and pathogens on the surface of mushrooms. Research has shown that mushrooms can accumulate heavy metals, for example (Sithole et al. 2017). Metal and organic contaminant hazards must be clearly established for each raw material used to make compost. Pathogens surviving on the surface of mushrooms will be associated with the compost substrate. Following normal farm hygiene standards and the pasteurisation protocols associated with phase II composting should effectively manage the vast majority of pathogen hazards. Substrate at the end of phase II is known to be selective for *A. bisporus*, but not all microorganisms are killed in it[20]. The regrowth of enteric bacteria in compost carbon sources is known to be associated with available nutrients, water availability and the degree of decomposition of the compost (Russ and Yanko 1981). Although new carbon sources are unlikely to introduce new human pathogens to a mix, bacterial pathogens from other components of the mix (e.g. poultry litter) may regrow in substrate if the compost is not stable. When changes are made to a compost mix,

[20] Mushroom substrate is not an axenic culture of *A. bisporus*. Although it favours the growth of *A. bisporus*, it contains an abundance of other microbes.

Table 4. Summary of hazards associated with alternative carbon sources

Hazard	Impact	Does it apply to feasible carbon sources?	Does it apply to other carbon sources?	Comments
Mushroom farm worker health and safety				
Glass, needles, other sharps	Cuts, disease risks	NA	Mixed municipal wastes like green and food waste	Use only single source waste streams, which are less likely to be contaminated. Avoid post-consumer food wastes
Pathogens	Disease risk from ingestion	NA	Manures and food waste	Awareness only. Hazard not greater with alternative carbon sources than under existing practises. Usual hygiene precautions apply
Bio-aerosols	Disease risk from dust and air-borne pathogens	NA	Manures and food waste	Awareness only. Hazard not greater with alternative carbon sources than under existing practises. Usual hygiene precautions apply
Hazards to the health of mushroom consumers				
Heavy metals and organic contaminants	Carcinogenic disease, poisoning, infertility etc	Possible with any crop residue	Greater likelihood with mixed solid wastes and turf grasses	Take usual precautions with respect to crop sprays (as they apply also for wheat straw). Some grassy waste streams from households and golf courses contain herbicide residues that can be persistent after composting (e.g. Chlopyralid)

Table 4 (continued). Summary of hazards associated with alternative carbon sources

Hazard	Impact	Does it apply to feasible carbon sources?	Does it apply to other carbon sources?	Comments
Pathogens	Disease risk from ingestion	Possible – see comments	Possible – see comments	Risk managed through effective composting and pasteurisation (i.e. existing practices should suffice) New substrates must be stable to prevent re-growth of bacterial pathogens. Produce substrates to specifications
Fine glass fragments			Mixed solid wastes	Mixed solid wastes can contain finely crushed glass that is difficult to see by the naked eye
Environmental compliance, food safety compliance and other Standards				
Environmental compliance	Litigation, licence to operate etc.	Possible with any new carbon source	Possible with any new carbon source	Appropriate approvals may be required from environmental regulator when new waste streams are brought onto site.
Odour	Litigation, licence to operate etc.	Paper wastes (poor porosity)	High nutrient, wet wastes (e.g. food) and those of poor porosity	Mushroom composting facilities already have challenges with management of odours due to poultry manure. The problem could be exacerbated if piles with new wastes in them become anaerobic.

Table 4 (continued). Summary of hazards associated with alternative carbon sources, where HACCP indicates Hazard Analysis and Critical Control Points, and SMS Spent Mushroom Substrate

Hazard	Impact	Does it apply to feasible carbon sources?	Does it apply to other carbon sources?	Comments
HACCP and other programs	Market access	Possible with any new carbon source	Possible with any new carbon source	HACCP plans require documentation of hazards and means of controls to be implemented
AS4454, 4419 etc	Market access, market confidence	Reuse of SMS	Mixed wastes highest risk	High soluble salts are a common issue with SMS. Could be exacerbated when SMS is reused in fresh mixes. Hazards of new carbon sources should be established before use
		Process management and productivity		
Process control	Substrate variability	Depends on consistency of carbon source	Mixed wastes or green waste are highest risk	Processes that adopt multiple waste streams or those that are highly variable may increase the risk of producing variable substrate
Poor substrate utilisation	Reduced yields and profitability	Possible with any new C source	Possible with any new carbon source	Address with research and development. Make new substrates to specifications then blend them in with standard substrate
Pests, diseases, weed moulds	Reduced yields and profitability	Unknown	Probably mixed wastes and other variable wastes	Standard approach to hygiene and process control probably sufficient in most cases. Substrates must be made to specifications that are known to inhibit pests and diseases

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

farm operators should be satisfied that the substrate has been effectively pasteurised and is appropriately stable.

Any changes to a composting operation bring with it risks to environmental compliance since licenced composting operations usually have limits for the volumes and types of raw carbon sources that can be brought onto site. In this case, approvals must be sought from the relevant state environment protection agency when a new waste may be used. Applications for the purposes of research and development trials at composting facilities may also be required. Probably the major issue to consider is odour generation during composting. For this reason, some studies on alternative substrates have investigated mushroom productivity *and* odour generation (Noble et al. 2002).

The major contributor to odour at mushroom composting operations is the loss of ammonia from poultry litter (as a component of the mix). Controlling the pH, temperature and aeration of the compost mix typically manages ammonia emissions, though it is always a challenge. It seems unlikely that the introduction of new carbon sources will contribute greatly to ammonia emissions, except for carbon sources like food waste. However, they may introduce other gases to the atmosphere that, when combined with ammonia, form a new odour cocktail with a lower odour threshold and greater pungency. The risk of this is greatest when the porosity of the compost mix is adversely affected by the introduction of the new carbon source resulting in a higher risk the piles will turn anaerobic.

Mushroom growers supplying to the major supermarket chains are likely to be required to meet maximum residue limits (MRLs) for chemical residues. Management of the hazards associated with the compost substrate, and, therefore, its make-up and production process, must be clearly documented. A plan to use new carbon sources would need to document any hazards associated with heavy metal and organic contaminants. Published sources can be used to establish the likely contaminants of concern, and regular laboratory testing of the substrate and mushroom protein may be necessary in some cases.

Standards, like AS4454 and AS4419, sometimes apply to landscaping products that contain spent mushroom substrate (SMS). These are voluntary industry standards, so in many cases their influence on the reuse of SMS may not be a matter of compliance per se, since many landscape products are not certified to these standards. The major issue with respect to these standards is frequently the level of soluble salts (measured by electrical conductivity

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

or EC) in SMS. Electrical conductibity is unlikely to be made worse by the use of new carbon sources, except where new compost mixes contain some recycled SMS. Soil/plant application guidelines in these standards do account for EC[21], but high EC will restrict the beneficial use of SMS and is likely to adversely impact market acceptance for the product. Nevertheless, the EC of SMS could potentially be lowered by more judicious use of chlorinated water, where it is used as a bacteriostatic mushroom cap treatment. Alternatively, hydrogen peroxide could be used in place of chlorine, which would also result in lower EC levels in SMS.

Hazards to process control during composting are increased with the complexity of mixes. Process control can be more difficult, especially at the start of composting, when a mix is comprised of multiple waste streams, each with different physicochemical characteristics. Some organic carbon sources by their very nature are inherently variable (e.g. green waste). This causes great uncertainty in how these carbon sources should be processed so that the end-product (the substrate) is of consistent quality for mushroom productivity. Where a variable waste stream is incorporated, more time and expense may be spent in managing the operation and in anticipating problems during composting.

Probably the most significant hazard of all is the potential effect that any new carbon source will have on mushroom productivity. Our research has shown that mushrooms can be grown in a range of substrates, not just those derived from wheaten straw. However, confidence in substrates based on straw is itself a major barrier to the willingness of mushroom farmers to trial alternatives. This is in spite of the fact that mushroom growers are sometimes faced with poorly performing wheaten straw based substrates, the reasons for which are not always clear.

The relationship between substrate specifications and mushroom yields is poorly understood because it is very complex. There are, however, some indicators of substrate quality that are widely relied upon, such as pH, ammonia levels, moisture content and the presence of firefang prior to spawning. These are not fail-safe as other factors can also influence substrate productivity. It is possible that these factors could vary from substrate to substrate. Mushroom productivity can be hampered by no other reason than slower than

[21] Application rates of compost are reduced with increasing electrical conductivity (EC).

normal growth of fungal hyphae through the substrate. Or else, hyphal growth appears adequate, but it does not lead to good fructification.

Pests and diseases can also adversely affect mushroom productivity. These are typically managed by (Howard et al. 1994):

- Paying strict attention to hygiene
- Careful management of process control during substrate preparation (e.g. degree of decomposition, pasteurisation conditions and aeration rates, especially during phase II composting)
- Strict management of conditions for mushroom cultivation (e.g. humidity, aeration and temperature)
- Managing specific aspects of substrate quality (e.g. substrate carbon:nitrogen ratio, pH and moisture content)

3.2.3.3 Summary of hazards

We did not find any papers that investigated the potential hazards associated with the four short-listed alternative carbon sources and pests and diseases of mushrooms, but we can make the following general comments:

- The factors presented above apply to all substrates and carbon sources. But any change to an operation may require changes being made to pest and disease control and other hazard strategies.
- Introducing new carbon sources to an operation could lead to increased pest and disease loads that may be more difficult to keep out of growing rooms. Improved air filtration systems may need to be installed, for example. This hazard is probably greater where carbon sources of mixed plant content are used (e.g. mixed green waste). The hazard from this type of material will likely vary from batch to batch.
- As discussed above, industry has concerns that some of the short-listed alternatives (like paper waste and pine bark) could result in increased risk of *Trichoderma spp.* infections. *Trichoderma spp.* and weed moulds are more likely to be a problem when substrates are not fully composted. According to Howard et al. (1994), they are less likely to be a problem in substrates with carbon:nitrogen ratios in the range of 15 to 18:1 — i.e. in substrates that are well decomposed.

- Pest and diseases are likely to be the same for all substrate types, and careful attention should be made to how the material is prepared through pasteurisation for example.
- Pests and diseases can also be caused by infected spawn or casing, or by the use of supplements added to the substrate just before spawning. The addition of undecomposed sources of carbon or protein at this stage can favour the growth of weed moulds by making the substrate less selective for *A. bisporus*.

Given our hazard review above, we suggest that the four substrates short-listed (paper, corn stover, sugar bagasse and forestry residues) have similar known and unknown hazards as any other carbon materials that could be used in compost. Therefore in the first instance, Australian and substrate specific research is required on hazards associated with any new substrates (see below). Significant investment would be required before the industry has the confidence to trial any new substrates on-farm. Where a mushroom composter is willing to trial new substrates, hazards to mushroom productivity could be managed by starting small and by blending the new substrate in with the conventional mix. As confidence grows through extensive testing and experience, the new substrate can be blended in with the conventional mix at an increasing rate.

