The Future of Casing -

Review of Casing Materials and Availability of Peat for Mushroom Cultivation

Ralph Noble[1], Helen Grogan[2], Eoghan Corbett[2], Greg Seymour[3]

[1] Microbiotech Ltd, Pershore College, Pershore, Worcestershire, WR10 3JP, UK

[2] Horticulture Development Department, Teagasc, Dublin 15, D15 DY05, Ireland

[3] International Society for Mushroom Science, Sydney, Australia

Executive Summary

This review examined the likelihood of disruption to the supply of peat casing to the Australian mushroom industry and the best options for delivering a sustainable casing material for Australia. Information for this review was obtained from peer-reviewed literature, technical publications, commercial literature, websites, and personal communications and on-line Zoom meetings with relevant consultees and stakeholders. Over 60 experts from 22 countries in six continents were consulted. A casing layer is essential for button mushroom fruitbody production in quantity. Annually, the global button mushroom industry uses about 4M m^3 of peat for casing of which Australia uses about 2%, mostly imported from Europe with a smaller volume from Canada. Mushroom casing represents around 10% of the global market for peat in growing media, and about 5% of the peat extracted for both growing media and energy. Peat extracted for energy continues to decline which will tend to increase the latter percentage. The regulatory situation regarding peat extraction and use in different European countries is dynamic and is likely to change periodically in the next few years. In Europe, it is becoming increasingly difficult to obtain new permissions for peat extraction and several countries now have phase-out plans for the use of peat in professional horticulture, starting in 2026; there is also pressure from supermarkets to stop using peat in casing. Peat derived from the decomposition of sphagnum moss species has predominated for use in mushroom casing. Although the supply of sphagnum peat from Baltic States, Finland, Sweden and Russia is secure, the quality of the less decomposed milled blond or brown peat is less suitable for mushroom casing than the more decomposed wet-dug dark brown or black peats from Ireland, Germany and Poland. This is partly due to the higher water holding capacity of wet-dug peats resulting in better mushroom yields and quality than from dried milled peats. The supply of peat in North America has been erratic due to unfavourable harvesting and transport conditions rather than environmental pressure. The governments of Great Britain, Norway and Switzerland are planning to prohibit the use of peat in professional horticulture by 2030 and it is likely that other European countries will follow suit. Since the British mushroom market may also be closed to the import of peat-grown mushrooms, major exporting countries such as Ireland, Poland and the Netherlands would also be impacted. However, there is sufficient wet-dug peat from bogs with extraction licences in Europe to supply the mushroom industry for several decades. Even if peat casing is banned for use in Europe, the major casing producers expect to have viable businesses supplying the Southern Hemisphere mushroom industries with wet-dug peat casing. This would depend on shipping costs; dry milled peat or New Zealand peat are alternative options.

There are no 100% peat alternatives which have been shown to produce the same mushroom yields and quality in the same timeframe as wet-dug peat casings; the

discrepancy can be largely attributed to poorer water retention, higher salinity (electrical conductivity) and/or susceptibility to mould growth of peat alternatives. The carbon footprints of peat alternatives are smaller than of peat, even if the energy required for processing and transport for some materials is considered. However, reductions in mushroom production efficiency and recycling of organic wastes into food production and increase in demand for water (e.g. for leaching and irrigation) will negate some or all the environmental benefits of peat substitution. Globally and in Australia, there is currently a plentiful supply of peat alternatives, such as bark and wood fibre products and imported coir although the price is generally higher than of peat. Demand for bioenergy and alternative horticultural uses will increase prices further and may lead to shortages. There is a large supply of recycled growing media in Australia such as spent peat, bark, coir and rockwool from other horticultural sectors which could be re-used as mushroom casing. Mushroom substrates (casing and/or compost) have been recycled to produce new casing although leaching to reduce salinity to an acceptable level is a significant challenge. Developments such as Cormo's TEFA from maize stalks, Newfoss's NFF from bioprocessed plant residues and sphagnum moss (a renewable resource extracted from the surface of degraded peatlands that were formerly mined as opposed to peat which is dug out of virgin peatlands) are undergoing mushroom cropping trials in Europe. All these raw materials are or could be available in Australia in sufficient quantity for casing. Despite a large research effort into peat substitution and replacement in Europe and elsewhere, there is not yet a commercial peat-alternative mix. Substituting a proportion of peat with organic alternatives can increase the risk of moulds, may reduce but not improve mushroom yield and quality, may increase the difficulty and demand for watering, will probably increase cost, and will not be usable if peat is banned. Repeating work now on total peat replacement with organic alternatives in Australia is similarly pointless since wet-dug and dry milled peats are likely to be available for decades. However, there are large supplies of filter-cakes from the quarrying and cane sugar industries in Australia which could replace sugar beet lime and some of the wet-dug peat in a casing blend. Current brown mushroom strains are more suited than white strains to dry milled peat and peat alternatives due to a lower water requirement, less risk of blotch or staining by watering close to harvest and smooth caps which do not attract specks of casing. There is therefore a need for new white strains bred for use on dry milled peat and peat alternative casings. Due to the recent and widespread dependence on imported ready-mixed casing, the casing mixing infrastructure that was previously present in Australia and other countries has been dismantled; this would need to be reassembled if casings are to be prepared from locally available materials.

Research Priorities and Action

- Watching brief on availability of wet-dug peat and dry milled peat for Australia
- Watching brief on the commercial development of peat alternatives elsewhere
- Examine the costs and effects on mushroom yield and quality of replacement of the 15% of imported sugar beet lime in wet-dug peat casing with up to 30% of local materials (sugar mill mud in Queensland and filter cakes elsewhere in Australia)
- Examine the use of these mineral materials with dry milled peat or New Zealand peat in casing
- Explore the cost and availability of mixing and wetting facilities for preparing casing blends
- Test white strain suitability for growing with dry milled peat casing blends.

This project has been funded by Horticulture Innovation Australia Limited (Hort Innovation), using the Australian mushroom industry 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.

Contents

1. Introduction

Information for this review was obtained from peer-reviewed literature, technical publications, commercial literature, websites, and personal communications and on-line Zoom meetings with relevant consultees and stakeholders. Over 60 experts from 22 countries in six continents were consulted in this review. These included scientists, consultants, mushroom growers, casing producers and representatives from other organisations and companies with an interest in peat, growing media and casing. References to the following numbered Zoom meetings are made in the text and a full list of consultees and their affiliations is presented in Appendix I; a template of the invitation email to Zoom meetings is in Appendix II:

Zooms 1, 2: Continental Europe

Zoom 3: Americas

Zoom 4: Pacific

Zoom 5: Asia/ Continental Europe

Zoom 6: Africa, Continental Europe, Israel

Zoom 7: Great Britain

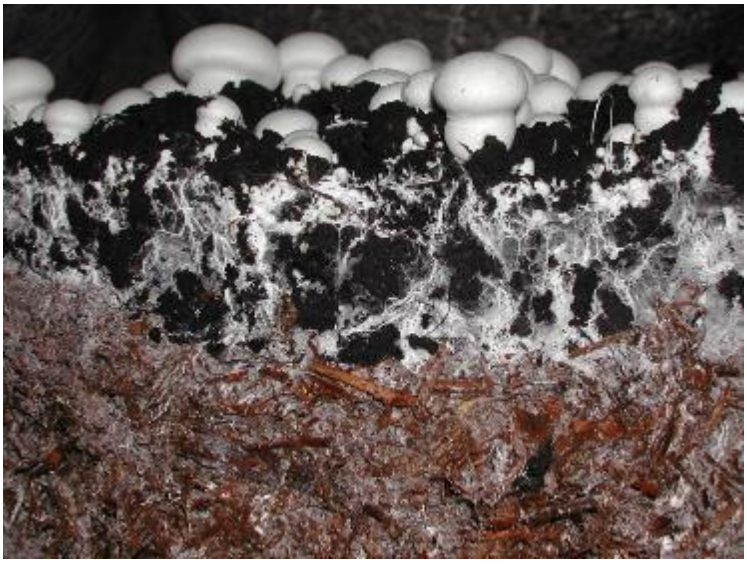
Zoom 8: Ireland/Great Britain/Continental Europe

1.1 What is mushroom casing and why do growers need it / use it

The covering of a mycelium-colonised compost with a layer of casing material or 'soil' (casing) is essential for stimulating and promoting the development of reasonable quantities of sporophores (fruitbodies) in button mushroom (*Agaricus bisporus*) cultivation. If casing is not applied to colonised compost, very few mushrooms develop. Casing functions to help reduce evaporative water loss from the compost, contains a suitable microbiome and allows sufficient gaseous exchange to promote the development of primordia (pins) and acts as a reservoir of water for developing mushrooms. Casing was originally a 1-inch (2.5 cm) depth layer of limestone 'marl', clay or clay-loam soil (Flegg & Wood 1985; Visscher 1988). Peat has been the main component of casing since the 1950s when it replaced soil due to higher and more reliable mushroom yields (Edwards & Flegg 1953). Peat derived from the decomposition of sphagnum moss species has predominated for use in mushroom casing over peat derived from decomposed sedge-grass or reed-sedge due to higher water holding capacity and better structure (Puustjarvi & Robertson 1976; Gallagher 1976). Since the 1950s, mixtures of sphagnum peat and chalk or lime have been used on mushroom farms in most countries, and the depth of the casing has increased to about 5 cm (Visscher 1988; Noble & Gaze 1995). The predominant types of sphagnum peat and lime have also changed from surface milled peat that was dried and baled to wet-dug peat taken from the deeper layers of the peat profile and from ground chalk or limestone to much finer particle sugar