4. Gap analysis and recommendations for research

In this section, a gap analysis is presented to assist in the identification of future research priorities for the development of composted substrates from alternative carbon sources. We identified knowledge gaps and barriers to adoption for the four short-listed alternative carbon sources through a review of the literature and also through discussions with industry stakeholders (Attachment B). We also considered the state of knowledge with respect to the biology of *A. bisporus*, and issues associated with substrate utilisation and compost process optimisation as they relate to the development of substrates from alternative carbon sources. From this evaluation, a list of prioritised research and development questions were identified.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

4.1 Gap analysis

Gaps in knowledge hamper progress being made towards the development of alternative substrates for *A. bisporus*. These knowledge gaps fall into one or more of the following categories:

1. Knowledge and experience with respect to alternative carbon sources;
2. Knowledge with respect to the biology of *A. bisporus* (and other edible mushroom species), particularly with respect to lignocellulosic biodegradation and optimisation of substrate utilisation;
3. Compost process optimisation as it relates to the production of selective growth substrates for *A. bisporus;* and
4. Other alternative approaches to the cultivation of mushrooms (e.g. the use of non-composted substrates and hydroponics).

The first category is specific to the search for alternative carbon sources, since there is a lack of both technical knowledge and practical experience associated with them. The second and third categories above are of a more general character because improvements in our understanding of them may lead to major advances in many facets of mushroom production, not just those to do with alternative carbon sources. The fourth category encompasses blue-sky approaches to the cultivation of mushrooms. It could be, for example, that longer-term solutions to the problem of finding alternative carbon sources can only be found outside the existing paradigm.

4.1.1 Gap associated with particular carbon sources

The process of evaluating alternative compost substrates for commercial mushroom production cannot be divorced from efforts to develop and apply new knowledge with respect to the biology of *Agaricus* and other edible mushroom species, along with process optimisation for composting and substrate utilisation (categories 2 and 3 above). Bearing this in mind, we will first consider gaps in knowledge with respect to particular carbon sources. We will cover the alternative carbon sources in the final short list (i.e. sugar bagasse, corn stover, paper waste and forestry residuals), and other carbon sources of particular interest to Hort Innovation (e.g. green waste and food waste).

The main gaps with respect to alternative carbon sources are associated with a general lack of research and experience with using them in Australia. It is true that some Australian mushroom composters have investigated a range of potential carbon sources in their own operations, but it is difficult to fully evaluate their findings in a scientific sense since their experience has not been documented in a systematic fashion (Attachment B).

There is a good basis in the literature to support the development of alternative mushroom substrates from:

- Bagasse (Kumar et al. 2011); and
- Corn stover (Penn State University 2011, 2017).

There are also other carbon sources that have proven to be successful in other countries, such as rice straw (Wang et al. 2016) and canola (Noble et al. 2002) but these are severely limited in Australia by cost and reliability of supply.

The gaps associated with the four alternative carbon sources are, therefore, related to lack of local experience, as well as technical information on managing hazards and process optimisation.

Hazards could relate to such things as the incidence of pesticides in the residues of these crops, which may vary from farm to farm (i.e. the source of the crop residue). Mushroom growers are already aware of these risks and must monitor for pesticide residues to meet food safety standards. We have not seen any research investigating pesticide residues with these particular crop residues in the context of mushroom composting.

Most pesticides will not persist during the composting process, but some may do so under certain conditions. One prominent example that we have already mentioned is the herbicide Clopyralid, which is used to control broadleaf weeds in turf. It has been known to persist in composting and caused many problems with respect to the reuse of compost in the market place (Coker et al. 2013). Although this herbicide is not used in the short-listed crops, it serves to illustrate that pesticide residues can be an issue and mushroom farms must be vigilant in understanding the hazards associated with their particular source of crop residue. In some cases, a pesticide may persist through to the substrate and directly affect mushroom yield. For example, one European study found that while most fungicides were degraded during composting, Flusilazole used on wheat straw could persist in concentrations high enough to inhibit the growth of *Agaricus* (Potočnik et al. 2012).

Other gaps in relation to the use of these particular carbon sources are potential hazards to mushroom productivity. Threats to mushroom productivity fall into two areas: increased incidence of pests and diseases (including weed moulds and the like); and yields. All of the research we have seen has focused on the latter issue.

We have noted the particular concern from industry stakeholders about paper and bark potentially causing increased risks of *Trichoderma* spp. infection in substrates. However we are not aware of any research that has investigated these hazards. This is a major gap in knowledge. If a particular carbon source increases hazards associated with pests and disease, further research is needed to overcome the problem. This is a process of optimisation, whereby culture conditions, such as pasteurisation for example, may need to be modified to reduce the incidence of pest and disease.

While the above-mentioned carbon sources have been shown in the literature to be viable alternatives to wheaten straw, local trials on process optimisation are clearly needed. The mushroom production process has been optimised for *A. bisporus* on wheat-poultry manure substrate following many years of research and practice. It follows that the same process needs to be undertaken with any new carbon source, particularly for those designed to be complete replacements for wheaten straw. The sorts of issues associated with process optimisation will be discussed in detail below. Consideration may also need to be given to the trade-offs associated with a change in practices. These might include, for example, small reductions in yield for lower costs of production where the alternative carbon source is cheaper than wheaten straw.

There are two other potential sources of carbon on our final short-list that are longer-shots than corn stover and sugar bagasse. These are forestry residuals (wood and bark) and paper wastes. Very little research has been published on these carbon sources. Furthermore, both industry practitioners and the researchers we have spoken to quickly dismiss them as possibilities. These shortcomings are serious (as described below), and barriers to their adoption may, therefore, be very high. However, we believe that these waste streams warrant further investigation since they are abundant sources of lignicellulose distributed across the country. In contrast, the supply of sugar cane (from which bagasse is derived) and

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

corn are more limited geographically. Given this, we have gone into further detail about risks and gaps for paper and forestry residuals below.

A major concern with paper wastes has been their potential impact on compost porosity. This is a valid concern and it means that paper can only be incorporated as a component of a mix (to be determined by research). However, paper could be considered as a high cellulosic supplement to alternative structural carbon sources like sugar bagasse, corn stover and forestry residuals. Or else paper could be used as a partial substitute for wheaten straw. A further question to consider is whether the incorporation of paper waste in a substrate would increase the risk associated with Trichoderma infection.

The woody nature and high lignin content of forestry residuals could be a major limitation. Forestry residuals can place pressure on a mushroom composting operations by adversely impacting the moisture-porosity relationship in a compost mix as well as the rates of decomposition. The latter issue can extend the duration of composting, and may also prevent the substrate from becoming selective for *A. bisporus*. Yet, there has been some research that has shown that bark, for example, could be used in mushroom composting primarily to provide structure, with other carbon sources such as food waste providing the nutrient and energy source for the mushroom fungus (e.g. Stoknes at al. 2008, 2013). We also believe that bark is superior to wood chips as a potential mushroom growth substrate. Pine bark is highly porous and is routinely used to manufacture potting media through a tightly controlled composting process. There is precedent, therefore, for the potential development of mushroom growth substrate from pine bark provided that it can be demonstrated that the substrate is selective for *A. bisporus*.

With respect to the biodegradability of wood, generalisations about this cannot be made because it varies greatly between species and different plant parts (Allison 1965). In general, softwoods are less biodegradable than hardwoods. An investigation is, therefore, warranted on different sources of forestry residuals such as hardwood species, softwood species with combinations of small branches, wood chips and bark. There is also the opportunity to consider the ideal make-up of particles in the product through the application of size-reduction via grinding, chipping and screening equipment. For example, we have established that the woodfibre processor Midway has the capacity to prepare their bark and wood mixes to any specification. Since there is no real market yet for this material (according to Midway), the product may be quite cost-effective even with pre-treatment.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

The last group of wastes streams (food and green wastes) have not made it through our feasibility assessment, but they cannot be written off entirely. The limitations associated with these waste streams have already been discussed, and we propose that further work is needed to identify particular clean and consistent streams of these wastes that might be suitable for mushroom composting. It was beyond the scope of this report to do that since the potential range of carbon sources that fall into the broad category of food and green waste is enormous. Further work should identify what these waste streams look like (i.e. their composition, consistency and hazards), where they are located in relation to mushroom composters, and their physicochemical properties. We believe that the focus of this search should be on pre-consumer sources since post-consumer organic waste streams can be highly contaminated.

Finally, we have established that 10 carbon sources could be used as partial replacements for wheaten straw based on their physicochemical properties. As per part two of the feasibility study, many of these materials may not be accessible to the industry. This, however, does not mean they should not be used if they do become available. These wastes, such as crop residues, are typically available on an opportunistic basis and vary from place to place and with season. Utilising materials on an opportunistic-availability approach should be encouraged within limits in order to reduce the exposure to wheaten straw supply issues and to gain greater familiarity with other carbon sources.

We have also been satisfied with the extent of work showing that SMS can generally be re-used at around 20 to 30% in fresh mixes, though results do vary from compost to compost (Bishop et al. 2016). Industry is already doing this to some extent in Australia, but the opinions of stakeholders on it vary (Attachment B). It may be worthwhile commissioning some work on promoting this practice more widely. The recycling of SMS should also be investigated as an option for newly developed substrates, especially where it is believed that biological efficiencies from the new substrates can be improved by the practice.

4.1.2 Lignocellulosic biodegradation and substrate utilisation

Some advances have recently been made with respect to the understanding of how *A. bisporus* degrades lignocellulosic carbon sources during its growth and fructification

(Ekman 2017). Whilst there has always been intensive interest in improving the biological efficiency[22] of substrate utilisation, the biochemical processes involved have been so far poorly understood. Jurak (2015) has shown that substrate utilisation by *A. bisporus* is limited by its inability to degrade particular forms of hemicellulose[23] (those substituted with arabinosyl and glucuronic acid). Jurak et al. (2015) propose that greater efficiencies could be made with the development of options for applying the missing enzymes directly to compost or by developing *A. bisporus* strains with enhanced enzyme-machinery. Although *A. bisporus* has the capacity to make a wide range of enzymes, whether or not the genes for making them are switched on or not is substrate dependent. For example, *A. bisporus* has the gene for the enzyme to degrade glucuronic acid but it is not switched on in composts based on wheaten straw[24]. However, it may be switched on when grown on other carbon substrates, but the processes involved are poorly understood.

We have seen how the basic physicochemical composition of lignocellulosic waste streams, as presented in Table 1, is of limited value in screening for potential new substrates. Analysis of percent cellulose, hemicellulose and lignin, as well as physical characterisation, is too crude a basis for determining the suitability of alternative carbon sources. Furthermore, the available methods for compost analysis are not always reliable in predicting mushroom yields[25]. More work is, therefore, needed to develop reliable physical, chemical and microbiological biomarkers for relating compost quality to mushroom yields.

The future drive to find alternatives to wheaten straw must consider how the new substrates are best utilised. This should also involve consideration of other *Agaricus* mushroom species, of which there are at least 200 worldwide (Calvo-Bado et al. 2000). One example is *A. blazei* (synonymous with *A. subrufescens* and *A. brasiliensis*). It is mainly

[22] Biological efficiency (BE) is typically calculated as fresh weight of mushrooms per unit of dry weight of the substrate. It is sometimes represented in percentage terms. In this case, a BE of 100% means a yield of 1 kg mushrooms per 1 kg dry substrate.

[23] Xylan is a group of hemicellulose that is the third most abundant biopolymer on earth. It is found in the secondary cell wall of dicots and in the cell wall of all grasses.

[24] Dr Edita Jurak, University of Groningen, the Netherlands. Personal communication.

[25] Where the relationship between compost quality and mushroom yields has been demonstrated, it is never just one or two factors involved. A reliable, cost-effective means of relating compost quality with mushroom yields is needed.

grown in Brazil and Japan, but there is also increasing interest in this species in Europe and elsewhere. *Agaricus blazei* is reportedly a choice edible mushroom with a pleasant aniseed or almond-like odour. In Europe it is normally grown on substrate similar to that of *A. bisporus*, but Stoknes *et al.* (2013) points out that it is a tropical mushroom and demands higher temperatures for growth and fruiting. In comparing the two *Agaricus* species cultivated on a food-waste–based substrate, Stoknes et al. (2013) found that *A. blazei* preferred a drier mix of 20% moisture compared to *A. bisporus* which had an optimum in their study of 60%.