beet lime (Noble & Gaze, 1995). From the 1960s onwards, black wet-dug peat from Germany was used on Dutch shelf farms (Vedder 1978), and later similar peat from England and Scotland was used on some English shelf farms. Until the 1990s, dried milled blond sphagnum peats, such as Vapo from Finland, or milled brown peats such as Novobalt from the Baltic States, Bord na Mona from Ireland or Acadian Moss Peat from Canada were commonly used in Europe and Australia (Noble & Gaze 1995; Nair & Bradley 1981; Huerta et al 2001). Although such less decomposed sphagnum peats are still used for casing in North America, elsewhere they have largely been replaced by the more decomposed wet-dug dark brown or black sphagnum peats for the following reasons:

- drying of peat causes irreversible damage to the structure, reducing the water holding capacity and mushroom yield potential (Noble et al. 1999)
- dry milled peats tend to 'over-pin' and together with lower water holding capacity, can result in smaller mushrooms than wet-dug peat casing (Noble & Dobrovin-Pennington 2005)
- wet-dug peat casing does not need watering between airing and the first flush, resulting in less blemishing and blotch disease of mushrooms
- flecks of dry milled peats tend to stick to mushroom caps (Noble & Gaze 1995)
- dry milled peats are difficult to hydrate, requiring mixing equipment and time, whereas wet-dug peats are ready to use and apply.



Mushrooms growing on wet-dug black peat casing and underlying Phase 3 compost

In the 1960s it was common to harvest five or six flushes of mushrooms from a crop (Genders 1969) and in the 1980s, harvesting four flushes was still widespread (van Gils 1988). The introduction of hybrid mushroom strains meant that nearly all the cropping potential came in the first three flushes. Nowadays, three-flush crops are most common for hand-picking and two flushes for mechanical harvesting. The loss in crop from the fourth flush onwards means casing is now filled into growing rooms more frequently, but this loss in casing use efficiency is outweighed by a greater yield of mushrooms in the first three flushes.

Current mushroom yields on wet-dug peat casing are typically in the range 35-37 kg/m^2, with some yielding up to as much as 40 kg/m^2 with >90% of produce harvested being categorized as class I grade produce. In the Netherlands, around 50% of the crop is mechanically harvested. A higher yield is reported for processing quality mushrooms by way of mechanical means relative to conventional harvesting techniques, however there is an additional requirement that all the mushrooms in the first and second flush must be ready for harvesting in one day (Zooms 1, 7). In Europe, each tonne of mushrooms harvested requires 1.73 m^3 peat for casing (GEPC, European Mushroom Growers Group).

1.2 What is the current situation for casing use in Australia including recycling into other industries

Australian mushroom farms originally used New South Wales peat consisting of grassy or sedge long fibres with relatively little sphagnum, mixed with agricultural lime. By the early 1980s, most farms were using imported peat such as German and Canadian sphagnum peat and adding ground lime at about 5% v/v (Clancy & Horton 1981; Nair & Bradley 1981; Ewan Harper 1993 AMGA Conference, unpublished). By 2000, most Australian farms had switched to imported ready-mixed casing from Europe consisting of wet-dug sphagnum peat mixed with sugar beet lime (Femia 2022). Due to inferior performance, €/$AUS exchange rate, low price of return global shipping containers and dwindling availability of local peat resources, casing production in Australia had ended. The price of imported casing to Australia has recently increased by x2 to x3; using a 5 cm depth casing layer, the cost has increased from €2 to €3 per square metre bed area (Zoom 3).

The mushroom industry utilises organic wastes from other agricultural sectors such as straw and animal manures and converts them into food, with a bioconversion efficacy of substrate into mushrooms of around 25%. Much of the feedstock wastes would otherwise be lost as CO_2 through composting or soil amendment although some are used for energy production through digestion or burning.