Culture conditions such as temperature, moisture content, pH, and humidity may also need to be adjusted when alternative substrates are investigated. As we have seen earlier, *Agaricus* species may indeed have the necessary genes to produce the enzymes required for optimum growth and fructification, but they may not always be switched on. Altering culture conditions may be one way to stimulate the enzyme machinery required to better utilise alternative carbon sources.

Compost-based substrates contain a complex community of microorganisms that assist in conferring selectivity for *A. bisporus*. Recent Australian research has elegantly demonstrated that there is a succession of microbial communities present from start to finish in the preparation of substrate prior to spawning (Kertesz et al. 2015). There is particular interest among many researchers in the role that *Scytalidium thermophilum* plays in conferring selectivity for *A. bisporus*, since this thermophilic fungus dominates the fungal flora of wheat-based substrates just prior to spawning (Figure 6). It appears that this fungal biomass is an important nutrient and energy source for the growth of the mushroom fungus. It also helps to confer selectivity by suppressing the growth of weed moulds.

Few papers, if any, have examined microbial community dynamics in conferring selectivity to *A. bisporus* (and other *Agaricus* species) in alternative substrates. For example, what role does *Scytalidium thermophilum* play (if any) in substrates made from other carbon sources? Can composting and/or cultural conditions be manipulated to encourage its growth in other substrates? Some researchers have proposed inoculating this fungus into sterilised non-composted substrates prior to spawning with *A. bisporus*, proposing that a composting phase could be avoided altogether (Sanchez et al. 2008; 2009).

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

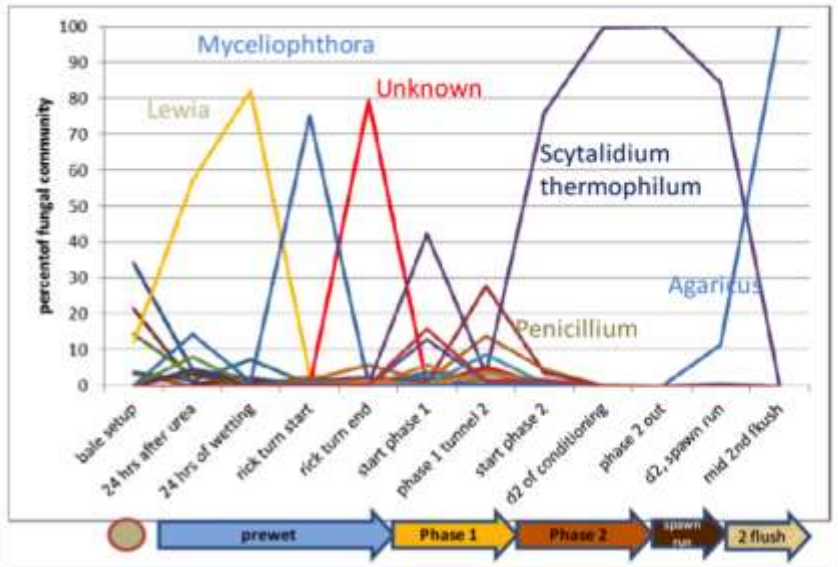

Figure 6. Changes in fungal species during substrate preparation and use (Kertesz et al. 2015)

Conferring selectivity for *A. bisporus* is obviously important in any given substrate. For example, the pasteurisation and conditioning process associated with phase II composting is known to be critical. Reports frequently cite as important the need to control aeration and temperature during phase II (Ekman 2017). Other cultural conditions, like carbon:nitrogen ratio of the substrate, and growing room temperature and humidity, are also known to be important. But we are dealing with a dynamic, complex biological system and we cannot assume that the conditions that are optimum for one substrate are the same for another.

Studies comparing alternative carbon sources use *A. bisporus* strains that have been commercially successful with conventional substrates based on stable manure and/or wheaten straw. Only a few papers have explored the efficacy of multiple *A. bisporus* strains when alternative substrates were evaluated. Although genetic development of new and improved *A. bisporus* strains continues to be an important area of work, it does not appear to have been applied to any significant extent to the area of alternative substrates.

This brings us to another important gap that we have identified. Few papers, if any, have reported on optimisation studies with respect to the cultivation of *A. bisporus* in alternative substrates. There is an understandable, but unfortunate tendency in many research projects to take what is known from the existing paradigm (i.e. the conventional

A. bisporus-substrate production system) and apply it directly to the evaluation of a new substrate. It is *understandable* in that one has to start somewhere, but the conclusions that can be drawn from that sort of approach are limited. For example, we have seen only one report of green waste being used as a component of mushroom substrate (Gerrits 1991). In this paper, green waste compost was obtained from a commercial composting facility in the Netherlands and it was blended at different rates with conventional mushroom substrate and put through pasteurisation and conditioning (i.e. phase II only). Mushroom yields were found to be inversely proportional to the percentage of green waste compost included in the substrate. However, the conclusions that can be drawn from this study were limited by the fact that the green waste compost was very mature and would have had very little energy left for mushroom growth[26]. This finding is not without value, but the picture is not complete. We do not know, for example, how *A. bisporus* would have fared if raw green waste or immature compost had been used in an optimised mushroom composting process (involving Phases I and II).

The studies by Stoknes et al. (2008 and 2013) are interesting, contrasting examples that involved at least some process optimisation for investigating the growth and yield of *Agaricus* species in substrates based on food waste. *Agaricus bisporus* yielded equally well on both a conventional substrate and one based on composted food waste and spruce bark, while *A. blazei* performed best on the latter.

4.1.3 Composting process optimisation

Process optimisation should also be considered for the composting process. One gets the impression that many studies approach the problem of evaluating alternative carbon sources by simply combining the components of a new mix together to see how it performs[27].

---

[26] The green waste compost had an ash content of about 61% suggesting that there was very little available carbon left in it. This is not surprising given that green waste composts in Europe can be composted for months on end.

[27] Using more colloquial language we might say, "*slap the ingredients together and see what happens*."

It is very difficult to replicate the moisture content-porosity conditions found in a conventional mushroom compost mix based on wheaten straw and poultry manure. As we have discussed earlier, the moisture content of phase I mushroom composting is usually around 73 to 75% — much higher than in municipal waste composting. It is generally not advisable to prepare straw-less composting mixes at moisture contents above about 55%. So, when new substrates are being developed, we believe that it is important to optimize the mix based on its particular physicochemical properties. It may not be necessary, or advisable, to try and match the characteristics of a conventional straw-based compost mix, as some researchers have done.

We have not been able to establish from a review of the scientific literature whether high moisture contents in phase I composting are absolutely necessary in all cases for the cultivation of *A. bisporus*[28], although it does seem to be the case that the final substrate (i.e. after phase II) should have relatively high water content for optimum mushroom yield. It could be that a 73 to 75% moisture content just happens to be the optimum for a phase I wheaten straw composting mix and that there is still sufficient residual water left over in the final substrate for the growth of the mushroom fungus. For straw-less based mixes composted at lower moisture contents, it may be necessary to add supplements along with additional moisture after phase II is complete. This accords with the general principle of process optimisation rather than attempting to replicate the processes used for conventional substrates.

Frequent reference is also made to the caramelisation process that occurs as a result of the Maillard reactions taking place during phase I composting at high temperatures (typically above 75°C). Such high temperatures are generally not desirable in municipal composting systems because microbiological activity and the rate of decomposition declines rapidly above about 65°C (Haug 1993). Indeed, the Maillard reactions taking place during mushroom composting are likely to be the result of chemical reactions taking place rather than microbiological activity (Miller et al. 1990). It is unclear to us how important this process is. It may be advantageous, or even necessary for straw-based compost mixes, but is it also important for substrate quality when other carbon sources are composted? Janssen

[28] The claim that high moisture contents are necessary may be true but we have not been able to establish clear evidence for it in the literature.

(2016) claims that the Maillard reaction protects carbohydrates such as cellulose and hemicellulose from degradation by other fungi, which are then utilised by *Agaricus*. But there is also support in the literature for the notion that good quality mushroom substrates can in fact be derived via quite different composting conditions (Wang et al. 2016).

Many researchers have also investigated the importance of different forms of nitrogen during composting, and in the final substrate for mushroom productivity. High levels of ammonia appear to be important for softening the straw as the cuticle is destroyed (Janssen 2016). But it may be that provided there is sufficient N in the substrate for mushroom growth, high ammonia levels may not be necessary when other carbon sources are composted. On the other hand, some level of residual ammonia in the final substrate may help to suppress weed moulds since *Agaricus* has a greater tolerance for it (Janssen 2016). Yet the use of alternative carbon sources during mushroom composting might have the additional spin-off of reduced environmental impact from the generation of odours. As discussed earlier, this has been the subject of some research, particularly in the UK. There is merit in exploring this possibility further since odour complaints frequently threaten the viability of composting facilities in Australia.

We earlier discussed the importance of creating a selective substrate for the growth of *A. bisporus*. Part of that process, at least for straw-based substrates, also involves manipulation of the composting process. In particular, conditions during phase II composting appear to be critical. Phase II typically involves two stages — the first is called pasteurisation, which is a period of six to eight hours at 55 to 60°C, followed by conditioning at 45 to 50°C until ammonia clears. Ross and Harris (1982) showed that conditioning at temperatures above 55°C or below 40°C resulted in composts that were not selective and supported the growth of competitor fungi as well as the mushroom. Aeration was also found to be an important factor. A reduction of average oxygen levels from 19 to 14%, accompanied by a corresponding increase in carbon dioxide levels, almost doubled the time required to complete phase II.

These factors appear to be very important for wheaten straw-based compost substrates, but whether or not they would apply for substrates based on other carbon sources is unknown. It is interesting that the first stage of phase II is called pasteurisation given that a period of high temperature composting has already occurred during phase I[29]. When the concept of pasteurisation is applied to municipal composting systems, it usually refers only to the first couple of weeks of composting (AS4454 2012). Phase II pasteurisation may be necessary as a means to cool the compost down to re-establish a beneficial microbiological community prior to conditioning[30]. How this concept should be applied to the manufacture of substrates from alternative carbon sources is unknown. If high phase I temperatures (i.e. greater than 75°C) were shown to be unnecessary for straw-less mushroom composting, then a two-stage phase II process may not be necessary either.

A further consideration is the greater than 14% high oxygen levels that are deemed to be necessary to complete phase II conditioning (Ross and Harris (1982). These levels of oxygen are probably the result of the high rate of aeration required for temperature control and for stripping ammonia from the compost matrix. There may not be the need for such high concentrations of oxygen per se because the required rates of aeration are usually much higher for effective temperature control and, in this case, for removal of ammonia than for the maintenance of aerobic composting conditions (Haug 1993). Such high rates of aeration may not be necessary for compost mixes based on other carbon sources. In fact, they may be detrimental since a lot of valuable water is also removed with high rates of aeration. Alternative substrates may require less cooling because of lower phase I temperatures and ammonia removal, and, therefore, less aeration. The operation of fans for aeration is a costly enterprise, so there could be benefit in compost process optimisation when alternative substrates are used.

4.1.4 Alternative approaches to mushroom cultivation

We have mentioned that the search for alternative carbon sources might require the industry, at least in the medium to long term, to consider a paradigm shift. As the

[29] If pathogenic and nuisance organisms are controlled at 55 to 60°C during phase II, then they are presumably also effectively controlled at 75°C during phase I. In pile systems, there will always be zones of high (e.g. 80°C) and low (e.g. 35°C) temperatures. It is therefore important to turn compost piles to ensure that all compost particles are exposed to pasteurising conditions.

[30] As mentioned earlier, the high temperature of phase I would typically adversely impact microbiological diversity and activity.

A. bisporus — wheaten straw substrate production system is highly developed and finely tuned, a move away from this system may be best served in the long run by thinking outside the square. These are higher-risk research projects so this should be factored in, but their importance cannot be ignored.

It is beyond the scope of this review to go into this field in any detail, but we have come across a couple of interesting concepts that would fall into this category. These include:

- The development of non-composted substrates. As mentioned previously, we have seen quite a lot of work published in this space about a decade or so ago (e.g. Bechara et al. 2006a, 2006b; Mammiro and Royse 2008). Despite the fact that these approaches showed some promise, we do not believe that they have been adopted commercially to any great extent. These systems could be investigated for the Australian context. Such an investment is relatively low risk since the past research that has been published is a firm foundation from which to build on. It is also worthy to consider since the business case for these approaches may become more attractive as pressures increase with respect to the price and availability of straw.
- Development of hydroponic systems. When talking to our industry contacts, the possibility of hydroponically grown mushrooms was raised as a blue-sky prospect. Hydroponic systems for mushroom farming certainly would require a complete paradigm shift. There has been little research done on this topic, and what has been done so far shows that the concept requires significant development for it to be commercially viable. Bechara et al. (2006) from Pennsylvania State University was one of the first to publish a significant study on this topic. A Masters student from Wageningen University in the Netherlands has since published a thesis on this subject (Calvo 2010).
- A shift in mushroom species grown, from *A. bisporus* to oyster and shimejii. These species and varieties are known to grow on abundantly available sources (e.g. wood) which are also less affected by climate change. See the Case Studies in Attachment 4 for further details.

4.2 Recommendations for research

We have seen in the previous discussion that the issues associated with the development of new substrates based on alternative carbon sources are potentially very complex — it is not necessarily the case that simple substitution for wheaten straw will be successful. Major changes to a production system as significant as complete replacement of wheaten straw

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

are likely to have a chain-reaction of effects, which could not only affect mushroom productivity, but also other factors affecting business viability.

More research is needed on mushroom biology, as well as the factors that lead to the production of growth substrates selective for *A. bisporus*. Changes to production systems can be more confidently proposed when the industry is armed with greater foundational knowledge such as this.

Priority should be given to research that approaches the problem in an integrated fashion. That is, experiments with alternative carbon substrates should consider process optimisation, rather than simply following the production processes that are known to work for conventional substrates. Therefore, although these recommendations are listed in order of priority, they are not necessarily discreet. New research on alternative carbon substrates should ideally cover multiple aspects in an integrated fashion. Our recommendations for research our shown below in Table 5.

Table 5. Research recommendations for the development of new substrates from alternative carbon sources. Items with the same first number (1,2, 3 or 4) are of equal priority

Composting and mushroom production trials	
Corn stover and bagasse	Compost process optimisation • Process development and control • Effect of moisture content-porosity conditions on capacity to produce selective growth substrates • Effect of nitrogen, ammonia and aeration strategies in relation to producing selective growth substrates Substrate utilisation • Effect of cultural conditions • Characterisation of substrates that reliably effect potential mushroom yield
1.2 Paper waste	Hazards • Addressing risks associated with *Trichoderma*
1.2 Other strategies	Safe reuse of spent mushroom substrate in new growth substrate

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Table 5 (continued). Research recommendations for the development of new substrates from alternative carbon sources

Further research on lignocellulosic carbon sources	
2.1 Green & food waste	Identification of potential clean and consistent sources of these waste streams
2.1 Forestry residuals	Further evaluation of bark and wood waste streams, particular pre-treatment options
2.2 Characterisation	Benchmarking of lignocellulosic waste streams used in substrate production
Mechanisms of lignocellulosic biodegradation by *A. bisporus* and other edible fungi	
3.1 Exploration of the genetic diversity of *A. bisporus* to develop strains that are able to better utilise alternative carbon substrates	
3.1 Exploration of other *Agaricus* species and other edible fungi to better utilise alternative substrates	
3.2 Factors affecting gene expression for lignocellulosic enzyme production	
3.3 Potential for genetic manipulation of *A. bisporus* to better utilise alternative carbon substrates	
Alternative approaches to mushroom cultivation	
4.1 Non-composted substrates	Australian research on the potential use of non-composted substrates, especially those derived from forestry residuals
4.2 Potential for development of hydroponic systems for mushroom cultivation	

5. Conclusions

Many different carbon sources could be used by mushroom composters on an opportunistic basis for the partial substitution of wheaten straw. But some of these have unreliable quality and/or supply, and many others are already used by other industries.

Waste paper (shredded and soft-mixed) is one example of an under-utilised waste stream that could potentially be used as a partial substitute on a relatively consistent basis. Carbon sources that could be viable as complete substitutes for wheaten straw include forestry residuals (subject to appropriate pre-treatment and significant investment in research and development), sugar bagasse and corn stover.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

This is due to the ready supply of these carbon sources both now and with the predicted climate change; their cost; the reliability of the waste stream; and their physical or chemical characteristics being suitable for mushroom composting. However, none of these substrates are considered completely viable alternatives to wheaten straw without further development and research. The use of shredded paper and soft-mixed paper requires over-coming the physical limitations, including inappropriate structure and the impacts of this on mushroom compost porosity. A blend of woodchips and bark can be sourced from sawmills where it could be pre-prepared to specifications by processes such as grinding and screening. But composting and mushroom production trials would be required to ensure that the new substrate is selective for the growth of *A. bisporus* and that good commercial yields are attainable. Finally, both corn stover and sugar bagasse could be ideal for use as a substitute for wheaten straw. But transport distances could be a logistical hurdle preventing the widespread use of these carbon sources by mushroom composters.

The major hazards associated with these new carbon sources are not new to mushroom farmers in that they are not necessarily specific to a particular carbon substrate but may be triggered by any significant change in practice. Perhaps the greatest hazard from the use of these carbon sources is the unknown effect they may have on mushroom yields. These hazards and other research questions were also identified in a comprehensive gap analysis.

We have shown that there is a need to approach the problem of alternative carbon sources in an integrated fashion. It is unlikely that simple substitution for wheaten straw for another carbon source will be successful on its own. Major changes to a production system as significant as complete replacement of wheaten straw are likely to have a chain reaction of effects, which could affect mushroom productivity and other factors affecting business viability.

There are major challenges associated with finding a complete substitute for wheaten straw. This is because the production of *A. bisporus* (and other edible mushrooms) in Australia is a well-developed and technically sophisticated process that has evolved over decades of research, development and commercial practice. We presented a list of research needs that includes basic, strategic and applied research areas and believe that priority should be given to experiments considering process optimisation, rather than simply following the production processes that are known to work for conventional substrates.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

6. Limitations

The following limitations apply to this report.

The costings of many of the substrates presented in Section 3.2.2 were provided verbally unless otherwise indicated, with figures presenting quotes from often only a single supplier. The price of many of these substrates is often negotiated on a case-by-case basis, and do not necessarily represent the costs which might be incurred by mushroom composters.

While many mushroom composting organisations were contacted by phone or by email for the purposes of this report, no response was received by a number of stakeholders within the timeframes of this report. Please see Attachment B for the stakeholder comments provided for this report. The information in Attachment B should be treated as commercial-in-confidence at the request of some members of the mushroom industry.

We note that the effects of climate change are difficult to predict. This report assumes that the materials listed will still have some availability under climate change (e.g. corn stover and bagasse). However, the actual availability of substrates as a result of climate change, or other impacts to the mushroom industry are unknown.

7. Acknowledgements

The authors of this report sincerely thank the mushroom composters who donated time and expertise on the subject of mushroom composting during the interviews conducted for this research. We have also been in touch with several experts in the field of mushroom research. We would like to acknowledge the invaluable contributions from the following researchers:

- Associate Professor Michael Kertesz, University of Sydney
- Professor David Beyer, Penn State University
- Doctor Ralph Noble, Microbiotech Ltd, United Kingdom
- Doctor Kerry Burton, independent consultant, United Kingdom
- Doctor Edita Jurak, Groningen University, the Netherlands

This report was externally reviewed by Therese Manning of Environmental Risk Solutions Pty Ltd, and internally reviewed by Doctor Jessica Drake of Murrang Earth Sciences. Both

Therese and Jessica were paid for their role in producing this report, and their efforts are gratefully acknowledged.

8. References

Adjapong, A.O., Ansah, K.D., Angfaarabung, F. and Sintim, H.O. 2015. Maize residue as a viable substrate for farm scale cultivation of oyster mushroom (*Pleurotus ostreatus*). Advances in Agriculture.

Agnew, J.M., Leonard, J.J., Feddes, J. and Feng, Y. 2003. A modified air pycnometer for compost air volume and density determination. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada, 45: 6.27–6.35.

AgriFutures. 2017a. Grain sorghum. Accessed on 27 June 2019. <https://www.agrifutures.com.au/farm-diversity/grain-sorghum/>.

AgriFutures. 2017b. Sugarcane. Accessed on 27 June 2019. <https://www.agrifutures.com.au/farm-diversity/sugarcane/>.

AgriFutures. 2017c. Canola. Accessed 28 June 2019. <https://www.agrifutures.com.au/farm-diversity/canola/>.

Allison, L. 1965. Decomposition of wood and bark sawdusts in soil, nitrogen requirements and effects on plants. USDA Technical Bulletin 1332.

Altieri, R., Esposito, A., Parati, F., Lobianco, A. and Pepi, M. 2009. Performance of olive mill solid waste as a constituent of the substrate in commercial cultivation of *Agaricus bisporus*. International Biodeterioration and Biodegradation, 63(8): 993–997.

Amin, R., Khair, A., Alam, N. and Lee, T.S. 2010. Effect of different substrates and casing carbon sources on the grow the and yield on *Calocybe indica*. Mycrobiology, 38(2): 97–101.

Arcadis (2019). National food waste baseline: final assessment report. Accessed on 27 June 2019. <https://www.environment.gov.au/system/files/pages/25e36a8c-3a9c-487c-a9cb-66ec15ba61d0/files/national-food-waste-baseline-final-assessment.pdf>.

Arce-Cervantes, O., Saucedo-Garcia, M., Leal Lara, H., Ramírez-Carrillo, R., Cruz-Sosa, F. and Loera, O. 2015. Alternative supplements for *Agaricus bisoporus* production and the response on lignocellulolytic enzymes. Scientia Horticulturae, 192: 375–380.

AS4454 2012. Composts, soil conditioners and mulches. Standards Australia, Sydney.

Australian Bureau of Agricultural and Resource Economics and Sciences. 2019. Australian Crop Report: June edition. Accessed on 27 June 2019. <http://www.agriculture.gov.au/abares/research-topics/agricultural-commodities/australian-crop-report>.

Australian Bureau of Statistics. 2019. Broadacre crops. Accessed 27 June 2019. <https://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/7121.0Main%20Features412017-8?opendocument&tabname=Summary&prodno=7121.0&issue=2017-18&num=&view=>.