Mushroom cultivation in Australia produces around 300,000 m^3 of spent mushroom compost (SMC). The SMC can be recycled into substrates for potting composts, thereby

reducing peat consumption in other sectors of horticulture, although there can be issues getting SMC certified for use in potting mixes (see Section 7.1). SMC can be spread on land as an organic soil amendment. A proportion of SMC can also be recycled back into producing fresh casing.

1.3 What are the concerns of growers and suppliers about the future of casing in Australia

The concerns of mushroom growers and casing suppliers globally are:

(a) Environmental pressure and regulation will prevent the extraction of peat for use in mushroom casing

(b) The relative uncertainty regarding agronomic performance of peat alternatives in terms of mushroom yield and quality. Their principle concern is that alternative casing media, will not provide sufficient performance to maintain economically viable levels of mushroom and casing production.

(c) A reduced availability of peat and an increased competition for resources within the wider bio-circular economy (especially bio-fuel and energy production end-use, either for direct burning or for biochar), is likely to reduce the availability of peat alternative casing components and will generally increase the price of casing.

For Australian mushroom growers and casing suppliers there are additional concerns:

(a) The shipping distance from countries that supply peat or casing means that a reduced availability of peat could make Australia particularly vulnerable

(b) Increases in shipping costs will lead to an increase in the price of casing

(c) Peat alternatives that are developed elsewhere will not be available in quantity or at a sufficiently low price in Australia.

1.4 What this review seeks to achieve

The aim of this review is to inform the AMGA so that it can make decisions on:

(a) The likelihood of disruption to the supply of peat casing to the Australian mushroom industry and the need for remedial action

(b) The best options for alternative casings based on current information

(c) The effects on the environment of switching from peat to alternative casings

(d) The requirements for research and commercial development to deliver a sustainable casing material for Australia.

2. The Science of Casing

2.1 General description

Originally soil was used as casing and work conducted in the 1930s and 1940s showed that clay soils produced better mushroom yields and quality than sandy soils (Genders 1969). Peat has been the main component of mushroom casing in Europe since the mid-late 1950s when it replaced soil due to its higher water holding capacity and mushroom yields (Bels Konig 1950; Edwards & Flegg, 1953). These experiments showed that even in the absence of disease, often a disadvantage of using unsterilized soil (Genders 1969), peat and chalk mixtures produced a better casing material than soil. Since then, mixtures of peat and chalk or lime have been used on almost all mushroom farms in countries where suitable peat is readily available, although the predominant types of peat (wet-dug instead of milled) and lime (sugar beet lime instead or chalk or limestone) have changed (Noble & Gaze 1995). This change has been driven by the increased productivity of mushroom spawn strains and composts, particularly spawn-run (Phase 3) composts, which have put additional demands on a high yielding casing material. Wet-dug peats have a higher water holding capacity than milled peats, enabling them to be heavily watered after application, avoiding the need for watering before the first flush, which can cause bacterial blotch, and the risk of surface 'panning' (Noble et al. 1999). In addition, the move away from wholesale markets to highly competitive multiple retailers in the 1980s and 90s has put additional quality requirements on mushrooms which were improved by the shift from milled peat to wet-dug peat casing (Noble & Gaze 1995).

Dried milled sphagnum peat is widely used for green plant horticultural uses and there has been considerable research and commercial development of peat alternatives for plant growing media. For mushroom casing, the use of wet-dug peat has given additional important cropping benefits over using dried milled peat. Replacing wet-dug peat in mushroom casing with alternatives therefore presents significant research and performance challenges compared with replacing dried milled peat in mushroom casing or in other horticultural (green plant) growing media.

2.2 Physical considerations

A full review of the physical characterisation of casing is given in Noble & Dobrovin-Pennington (2023). This section provides a summary of the main physical considerations. Mushroom fruitbodies obtain about half of their water from the casing and about half from the compost (Kalberer 1986). Attempts to change this ratio by applying a thinner or drier than normal casing to a wetter than normal compost, or vice versa, can result in reduced yields and mushrooms with water stress symptoms such as split stipes and water-soaked areas in

the flesh (Kalberer 1986; Noble 1999; Noble et al. 2001). Good water holding capacity of casing is required to supply water to the mycelium and developing fruitbodies (Flegg & Wood 1985; Visscher 1988). More specifically, casing must provide the following water and air holding characteristics:

- very high capacity of easily available water (>50% v/v); this compares with 26 to 48 %v/v typical of plant growing media (Bunt 1976; Mullholland & Watson 2019)
- good water retention under applied suction (or reserve water) (>15% v/v) (Noble et al. 1999; Barry et al. 2008; Taparia et al. 2021); this compares with 11 to 18 %v/v typical of plant growing media (Bunt 1976; Mullholland & Watson 2019); this property requires micropores and/or small particles
- a structure that allows mushroom mycelium to grow through it and then translocate nutrients and water from the compost to the developing mushrooms (Visscher 1988)
- low to medium air-filled porosity (10-20%) to enable carbon dioxide from the compost to diffuse into the atmosphere and enable fruitbody initiation (Flegg & Wood 1985; Visscher 1988; Noble et al. 2007). This is similar to the optimum values for plant growing media where higher values can be tolerated or desirable if there is frequent or continuous irrigation (see below) (Bunt 1974; Mullholland & Watson 2019)
- Visscher (1988) indicated that following application of casing, a dense casing with low porosity was desirable whereas during fruitbody initiation and cropping a higher porosity was desirable. Mechanical ‘ruffling’ of casing several days after application increases the casing porosity and was widely practiced on shelf farms from the 1970s onwards (Vedder 1978; Visscher 1988). However, since the introduction of compost or spawn ‘caccing’ into the casing at filling, the practice of casing ruffling has largely been superseded without any detrimental effects.

Although Rainey (1985) could find no relationship between water holding capacity of casing and mushroom yield and indicated a much higher optimum air filled porosity than stated above of 30-45% v/v, his casing materials did not include sphagnum peat for comparison. For plant growing media, a high porosity of peat alternatives such as rockwool can be an advantage, as in hydroponic systems where a lower water holding capacity can be compensated by frequent or continuous waterings with automated irrigation systems. In mushroom cultivation, frequent or over-watering can increase the risk of bacterial blotch and waterlogging of the underlying compost. No commercial hydroponic systems have been developed for mushroom cultivation, and problems with contamination were encountered in Dutch experimental systems (Zoom 8).

The casing must also provide the following other physical characteristics and functions (Flegg & Wood1985; Visscher 1988):

- structure must resist compaction or surface ‘panning’ following repeated waterings
- provide sufficient support for developing mushrooms
- prevent the underlying compost from drying out or from being waterlogged by casing leachate
- absence of contaminants such as glass and plastic (most edible crops are not in direct contact with the growing medium, unlike mushrooms which grow on the casing)
- must not stick to the mushrooms since cleanness is a major quality requirement.

2.3 Chemical considerations

Casing must have the following chemical characteristics (Flegg & Wood 1985; Visscher 1988):

- very low soluble nutrient and salt content; mushroom mycelium and yield are very sensitive to osmotic stress (Kalberer 1986; Magan et al. 1995)
- very low content in organic nutrients, otherwise the mycelium remains vegetative and the stimulatory effect of the casing on fruitbody initiation is lost
- a pH value of between 7 and 8.5; lower pH values encourage the growth of green moulds, higher pH values reduce the growth of mushroom mycelium
- absence of heavy metals, oils, terpenes and other volatile organic compounds
- absence of significant concentrations of magnesium, for example by using dolomitic limestone instead of calcium carbonate as a neutralizing agent, since a toxic effect on mushrooms has been reported by some workers.

For plant growing media, background levels of N, P and K and other soluble nutrients can contribute to a reduced fertiliser requirement (Bunt 1976); for mushroom casing, soluble salts are undesirable (Flegg & Wood 1985). They found the concentration of salts in casing increased from 0.07 to 0.49% of dry matter during a crop but did not expect this to affect the mushroom. However, experiments have shown that adding 30-50% recycled casing to fresh casing reduces mushroom yield (Zied et al. 2020; Taparia et al. 2021). The threshold in casing EC before mushroom yield is adversely affected is around 1.5 mS/cm (Barry et al. 2008; Noble & Dobrovin-Pennington 2016a; Taparia et al. 2021). The alkaline pH requirement of casing is an advantage compared with plant growing media where acid to neutral pH values are required since it is easier and cheaper to increase the pH of substrates with chalk or lime than to reduce pH with acids.

2.4 Biological considerations

Casing must contain stimulatory bacteria (*Pseudomonas* species including *P. putida*) necessary for stimulating mushroom initiation since most sterilised casing materials do not