Baldrian, P., and Valaskova, V. 2008. Degradation of cellulose by basidiomycetous fungi. FEMS Microbiology Reviews, 3: 501–521.

Barman, S., Acharya, A., Chakraborty, W. and Chakraborty, B. N. 2017. Evaluation of the effect of different compost formulation and casing carbon sources on button mushroom production. International Journal of Science and Nature, 8(2): 377–385.

Bechara, M.A. 2007. Alternative mushroom production system using non-composted grain-based substrates. PhD Thesis. Penn State University.

Bechara, M.A., Heinemann, P., Walker, P.N. and Romaine, C.P. 2006a. Non-composted grain-based substrates for mushroom production (*Agaricus bisporus*). Transactions of the American Society of Agricultural Engineers, 49(3): 19–824.

Bechara, M.A., Heinemann, P., Walker, P.N., Romaine, C.P. and Wilkinson, V.L. 2006b. Evaluating non-composted grain substrates for the production of *Agaricus bisporus* and *Agaricus blazei* mushrooms. American Society of Agricultural and Biological Engineers. 2006 American Society of Agricultural Engineers Annual Meeting.

Bechara, M.A., Heinemann, P., Walker, P.N. and Romaine, C.P. 2006. *Agaricus bisporus* mushroom cultivation in hydroponic systems. Transactions of the ASABE, 49(3): 825–832.

Beckingham, C. 2007. Sweet corn growing. Accessed on 15 July 2019. < https://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/commodity-growing-guides/sweet-corn>.

Beyer, D.M. 2017. Basic procedures for *Agaricus mushroom* growing. Accessed on 17 June 2019. <https://extension.psu.edu/basic-procedures-for-agaricus-mushroom-growing>.

Bishop, E.L., Pecchia, J.A., Wilkinson, V., Albert, I., and Royse, D.J. (2016). Effects of Spent Mushroom Compost (SMC) as an ingredient in phase I compost on production of *Agaricus bisporus*. Compost Science & Utilization, 24(4): 246–258.

Bisht, N.S. and Harsh, N.S.K. 1985. Biodegradation of *Lantana camara* and waste-paper to cultivate *Agaricus bisporus* (Lange) singer. Agricultural Wastes. 12(3): 167–172.

Bouasker, M., Belayachi, N., Hoxha, D. and Al-Mukhtar, M. 2014. Physical characterization of natural straw fibers as aggregates for construction carbon sources applications. Carbon sources, 7(4): 3034–3048.

Calvo-Bado L., Noble R., Challen M., Dobrovin-Pennington A. and Elliott T. 2000. Sexuality and genetic identity in the *Agaricus* section Arvenses. Applied and Environmental Microbiology, (2): 728–734.

Calvo, M.H. 2010. Development of a growth model system for *Agaricus bisporus*. M.Sc. dissertation, Wageningen University, The Netherlands.

Campbell, A. 2012. Organics recycling in Australia: industry statistics 2012. Department of Sustainability, Environment, Water, Population, and Communities' Recycled Organics Unit, Canberra.

Cao, W., Xu, H., and Zhang, H. 2013. Architecture and functional groups of biofilms during composting with and without inoculation. Process Biochemistry. 48: 1222–1226.

Carrasco, J., Zied, D.C., Pardo, J.E., Preston, G.M. and Pardo-Gimenez, A. 2018. Supplementation in mushroom crops and its impact on yield and quality. AMB Express, 8: 146–154.

Castillo, J.V. 2004. Inoculating composted pine bark with beneficial organisms to make disease suppressive compost for container production in Mexican forest nurseries. Fall 2004, pp. 181–185.

Chalfin, J. Date unknown. Mushroom compost Q & A. Accessed on 15 June 2019. <https://pasafarming.org/mushroom-compost-qa/>.

Chen, Y., Chefetz, B., van Heemst, J.D.H., Hatcher, P.G., Rosario, R. and Romaine, C.P. 2000. Chemical nature and composition of compost during mushroom growth. Compost Science & Utilization, 8(4): 347–359.

Coelle-Castillo, M.M., Sánchez, J.E. and Royse, D.J. 2009. Production of *Agaricus bisporus* on substrates pre-colonized by *Scytalidium thermophilum* and supplemented at casing with protein-rich supplements. Bioresource Technology. 100: 448–4492.

Coker, C. 2012. Odor defense strategy. BioCycle, 53(5): 35.

Coker, C., Goossen, D., Kelly, J., Hazelrigg, A. and Maia, G. 2016. Compost bioassay tests show persistent herbicide impacts. BioCycle, 57(3): 53–57.

Colmenares-Cruz, S. Sanchez, J.E., and Valle-Mora, J. 2017. *Agaricus bisporus* production on substrates pasteurized by self-heating. AMB Express. 7: 135.

Commonwealth of Australia. 2017. National food waste strategy halving Australia's food waste by 2030. Commonwealth of Australia, Canberra.

Costa, M.S.S. de M., Bernardi, F.H., Costa, L.A. de M., Pereira, D.C., Lorin, H.E.F., Rozatti, M.A.T. and Carneiro, L.J. (2017). Composting as a cleaner strategy to broiler agro-industrial wastes: Selecting carbon source to optimize the process and improve the quality of the final compost. *Journal of Cleaner Production*, 142: 2084–2092.

Ekman, J. 2017. Pre- and post-harvest management of mushrooms: A review. Horticulture Innovation Australia Limited, Sydney.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Epstein, E. 1997. The science of composting. Technomic Publishing Co., Inc., Lancaster, Pennsylvania.

Finstein, M.S. and Hogan, J.A. 1992. Integration of composting process microbiology. Facility structure and decision-making. Renaissance Publications, Columbus OH, Proceedings of the International Composting Research Symposium.

Forbes, L. 2019. Australia's livestock feed supplies in precarious position due to drought. Accessed on 27 June 2019. < https://www.abc.net.au/news/rural/2019-05-09/livestock-feed-supplies-shortage-due-to-drought/11092472>.

Gbor, N. Date unknown. War on waste: It's time to step off the fashion trend-mill. Accessed on 22 July 2019. <http://about.abc.net.au/war-on-waste-its-time-to-step-off-the-fashion-trend-mill/>.

González-Matute, R. and Rinker, D.L. 2006. Compatibility of ammonia suppressants used in poultry litter with mushroom compost preparation and production. Bioresource Technology, 97: 1679–1686.

González-Matute, R., Figlas, D. and Curvetto, N. 2010. Sunflower seed hull based compost for *Agaricus blazei* Murrill cultivation. International Biodeterioration & Technology, 64: 742–747.

Grains Research and Development Corporation. 2018. Grownotes. Accessed 28 June 2019. <https://grdc.com.au/__data/assets/pdf_file/0035/369287/GrowNote-Canola-West-0-Introduction.pdfhttps://grdc.com.au/about/our-industry/growing-regions>.

Grains Research and Development Corporation. 2019. Growing regions. Accessed 27 June 2019. <https://grdc.com.au/about/our-industry/growing-regions>.

Grant, B. 2012. Horse stable organics resource recovery opportunity assessment. Blue Environment/BEAM Mitchel Environment Group, Surry Hills.

Grimm, D. and Wösten H.A.B. 2018. Mushroom cultivation in the circular economy. Applied Microbiology and Biotechnology, 18: 7795–7803.

Grocycle. Date unknown. Growing mushrooms in coffee grounds. Accessed 12 June 2019. <https://grocycle.com/growing-mushrooms-in-coffee-grounds/>.

Haug, R.T. 1993. The practical handbook of compost engineering, L. Publishers, Boca Raton, Florida.

Hoa, H.T., Wang, C. and Wang, C. 2015. The effects of different substrates on the yield, and nutritional composition of two mushrooms (*Pleurotus ostreatus and Pleurotus cyctidiosus*) Mycobiology, 43(4): 423–434.

Hochman, Z., Gobbett, D.L. and Horan, H. 2017. Climate trends account for stalled wheat yields in Australia since 1990. Global Change Biology, 23(5): 2071–2081.

Hoitink, H.A.J. and Fahy, P.C. 1986. Basis for the control of soilborne pathogens with composts. *Annual Review of Phytopathology*, 24: 93–114.

Hort Innovation. 2018. Australian horticulture statistics handbook. Horticulture Innovation Australia Limited, Sydney.

Hort Innovation. Date unknown. Mushroom strategic investment plan 2017–2021. Horticulture Innovation Australia Limited, Sydney.

Howard, R.J., Garland, J.A. and Seaman, W.L. (eds) 1994. Diseases and pests of vegetable crops in Canada: an illustrated compendium. The Canadian Phytopathological Society and the Entomological Society of Canada.

Janssen, J. 2016. Aerated composting. A silent practical breakthrough. Proceedings of the International Society for Mushroom Science, 19: 175–179.

Jurak, E. 2015. How mushrooms feed on compost: Conversion of carbohydrates and lignin in industrial wheat straw based compost enabling the growth of *Agaricus bisporus*. Dissertation, Wageningen University.

Kamenik, I. and Marecek, J. 2011. The use of waste cellulose in production of white mushroom substrate. Acta Universitatis Agriculturae Et Silvicultura Medelianae Bruensis, Volume 15(5): 131–136.

Kertesz, M.A., Bell, T.L. and Safianowicz, K. 2015. Improving consistency of mushroom compost through control of basic biotic and abiotic parameters. Final Report MU10021. Horticulture Innovation Australia Limited, Sydney.

Krupodorova, T.A. and Barshteyn, V.Y. 2015. Alternative substrates for higher mushrooms mycelia cultivation. Journal of BioScience and Biotechnology, 4(3): 339–347.

Kumar, A.P., Kumar, C.D., Anil, P. and Johri, B.N. 2011. Bacterial diversity in a bagasse-based compost prepared for the cultivation of edible mushrooms *Agaricus bisporus*. Journal of Agricultural Technology, 7(5): 1303–1311.

Kyung, K., Lee, H., Jung, Y., Jang, K. and Yoon, M. 2010. Influence on composting of waste mushroom bed from *Agaricus bisporus* by using mixed organic carbon sources. Korean Journal of Soil Science and Fertilizer, 43.

Leiva, F.J., García, J., Martínez, E., Jiménez, E. and Blanco, J. 2017. Scenarios for the reduction of environmental impact in *Agaricus bisporus* production. Journal of Cleaner Production, 143: 200–211.

Linnenlueacke, M. 2019. Sugarcane industry weathers climate change. Accessed 26 July 2019. <https://future.business.uq.edu.au/sugarcane-industry-weathers-climate-change>.

Liu, R., Yu, H. and Huang, Y. 2005. Structure and morphology of cellulose in wheat straw. Cellulose, 1: 25–34.

Lyons, G.A., Sharma, H.S.S., Cheung, L., Moore, S. and Kilpatrick, M. 2006. Monitoring of changes in substrate characteristics during mushroom compost production. Journal of Agricultural and Food Chemistry, 54(13): 4658–4667.

Mammiro, D.P. and Royse, D.J. 2008. The influence of spawn type and strain on yield, size and mushroom solids content of *Agaricus bisporus* produced on non-composted and spent mushroom compost. Bioresource Technology, 99(80): 3205–3212.

Manu-Tawiah, W. and Martin, A.M. 1986. Cultivation of *Pleurotus ostreatus* mushroom in peat. Journal of the Science of Food and Agriculture, 37: 833–838.