promote fruitbody initiation (Hayes et al. 1969). Colonised mushroom compost as well as peat and a range of non-peat casings contain Pseudomonads including *P. putida* which rapidly multiply in the casing layer after application to cropping beds (Hayes & Nair 1974; Miller et al. 1995; Fermor et al. 2000). Casing Pseudomonads can be closely attached to mushroom mycelium and utilise volatile 8-carbon compounds such as 1-octen-3-ol and 2-ethyl-hexanol it produces as a nutrient source (Miller et al. 1995; Noble et al. 2009). The size of the initial inoculum dose of *P. putida* added to a sterile casing was found to have no effect on the number of primordia produced (Fermor et al. 2000). It is therefore unnecessary to inoculate peat or other casing materials with *P. putida*, particularly if they contain compost 'caccing'. However, a delay in colonisation of casing with stimulatory bacteria, for example following sterilisation, can reduce the number of mushroom primordia formed (Fermor et al. 2000) and subsequent yield (Hayes & Nair 1974), although Taparia et al. (2021) found no significant effect on mushroom yield of steaming casing at 70°C for 8 h. Chemical sterilisation of casing with formaldehyde was used in the Netherlands until the 1980s (Vedder 1978); this did not adversely affect mushroom cropping providing that there was a sufficient delay in allowing the formaldehyde to volatilise. The stimulatory effect of *P. putida* can be replaced by using sterilised activated charcoal or lignite as a casing layer (Fermor et al. 2000; Noble et al. 2009) by removal of the above volatile 8-carbon compounds produced by mushroom mycelium that inhibit fruitbody initiation. However, sterile animal or lumpwood charcoals were ineffective in producing a stimulatory effect.

Despite the need for a stimulatory effect of casing on fruitbody initiation, this is a very inefficient process with less than 5% of the primordia that are initiated progressing to form a fruitbody (Flegg & Wood 1985; Eastwood et al. 2013). The number of primoridia and the proportion that develop into mushrooms are influenced by the casing environment, particularly temperature and the concentrations of carbon dioxide and inhibitory volatiles produced by mushroom mycelium (Eastwood et al. 2013). Crops with large numbers of tightly packed, small mushrooms are referred to as 'over-pinned'. This can be caused by rapid decreases in temperature and carbon dioxide at 'airing' as well as by certain casing materials such as milled peats. However, the relationships between the number of primordia formed and the proportion and numbers that subsequently develop into mushrooms is not fully understood.

Casing must be free from and resistant to colonization by competitor fungi such as green moulds (*Trichoderma* species) which can be abundant in some plant growing media such as bark, wood fibre and coconut fibre (coir). Easily degradable materials such as paper wastes can be colonised by saprophytic fungi such as *Peziza* and *Coprinus* species. The presence of mushroom pathogens can be problematic in the recycling of spent mushroom substrates into casing, as well as the presence of mushroom pests and attraction to sciarids.

Sources of peat for casing have also been found to be contaminated with bacterial blotch pathogens including *P. 'gingeri'* leading to outbreaks of ginger blotch. Taparia et al. (2021) found that steaming of casing containing various alternative materials at 70°C for 8 h reduced the incidence of blotch.

Freedom from human and animal pathogens such as *Salmonella* and *Listeria* species is also critical. An occurrence of sugar beet lime contamination with *Salmonella kedougou* occurred in Ireland in 2001, but it was not linked to any food poisoning incidents (Betts, 2021; FSA 2003). Nonetheless it resulted in the decision to implement the heat treatment of sugar beet lime for some years to eradicate the potential risk. This is no longer required because all the sugar beet lime used for Irish casing is imported from British Sugar, and the pressed lime requires a shorter maturing process than the traditional lime produced by sugar factories that have now closed.

2.5 Other considerations

Overall, alternative casing media should provide the adequate mushroom yield and quality within the same cropping period as peat casing, or more specifically, wet-dug peat casing. Secondary benefits which reduce input costs should also be considered, for example some alternatives may lessen the required liming input. There are several other economic and environmental factors to be considered in the determining the suitability of an alternative casing material:

- it must be in sufficient quantity to satisfy the demand from the mushroom industry (either global or local), as well as other horticultural and non-horticultural uses
- it should be available locally or within a reasonable transport distance from mushroom farms
- the price must not make mushroom cultivation uneconomic; usually this means that the (raw) material will be a by-product from another process and does not have excessive reprocessing costs; the cost of casing in the Netherlands is around 110 €/m^3 (B. Driessen); in Australia the price of imported casing has increased by x2 to x3 in recent years and represents 8-9% of the total production cost of mushrooms (Zoom 3)
- there should be uniformity between batches
- there should be year-round availability and/or potential for storage without deterioration
- the carbon footprint of production (mechanical processing, heat treatment etc) should be lower than that of using peat
- there should be no other negative environmental impacts.

3. Global use of peat as a mushroom casing

3.1 Current supply of peat for mushroom casing in different countries

Volumes of peat used for casing to cultivate *Agaricus* mushrooms, almost entirely *A. bisporus*, in different countries are shown in Table 1. Much smaller quantities of casing used for cultivating other mushrooms such as king oyster (*Pleurotus eryngii*) and wood blewits (*Lepista nuda*) are excluded. Where direct volumes of casing were not available, an estimate was made based on the button mushroom production of a country and a ratio of 1.73 m^3 wet-dug peat casing per tonne of mushrooms harvested (GEPC, European Mushroom Growers Group). In North America, milled peat is dried and compressed to about 50% volume before transportation in 1.56 m^3 bales. An estimate of the volume of peat casing after mixing and wetting was made by doubling the volume of compressed baled peat. This gave a ratio of 1.4 m^3 peat casing per tonne of mushrooms harvested. This slightly smaller ratio than on European farms may be due to a slightly shallower average casing depth in North America of 4.5 cm (J. Pecchia; Samp & De Santis 2022). In Australia, the ratio is 1.3 m^3 peat per tonne of mushrooms produced, although the wet-dug peat is slightly dried and compressed so that more can be put in a shipping container from Europe (den Ouden 2016). The blond peat exported to Australia is also compressed in bales. If the loose volume of casing after remixing and rewetting is considered, the ratio of peat volume per tonne of mushrooms produced may be more similar to the North American or European ratios.

According to Royse et al. (2017), countries listed in Table 1 would account for 97% of the global production of button mushrooms. Since the remaining 3% in their figures did not include Russia, Iran or any Southern Hemisphere countries, which are included in Table 1, it can be assumed that global percentage of peat casing not included in Table 1 is small.

Compressed bales or dried milled sphagnum peat for casing in Hungary

Table 1. Sources and annual quantities of peat used for button mushroom casing on farms in different countries

Country	Source of peat	Type of peat	Volume 000, m^3	Ref.
Australia	Germany, N. Ireland Canada, Baltic	Wet-dug, Brown and blond milled peats	85*	5,11
Belgium	Germany	Wet-dug	44	1
Brazil	Brazil	Milled black peat	9*	9
Canada	Canada	Brown milled	204**	8
China	China	Brown milled	500	7
Denmark	Germany	Wet-dug	15	12
France	Germany	Wet-dug	90	1
Germany	Germany, Poland	Wet-dug	100	1
Great Britain	N. Ireland, Great Britain	Wet-dug	80*	2
Hungary	Albania, Romania, Poland	Blond, Black wet-dug	47	1
Iran	Iran	Brown milled	140	21
Ireland	N. Ireland	Wet-dug	135	1
Israel	Germany, N. Ireland	Wet-dug	35	14
Italy	Italy	Wet-dug	95	1,11
Japan			12*	18
Korea, South			18*	18
Lithuania	Lithuania	Local peat	18	20
Mexico	Canada, Poland, Russia	Brown milled	108**	17
Netherlands	Germany	Wet-dug	500	1
New Zealand	New Zealand Germany	Sphagnum/sedge/reed Wet-dug	22	13
Poland	Poland, Lithuania	Wet-dug, Blond peat	700	1
Russia	Russia	Local peat	138*	4
South Africa	N. Ireland, Germany	Wet-dug	29*	3
Spain	Spain Germany	Local black peat Wet-dug	184	1,16
Turkey	Turkey	Local peat	86*	10
USA	Canada	Brown milled peat	509**	6
TOTAL			**3903**	

* Assumes 1.73 m^3 peat/t mushrooms** Compressed peat equivalent to 1.4 m^3 peat/ t mushrooms

1: GEPC European Mushroom Growers Group Survey, March 2022
2: DEFRA Horticultural statistics 2021
3: Sylvan Inc., South Africa
4: Mishurov et al. (2021)
5: Australia Horticulture Statistics Handbook 2020/21
6: USDA, National Agricultural Statistics Service 2020-21
7: Prof Cai Weiming, Zhejiang Academy of Agricultural Sciences, Hangzhou, China
8: Statistics Canada, Mushrooms Growers Survey 2021
9: Prof DC Zied, Universidade Estadual Paulista, Brazil
10: Prof E. Polat, University of Akdeniz, Turkey
11: E. Vernooij, Champfood, The Netherlands
12: K. Hansen, Tvedemose Champignon, Lungby, Denmark
13: K. Armstrong, Meadow Mushrooms, Christchurch; C. Chambers, Mercer Mushrooms, Auckland
14: Dr O. Danay, Champignon Farm, Israel
15: C. Callisto, Global Axis Pty, Australia
16: Dr A. Pardo, CIES, Spain
17. Salmones et al. (2018); H. Leal Lara; D. Martinez-Carrera
18: Mustafa Kemal Soylu, Mingu Kang (2017) Mushroom cultivation in South Korea 8:225-229.
19: https://asia.nikkei.com/Editor-s-Picks/Interview/Japanese-mushroom-grower-sees-fertile-ground-in-Southeast-Asia
20: https://www.selinawamucii.com/insights/market/lithuania/mushrooms/
21. Singh et al. (2020).