Matute, R.G. 2011. *Agaricus blazei* production on non-composted substrates based on sunflower seed hulls and spent oyster mushroom substrate. World Journal of Microbiology and Biotechnology, 27(6): 1331–1339.

Mellilo, J.M., Aber, J.D., Linkins, A.E., Ricca, A., Fry, B., Knute, J. and Nadelhoffer, J. 1989. Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic matter. Plant and Soil, 115(2): 189–198.

Miller, F. and Macauley, B. 1989. Substrate usage and odors in mushroom composting. Australian Journal of Experimental Agriculture, 29: 119–124.

Miller, F.C., Harper, E.R., Macauley, B.J. and Gulliver, A. 1990. Composting based on moderately thermophilic and aerobic conditions for the production of commercial mushroom growing compost. Australian Journal of Experimental Agriculture, 30(2): 287–296.

Mupondi, L.T., Mnkeni, P.N.S. and Brutsch, M.O. 2006. The effects of goat manure, sewage sludge and effective microorganisms on the composting of pine bark and the nutritional value of composts. Compost Science and Utilization, 14: 201–210.

Nair, N.G. and Markham, J. 2008. Recycling solid waste from the olive oil extraction process. Rural Industries Research and Development Corporation, Canberra.

Nell, J.H. and Krige, P.R. 1971. The disposal of abattoir waste by composting. Water Research, 5: 1177–1189.

New South Wales Department of Primary Industries. 2007. Sweet corn growing. Accessed 27 June 2019. <https://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/commodity-growing-guides/sweet-corn>.

Noble, R. 2008. Mushrooms: Carbon and nitrogen sources for organic and odourless mushroom composts. Final report for the Agriculture and Horticulture Development Board, United Kingdom.

Noble, R. 2010. Mushrooms: Effect of mixing proportions of phase II and phase III composts on cropping. Final report for the Agriculture and Horticulture Development Board, United Kingdom.

Noble, R. and Dobrovin-Pennington, A. 2005. Partial substitution of peat in mushroom casing with fine particle coal tailings. Scientia Horticulturae, 104(3): 351–367.

Noble, R., Fermor, T.R., Lincoln, S., Dobrovin-Pennington, A., Evered, C., Mean, A. and Li, R. 2003. Primordia initiation of mushroom (*Agaricus bisporus*) strains on axenic casing carbon sources. Mycologia. 95(4): 620–629.

Noble, R. and Gaze, R.H. 1996. Preparation of mushroom (*Agaricus bisporus*) composts in controlled environments: Factors influencing compost bulk density and productivity. *International Biodeterioration and Biodegradation*, 37: 93–100.

Noble, R., Hobbs, P.J., Dobrovin-Pennington, A. and Mead, A. 2002. Influence of straw types and nitrogen sources on mushroom composting emissions and compost productivity. Journal of Industrial Microbiology & Biotechnology, 29(3): 99–110.

Noguerira de Andrade, M.C., Zied, D.C., Minhomi, M.T. and de Filho, A. J. K. 2008. Yield of four *Agaricus bisporus* strains in tree compost formulations and chemical composition analyses of the mushrooms, Brazilian Journal of Microbiology, 39(3).

Norstedt, R.A., Barkdoll, A.W. and Schroeder, R.M. 1993. Composting of yard wastes. In Science and engineering of composting: Design, environmental, microbiological and utilization aspects, HAJ Hoitink and H Keener (eds). Renaissance Publications, Ohio.

Owaid, M.N., Abed, A. M. and Nassar, B.M. 2015. Recycling cardboard wastes to produce blue mushroom *Pleurotus ostreatus* in Iraq. Emirates Journal of Food and Agriculture, 27(7): 537–541.

Owaid, M.N., Barish, A. and Shariati, M.A. 2017a. Cultivation of *Agaricus bisporus* (button mushroom) and its usages in the biosynthesis of nanoparticles. Open Agriculture, 2: 537–543.

Owaid, M., Muslat, M. and Al-Assaffii, I. 2017b. Cultivation of *Agaricus bisporus* X25 on reed plant (*Phragmites australis*) straw decomposed by using actinomycetes. Hacettepe Journal of Biology and Chemistry, 45.

Pardo-Gimenez, A. and Pardo-Gonzalez, J.E. 2008. Evaluation of casing carbon sources made from spent mushroom substrate and coconut fibre pith for use in production of *Agaricus bisporus* (Lange) Imbach. Spanish Journal of Agricultural Research, 4: 683–690.

Pardo-Gimenez, A., Pardo-Gonzalez, J.E. and Zied, D.C. 2011. Evaluation of harvest mushrooms and viability of *Agaricus bisporus* growth using casing carbon sources made from spent mushroom substrate. International Journal of Food Science and Technology, 46(4).

Pardo-Gimenez, A., Zied, D.C. Alvarez-Orti, M. Rubio, M. and Pardo, J.E. 2012. Effect of supplementing compost with grapeseed meal on *Agaricus bisporus* production. Journal of the Science of Food and Agriculture, 92(8).

Peace, C. 2016. Crops for hay understanding the local regional and export markets. Grains Research Development Corporation, Canberra.

Peace, C. 2019. Hay — how is it stacking up?. Grains Research Development Corporation, Canberra.

Penn State University. 2011. Substrate preparation for white button mushrooms. Accessed 12 June 2019. <https://extension.psu.edu/substrate-preparation-for-white-button-mushrooms>

Penn State University. 2017. Basic procedures for *Agaricus* mushroom growing. Accessed 12 June 2019. <https://extension.psu.edu/basic-procedures-for-agaricus-mushroom-growing>.

Philippousis, A.N. 2009. Production of mushrooms using agro-industrial residues as substrates. In: P. Singh nee' Nigam, A. Pandey (eds.), Biotechnology for agro-Industrial residues utilisation, pp. 163–196. Springer Science & Business Media, Berlin.

Pickin, J., Randell, P., Trinh, J. and Grant, B. 2018. National waste report 2018 final. Department of the Environment and Energy, Canberra.

Potočnik, I. Vukojević, J., Kosanović, D., Rekanović, E., Stepanović, M. and Milijašević-Marčić, S. 2012. Impact of fungicides used for wheat treatment on button mushroom cultivation, Pesticidi I Fitomedicina, 27:9–14.

Rangel, J.L., Leal, H., Palacios-Mayorga, S., Sanchez, S., Ramirez, R. and Mendex-Garcia, T. 2006. Coconut fiber as casing material for mushroom production. Terra Latinoamericana, 24(2): 207–213.

Rao, M.S., Reddy, P.P. and Tewari, R. P. 1991. Comparative efficacy of certain oil cakes against mushroom nematode, *Aphelenchoides acchari* and their effect on yield of *Agaricus bisporus*. Indian Journal of Nematology, 21(2): 101–106.

Rosen, C.J., Halbach, T.R. and Mugaas, R. 2000. Composting and mulching: a guide to managing organic yard wastes. University of Minnesota Extension Service, Minnesota.

Ross, R.C. and Harris, P.J. 1982. Some factors involved in phase II of mushroom compost preparation. Scientia Horticulturae, 17(3): 223–229.

Ruan, R., Ding, L., Luo, Y. and Ruan, H. 2011. Cultivation of *Agaricus bisporus* in vineyards using spent pig litter. Acta Edulis Fungi, 18(3): 31–34.

Russ, C.F. and Yanko, W.A. 1981. Factors affecting *Salmonellae* repopulation in composted sludges. Applied Environmental Microbiology, 41: 597–602.

Sanchez, C. 2004. Modern aspects of mushroom culture technology. Applied Microbiology and Biotechnology, 64(6): 756–762.

Sanchez, J.E., Mejia, L. and Royse, D. J. 2008. Pangola grass colonized with *Scytalidium thermophilum* for production of *Agarics bisporus*. Bioresource Technology, 99(3): 655–662.

Sanchez, J. E. and Royse, D. J. 2009. *Scytalidium thermophilum*-colonized grain, corncobs and chopped wheat straw for substrates for the production of A*garicus bisporus.* Bioresource Technology, 100(4): 1670–1674.

Sanchez, J.E. and Royse, D. J. 2001. Adapting substrate formulas used for Shiitake for production of brown *Agaricus bisporus*. Bioresource Technology, 77(1): 65–69.

Sassine, Y.N., Ghora, Y., Kharrant, M., Bohme, M. and Abdel-Mawgood, A.M.R. 2005. Waste paper as an alternative for casing soil in mushroom (*Agaricus bisporus*) production. Journal of Applied Sciences Research, 1(3): 277–284.

Savoie, J.M., Vedie, R., Blanc, F., Minvielle, N., Rousseau, T. and Delgenes, J.P. 2011. Biomethane digestate from horse manure, a new waste usable in compost for growing the button mushroom, *Agaricus bisporus*? Proceedings of the 7th International Conference on Mushroom Biology and Mushroom Products, 176–181.

Shekhar Sharma, H.S. and Kilpatrick, M. 2000. Mushroom (*Agaricus bisporus*) compost quality factors for predicting potential yield of fruiting bodies. Canadian Journal of Microbiology, 46(6): 515–519.

Sithole, S.C., Mugivhisa, L.L., Amoo, S.O. and Olowoyo, J.O. 2017. Pattern and concentrations of trace metals in mushrooms harvested from trace metal-polluted soils in Pretoria, South Africa. South African Journal of Botany, 108: 315–320.

Smith, J.F. and Spencer, D.M. 1977. The use of high energy carbon sources in rapidly prepared mushroom composts. Scientia Horticulturae, 7: 197–205.

Stoknes, K., Beyer, D.M. and Norgaard, E. 2013. Anaerobically digested food waste in compost for *Agaricus bisporus* and *Agaricus subrufescens* and its effect on mushroom productivity. Journal of the Science of Food and Agriculture, 93(9): 2188–2200.

Stoknes, K., Høiland, K., Norgaard, E. and Hammer, J.P. 2008. From food to waste to food—a high yield of mushrooms from food-waste compost. Proceedings of the 17th Congress of the International Society for Mushroom Science, pp. 273–287.

Straatsma, G., Gerrits, J.P.G., Amsing, J.G.M., Van Griensven, L.J.L.D., Thissen, J.T.N.M. and Loeffen, H. 2000. Adjustment of the composting process for mushroom cultivation based on initial substrate composition. Bioresource Technology, 72(1): 67–74.

Tavakoli, H., Mohtasebi, S.S. and Jafari, A. 2008. A comparison of mechanical properties of wheat and barley straw. Agricultural Engineering International: CIGR Journal, 10: 1–9.

Vazquez, J.E.S., Royse, D.J., and Hernandez, G. 2002. Development of non-composted substrates for production of *Agaricus bisporus*. Accessed 12 June 2019. <https://setascultivadas.com/2004articulomayoingles.html>.

Wang, L., Mao, J., Zhao, H., Li, M., Wei, Q., Zhou, Y. and Shao, H. 2016. Comparison of characterization and microbial communities in rice straw- and wheat straw-based compost for *Agaricus bisporus* production. Journal of Industrial Microbiology and Biotechnology: (9), 1249–1260.

Wang, Q., Li, B.B., Li, H. and Han J.R. 2010. Yield, dry matter and polysaccharides content of the mushroom *Agaricus blazei* produced on asparagus straw substrate. Scientia Horticulturae, 125(1): 16–18.

Watson, K. and Weidemann, S.G. 2018. Review of fresh litter supply, management and spent litter utilisation. AgriFutures Chicken Meat, Wagga Wagga.

Watts, P. and McCabe, B. 2015. Feasibility of using feedlot manure for biogas production. Meat & Livestock Australia, Sydney.

Wilkinson, K., Paulin, R., Tee, E. and O'Malley, P. 2002. Grappling with compost quality down under. Proceedings of the International symposium on composting and compost utilization, pp. 527–539. Ohio State University, Columbus Ohio.

Wilkinson, K., Tee, E. and Hood, V. 2000. Does AS4454 adequately benchmark compost quality. Proceedings of the Compost 2000 Down Under Conference, Melbourne, Vic.

Wright, C.T., Pryfogle, P.A., Stevens, N.A., Steffler, E.D., Hess, J.R. and Ulrich, T.H. 2005. Biomechanics of wheat/barley straw and corn stover. Applied Biochemistry and Biotechnology, 121: 5–19.

Zakaei, M., Bazyar, S., and Khanehbad, M. 2011. Post technology casing soil with the use of vermicompost in mushroom (*Agaricus bisporus* (L.)) Sing.) cultivation. The Quarterly Journal of Animal Physiology and Development, 4(1): 19–26.

Attachment A:
Potential alternative substrates and viability analysis

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Attachment A: Table of potential alternative substrates and viability analysis. *Options are 1) Proceed for feasibility analysis, no current barriers for use, or 2) Proceed for feasibility analysis, possible barriers for use, or 3) Do not proceed for feasibility analysis, unlikely to be adopted in Australia ** Accessed via science-direct, a not-publicly available scientific database

Compost substrate	Where used	How used	Research and development	Viability analysis (options 1 – 3)*	Relevant references
Substrates used in industry or considered in scientific literature					
Horse, pig and chicken bedding/litter	Europe, USA, Asia	Currently used for *A. bisporus*, and includes both C and N sources	Currently used for *A. bisporus*	1	Penn State University 2017 Penn State University 2011 Savoie et al. 2011 González-Matute and Rinker, 2006
Peat	Europe and Americas	Traditionally in compost and now just in casing	No longer used in compost	3 – No peat production in Australia	
Paper and cardboard	UK, USA	Currently being used for oyster mushrooms as a substrate, and is noted as an alternative to wheat straw	As an alternative casing for *A. bisporus*	2 – Physical impacts on compost structure	Manu-Tawiah and Martin 1986 Sassine et al. 2005 Owaid et al. 2015 Owaid et al. 2017a Bisht and Harsh 1985
Spent or fresh grain	USA	Used in oyster and other Japanese varieties	On fresh grain such as millet for *A. bisporus*	1	Sanchez and Royse 2009 Penn State University 2011 Bechara et al. 2006a Sanchez et al. 2008 Bechara et al. 2007
Spent coffee grounds	Australia and worldwide	Oyster mushroom cultivation	Non-peer review research available for *A. bisporus*.	2 – Not specific to *A. bisporus*	Growcycle ND Vazquez et al. 2002
Corn stover	USA, Asia, Africa, India	*Calocybe indica* tropical mushroom, oyster mushrooms, *A. bisporus*	On corncob for *A. bisporus* and for maize by-products for oyster mushrooms	1	Penn State University 2017 Sanchez and Royse 2009 Adjapong et al. 2015 Penn State University 2011 Sanchez et al. 2008 Hoa et al. 2015 Colmenares-Cruz et al. 2017 Owaid et al. 2017a

Compost substrate	Where used	How used	Research and development	Viability analysis (options 1 – 3)*	Relevant references
Seed hulls (cottonseed, cocoa, wheat, soy)	Worldwide	Used for oyster and Japanese mushroom varieties	Available for some species including *A. blazei*	2 – Not specific to *A. bisporus*	Krupodorova and Barshteyn 2015 Matute and Curvetto 2010 Also see non-composted substrate below
Oil seed waste (e.g. seeds, wheat germ, nuts, olive etc.)	Worldwide	Various species as a non-composted substrate; olive mill solid waste found to increase mushroom yields over traditional compost substrates (Altieri et al., 2009)	Some available for *A. bisporus*	1	Krupodorova and Barshteyn 2015 Pardo-Gimenez et al. 2012 Rao et al. 1991 Altieri et al. 2009 Also see non-composted substrate below
Crop waste (non-wheat cereal straw, rice and cotton, asparagus straw, hay)	Worldwide	*Calocybe indica* tropical mushroom, oyster, shiitake, shimeji and others. A. *bisporus* compost production for hay	For *A. blazei.* Life-cycle assessment shows hay has lowest impact of C-substrates	2 – far less alternative crops grown than under wheat. Summer alternatives limited to Northern Region	Amin et al. 2010 Wang et al. 2010 Owaid et al. 2017a Nogueira de Andrade et al. 2008 Kumar et al. 2011 Barman et al. 2017 Kyung et al. 2010 Ruan et al. 2011 **Leiva et al. 2017
Sugar bagasse	Asia	*Calocybe indica* tropical mushroom	For *Calocybe indica*	1	Amin et al. 2010 Hoa et al. 2015 Nogueira de Andrade et al. 2008 Kumar et al. 2011
Coconut coir	Asia, South America, India	*Calocybe indica* tropical mushroom as casing material	For *Calocybe indica* and A. bisporus as casing material	3 – no coconut industry in Australia	Amin et al. 2010 Pardo-Gimenez and Pardo-Gonzalez 2008 Rangel et al. 2006

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Compost substrate	Where used	How used	Research and development	Viability analysis (options 1 – 3)*	Relevant references
Wood chips and sawdust	Worldwide	Usually used for Japanese mushroom varieties (shimeji, miatake) and also oyster. Commonly used in combination with other substrates, such as seed hulls and oil seed waste	For *A. bisporus*	2 – Not specific to *A. bisporus*	Sanchez et al. 2008 Hoa et al. 2015 Kamenik and Marecek 2011 Kyung et al. 2010 Ruan et al. 2011 See oil seed waste and seed hull waste
Green waste - leaves, grass cuttings, wood chip, mulched green matter (municipal sourced)	Not currently being used	Can also be used in Vermicompost.	No R&D available	2 – minimal research initially but could be viable	See Vermicompost, wood chips and sawdust
Food waste	Tea leaves being used in Asia and India	Research and development only. May also be used post-processed as vermicompost	Research on waste tea leaves for *A. bisporus,* and food waste converted to vermicompost	2 – some research available, too many issues associated with plastic, glass and metal contamination	Owaid et al. 2017a Barman et al. 2017 See Vermicompost
Other potential substrates, not specifically identified/used by industry or in scientific literature					
Green waste - leaves, grass cuttings, wood chip, mulched green matter (supplier or single origin sourced)	Worldwide	Whole logs used for shiitake mushroom production	Some R&D available on grasses for *A. bisporus* as well as Lantana	2– minimal research initially but could be viable	Sanchez et al. 2008 Colmenares-Cruz et al. 2017 Bisht and Harsh 1985 Owaid et al. 2017a Owaid et al. 2017b See woodchips and sawdust
Biosolids (processed sewage also known as Municipal Solid Waste)	Not currently being used	Not currently being actively used	No Research and development available. Biosolids are considered high risk for agriculture by Environmental Protection Authorities due to chemical contaminant loading.	3 – chemical risks too substantial	-

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Compost substrate	Where used	How used	Research and development	Viability analysis (options 1 – 3)*	Relevant references
Coal/Brown Coal	Not currently being used	Not currently being actively used	For casing carbon sources only	3 – chemical risks too substantial	Noble and Dobrovin-Pennington 2005 Noble et al. 2003
Vermicompost	Not currently being used	Research and development only	For *A. blazei* and *A. bisporus* for use as a partial casing and enriching compost substrate	3 – Vermicomposting is not a major industry in Australia	Matute and Curvetto 2010 Zakaei et al. 2011 Barman et al. 2017
Paunch	Investigated in South Africa	For use in general compost	Only for use in general compost	3 – limited research available	**Nell & Krige 1971
Dairy by-products (e.g. whey)	Laboratory scale experiments	Research and development only	For *A. bisporus*	3 – limited research available	**Smith and Spencer 1977
Other potential approaches					
Re-use of spent compost/partial reuse of spent compost	In Australia and abroad	At ratios of 1 part spent compost to between 3 and 5 parts fresh mushroom compost	For *A. bisporus* and other species, including as casing material	1	Mamiro and Royse 2008 Matute and Curvetto 2010 Pardo-Gimenez et al. 2011 Barman et al. 2017
Re-use of spent substrates e.g. casing layer, other mushroom composts (not *A. bisporus*)	Not currently being used	Research and development only	For *A. blazei* and *A. bisporus*	2 – research stage only	Matute and Curvetto 2010 Bisht and Harsh 1985
Partial substitution – wheat with other substrates OR blends	Asia, America, EU	Used in some cases e.g. rice straw instead of wheat straw in Asia, or for Japanese mushroom varieties	For wheat straw mixed with other substrates for *A. bisporus*	2 – research stage only	Sanchez and Royse 2009 Penn State University 2011 Kamenik and Marecek 2011 See Crop Waste, Oil Seed Waste, Woodchips and sawdust

Compost substrate	Where used	How used	Research and development	Viability analysis (options 1 – 3)*	Relevant references
Non-composted substrate from grain and seed waste e.g. millet, soybean, rye, sawdust, bran, oil sunflower seed waste, Pangola grass, soybean, blackbean and cowpeas	USA, Asia, Mexico	Usually used for Japanese mushroom varieties (shimeji, miatake) and also oyster, and various other species A study using different proportions of corn by-products (oil, bran, and gluten) found yields did not decrease from substrates composed of cracked soybean (Arce-Cervantes et al. 2015) Sunflower seed hulls used successfully as carbon substrate for *A. bisporus* Research in Mexico and USA on colonisation by *Scytalidium thermophilum* on non-composted substrates including Pangola grass, soybean, blackbean and cowpeas. Has also been evaluated in casing carbon sources	Currently actively used for Japanese varieties, and in research and development for other species. R&D for *A. bisporus* Research. No known commercial uptake so far	1 for non- *A. bisporus* mushrooms 2 for the use of non-composted substrates for cultivation of *A. bisporus*	Krupodorova and Barshteyn 2015 Bechara 2007 Sanchez 2004 Mamiro and Royse 2008 Bechara et al. 2006a Matute and Curvetto 2010 Sanchez and Royse 2001 Bechara et al. 2006b Bechara et al. 2007 Vazquez et al. 2002 **Arce-Cervantes et al. 2015 **González Matute et al., 2010 **Coello-Castillo et al. 2009 **Sanchez and Royse 2008 Sanchez et al. 2009 See oil seed waste, and grain

Attachment B:
Stakeholder feedback

Confidential

Detail contained in Attachment B has been redacted in the public version of the report in line with Hort Innovation's privacy policy.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Attachment C:
Ready reckoner

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Ready reckoner — trialling an alternative to wheaten straw for mushroom composting

The substrates used to make mushroom compost provide a source of energy, nutrients, and a physical structure from which mushrooms can grow. Straw harvested from wheat is one of the main ingredients in Australian mushroom compost and has ideal nutritional and physical properties. Due to changing farming practises, competition from feedstock industries, and climate change, the supply of straw is becoming more competitive and difficult to secure.

Other substrates can be used to supply the nutrients and the physical structure usually provided by wheaten straw in mushroom compost. Some of these substrates have an advantage over wheaten straw, as they are closer to mushroom composting enterprises or are cheaper in price. Developing productive substrates from these materials could contribute to lowering the costs of production for mushroom farmers.

The ready reckoner on the following pages presents an outline of alternative carbon sources from which new mushroom substrates can be developed. It is important to note commercial strains of *Agaricus bisporus* were developed and optimised for straw based mushroom compost. While significant research and development is required to develop new substrates for mushroom compost, mushroom farmers can begin to investigate alternatives to wheaten straw with the use of this Ready Reckoner. We suggest beginning cautiously with on-farm trials. Start by substituting a small amount of wheaten straw for an alternative carbon source, and increase the rate of substitution as confidence in the new substrate grows.

Ready reckoner - which substrate should be trialled as replacement for wheaten straw?

Carbon source	Rate of substitution for wheaten straw (%)*	Rating criteria and weighting (%): Chemical quality (10%)	Physical quality (15%)	Health and safety risk rating (5%)	Commercial risk rating (30%)	Transport (10%): Melbourne	Transport (10%): Sydney	Transport (10%): Adelaide	Price rating (10%)	Research & develop-ment (20%)	Total score relative to wheaten straw (%)
Wheaten straw	*0*	*5*	*5*	*4*	*3*	*3*	*3*	*3*	*1*	*4*	***100***
Paper waste	<20 only	4	1	3	3	5	5	5	5	2	**75**
Bark and woodchips (blend)	40-100	3	3	5	1	4	3	2	4	1	**55**
	<40	3	3	5	2	4	3	2	4	2	**75**
Sugar bagasse	40-100	4	4	3	2	1	1	1	4	2	**70**
	<40	4	4	3	3	1	1	1	4	3	**85**
Corn crop waste	40-100	4	4	3	2	2	2	1	4	2	**70**
	<40	4	4	3	3	2	2	1	4	3	**80**

*Rate of substitution for wheat affects commercial risk and extent of R&D required. All other factors are the same for each carbon source except for regional variation in transport costs

Rating description	
>60	Potential substitute which requires substantial research and development to address commercial, health or disease risks, or has substantial transport or cost constraints
60+	Potential substitute which requires research and development to address commercial, health or disease risks, or has large transport or cost constraints
70+	Potential substitute with some commercial, health, or disease risks, with some transport or cost constraints
80+	Viable substitute with minimal commercial, health, or disease risks with few transport or cost constraints
90+	Highly viable substitute with negligible commercial, health, or disease risks, with minimal transport or cost constraints

Ready reckoner - which substrate should be trialled as replacement for wheaten straw?

Individual category rating description	
Chemical quality rating	
1	Poor degradability/source of energy for *Agaricus bisporus*
2	Limited degradability/source of energy for *Agaricus bisporus*
3	Good degradability/source of energy for *Agaricus bisporus*
4	Desirable degradability/source of energy for *Agaricus bisporus*
5	Optimal degradability/source of energy for *Agaricus bisporus*
Physical quality rating	
1	Poor source of physical structure
2	Inadequate source of physical structure
3	Structurally adequate
4	Structurally desirable
5	Structurally optimal
Health and safety risk rating	
1	Highly prone to human risks and disaease or chemical contamination relative to other composting substrates
2	Prone to human risks and diseases or chemical contamination relative to other composting substrates
3	Some proneness to human risks and diseases or chemical contamination relative to other composting substrates
4	Not prone to human pests and diseases or chemical contamination relative to other composting substrates
5	No known human pests and diseases or sources of chemical contamination
Commercial risk rating	
1	High uncertainty in compost quality or yeild of mushroom produced relative to wheaten straw based compost
2	Prone to uncertainty in compost quality or yeild of mushroom produced relative to wheaten straw based compost
3	Some proneness to uncertainty in compost quality or yeild of mushroom produced relative to wheaten straw based compost
4	Not prone to uncertainty in compost quality or yeild of mushroom produced relative to wheaten straw based compost
5	No known uncertainty in compost quality or yeild of mushroom produced relative to wheaten straw based compost
Transport	
1	Located more than 700 kms from mushroom composters
2	Between 300 and 700 kms of mushroom composters
3	Between 100 and 300 kms of mushroom composters
4	Within 50 to 100 kms of mushroom composters
5	Within tens of kms from mushroom composters
Price Rating	
1	$300 per tonne or more, plus transport and loading
2	$100 to $300 per tonne, plus transport and loading
3	$25 to $100 per tonne plus transport and loading
4	A nominal fee plus transport and loading
5	Transport and loading only
Research and development	
1	Requires substantial research to develop as viable alternative to wheaten straw
2	Requires further research to develop as viable alternative to wheaten straw
3	Further research is likely to lead to improvements in mushroom yields
4	Further research could lead to improvements in mushroom yields
5	No further research needed

Attachment D: Case studies — shimeji and oyster mushrooms

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Shimeji mushroom case study

Background

The decreased availability of wheaten straw as a carbon source for production of *Agaricus bisporus* mushroom compost inspired a project undertaken by Hort Innovation. The project focuses on a review into alternative carbon sources with a focus on the *A. bisporus* Mushroom Industry, titled "*Feasibility of compost substrate alternatives for mushroom production (MU17007)*". The project was funded by Hort Innovation, using the mushroom research and development levy and contributions from the Australian Government. Hort Innovation is the grower owned, not-for-profit research and development corporation for Australian horticulture. The project short-listed alternative carbon sources to wheaten straw. These alternative sources may also be useful for the cultivation of shimeji mushroom species, with this case study undertaken to help shimeji growers in the selection of compost substrates.

Shimeji mushroom species that are cultivated are mostly saprotrophs, with the exception of *Lyophyllum shimeji* (known as Hon-Shimeji). Saprotrophs grow on dead or decaying organic matter. They gain their energy sources by feeding off the decaying organic matter through the secretion of enzymes allowing energy to be adsorbed through the fungi's cell walls. Shimeji mushroom species include, but are not limited to, *Hypsizygus* species, *Lyophyllum* species and *Agrocybe* species. They are commonly found in East Asia and Europe, usually associated with decaying wood and trees, and are now cultivated worldwide.

Cultivation of shimeji mushroom usually occurs on a range of substrates depending on the species/variety. Buna-shimeji are widely cultivated worldwide using a range of techniques. For example, a mixture of 80% wood (coarse and fine), 10% bran, and 10% cereals are used for Buna-Shimeji, as well as partial and complete substitution with food waste. These substrates have been sterilised or pasteurised prior to use, and then made up to the correct moistness before spawn is added. For other species, such as Hon-Shimeji, there are a range

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

of ingredients in the cultivation mix, with the core carbon substrates being starch and peat moss, or wood logs.

Buna- and Hon-Shimeji species' names are often used interchangeably. In this case study, we refer to shimeji species as a whole.

Suggested carbon alternatives — advantages and disadvantages

Alternative carbon sources for *A. bisporus* compost production were short-listed as being paper, forestry residuals, sugar bagasse and corn stover. These carbon sources were determined to be a feasible for whole or partial replacement of wheaten straw, based on physicochemical properties, cost, accessibility, general nature of hazards and required research and development. We note that the materials short-listed are specific to the cultivation of A. *bisporus*, and different requirements, hazards and research and development will be required for shimejii mushrooms in relation to these substrates.

The following table lists the advantages and disadvantages of each of the five short-listed carbon substrates when specifically considered for cultivation of all shimeji mushrooms. Whilst in general, the alternative carbon sources could be a substitute or are already being used, some research on its use as a replacement for a log or wood is needed. We note, however, that logs (as a forestry residual) will most likely continue to be available under climate change scenarios and thus alternative substrates may not be required. Further research is needed to understand the benefits, hazards and gaps in knowledge for these substrates when used in shimejii mushroom cultivation.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Carbon substrate	Advantage	Disadvantage
Paper	• Has potential to replace some wood • Cheap and easily sourced	• Research needed as a log replacement and in cost/benefit • Potential risk of Trichoderma infection
Forestry residuals	• Logs already being used in Buna-Shimeji production	• Research needed for wood waste as a log replacement
Sugar bagasse	• Hon-Shimeji species are known to be grown in Queensland (Brisbane Metropolitan Area, Granite Belt, Maclean) closer to bagasse sources • Research available on its use for some shimeji species	• Research needed for use as a wood or log replacement • Cost limiting outside Queenlsand • Climate change effects
Corn stover	• Research available on its use for some shimeji species	• Research needed for use as a wood or log replacement • Cost may be high; supply limited to irrigation areas • Climate change effects

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Oyster mushroom case study

Background

The decreased availability of wheaten straw as a carbon source for production of *Agaricus bisporus* mushroom compost inspired a project undertaken by Hort Innovation. The project focuses on a review into alternative carbon sources with a focus on the *A. bisporus* mushroom industry, titled "*Feasibility of compost substrate alternatives for mushroom production (MU17007)*". The project was funded by Hort Innovation, using the mushroom research and development levy and contributions from the Australian Government. Hort Innovation is the grower owned, not-for-profit research and development corporation for Australian horticulture. The project short-listed alternative carbon sources to wheaten straw. These alternative sources may also be useful for the cultivation of oyster (*Pleurotus* spp.) mushroom species, with this case study undertaken to help shimeji growers in the selection of compost substrates.

Oyster mushrooms are primary decomposers. They degrade cellulose, hemicellulose, lignin and other components of plant material. They are able to degrade a range of organic matter carbon sources from straw and crop wastes, to coffee pulp, wood and corn stover. They produce enzymes which help in the degradation of plant material.

Cultivation of oyster mushrooms usually occurs on a range of substrates, depending on the species or variety. They are commonly cultivated on moist straw, hay or sawdust inside polyethylene bags. Spawn occurs between layers of carbon material. The preferred straw or hay is derived from wheat. More recently, spent coffee grounds are also being used to cultivate oyster mushrooms through Life Cykel (https://lifecykel.com/). It is suggested that all carbon sources be pasteurised or sterilised before use.

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958

Suggested carbon alternatives — advantages and disadvantages

Alternative carbon sources for *A. bisporus* compost production were short-listed as being paper, forestry residuals, bagasse and corn stover. These carbon sources were determined to be a feasible for whole or partial replacement of wheaten straw based on physicochemical properties, cost, accessibility, general nature of hazards and required research and development. We note that the materials short-listed are specific to the cultivation of A. *bisporus*, and different requirements, hazards and research and development will be required for oyster mushrooms in relation to these substrates.

The following table lists the advantages and disadvantages of each of the four short-listed carbon substrates when specifically considered for oyster mushrooms. Given that the straw or hay used in oyster mushroom cultivation is largely wheaten, there are plenty of alternatives to this source that are readily available and are already known to be an effective substitute. Three of the alternative carbon sources are already being used commercially. Bagasse is the only substrate not already being used commercially, and will require some research into substrate optimisation and other hazards. Further research is needed to understand the benefits, hazards and gaps in knowledge for these substrates when used in oyster mushroom cultivation.

Carbon substrate	Advantage	Disadvantage
Paper	• Already being used as an alternative to wheat straw • Cheap and easily sourced	• Potential risk of Trichoderma spp. infection
Forestry residuals	• Sawdust already being used • Cheap and easily sourced	• NA
Sugar bagasse	• Has potential to replace wood or straw, with some research available	• Cost limiting outside Queensland • Research and development needed • Climate change effects
Corn stover	• Corn stover already being used	• Cost may be high depending on location of facilities • Supply limited to irrigation areas • Climate change effects

02 6161 1762
contact@murrang.com.au
www.murrang.com.au
ABN 96 162 928 958