The global annual volume of peat used in mushroom casing in Table 1 is 3.90M m^3. If countries using smaller volumes of peat casing than those shown in Table 1 are added, the total global annual volume of peat used in mushroom casing is around 4M m^3. According to Royse et al. (2017) and Singh et al. (2020), the global production of button mushrooms is 4.38M and 4.73M tonnes respectively. Excluding the Indian (0.2M tonnes) and 70% of Chinese (1.74M tonnes) mushrooms that are not grown on peat casing (see below), this gives a global button production of around 2.62M tonnes grown on peat casing. Assuming an average requirement of 1.5 m^3 peat per tonne of mushrooms produced, this gives a global annual volume of 3.93M m^3 peat used for growing button mushrooms, almost the same figure as above. This represents about 10% of the 40M m^3 peat used globally for growing media (Blok et al. 2021), and about 5% of peat extracted for both growing media and energy (Folkert Moll, Kekkila BVB). In 2022, similar quantities of peat were extracted for use as growing media and energy, with most of the peat being extracted from European sources. However, the peat market for energy has declined rapidly since 2017 (Anja Kretschmann & Olivier Hirschler, Thünen Institut, Braunschweig, Germany).

Currently between 1.6M and 2M m^3 of peat are required by the EU mushroom casing industry; around 25% of the volume is supplied from the Lower Saxony region of Germany (Zoom 1). A small proportion of this casing (less than 10%) is exported to the southern hemisphere, Asia and the Americas. There are sufficient peat reserves in Germany to supply the mushroom industry for at least another 100 years (Zoom 1). The supply of peat from Estonia, Finland and Sweden is more secure but these are usually blond peats and the quality is variable. The re-wetting of dried blond peats can be problematic (Zoom 1). Dutch and Belgian casing producers use predominantly German wet-dug black peat with smaller quantities of Baltic peat. Legro and BVB Kekkila have significant market shares in the Southern Hemisphere and this would probably remain viable even if mushroom production in Europe could no-longer use peat for casing.

Nearly half of the peat used for growing mushrooms in the EU is used in Poland. Although ranked third in terms of button mushroom production, Poland uses the world's largest volume of peat casing (Table 1) due to the use of wet-dug black peat and possibly a greater average depth of casing than in North America. The largest producer, China, uses predominantly mineral soil casing and the USA uses dried milled peat for casing so the volume of wet harvested peat may be similar or greater than that used in Poland. Currently there is a plentiful supply of Polish peat although it is becoming increasingly difficult to get new permissions for peat extraction. Some blond peat from the Baltic States is now imported (Zoom 2). About 10% of the Polish casing is exported.

Ireland (IRL) and Northern Ireland (NI, UK) have traditionally been major suppliers of peat for horticulture (Robinson & Lamb 1975). Less peat is now extracted from bogs for this

purpose but it is still being extracted from approved sites in Northern Ireland (UK) and from sites in Ireland which are compliant with the < 30 hectare rule (DAFM, 2022). There are still several sites of this size. The entire UK and Irish mushroom industries use between 1 and 2 ha of peat bog per year. Unless further restrictions are imposed, there is therefore a plentiful supply of wet-dug peat on the island of Ireland for several decades. Some peat for horticultural use is imported to Ireland from Baltic States and estimates of the cost are variable from being similar to Irish peat (Zoom 8) to being three times the price (Donal Gernon, Teagasc). About 60% of Irish peat casing is exported, and of this, 40% is for the British market. As with Dutch casing, Irish casing production for the Southern Hemisphere would probably remain viable even if peat casing was no longer permitted in Europe.

There is still one significant peat casing producer in Scotland (McGregor) and peat is extracted for general professional horticultural use in England and Scotland. However, policy on peat extraction in the UK is fragmented with different policies applying to England, Wales, Scotland and Northern Ireland.

In Italy, good quality peat for casing is obtained from the Northeast of the country (E. Vernooij). Local sources of peat are also used in some other European mushroom industries such as in Spain and Turkey although the water holding capacity and other quality attributes for mushroom casing are lower than of German and Irish wet-dug peats (A. Pardo; E. Polat).

European countries producing smaller quantities of button mushrooms and using peat casing not shown in Table 1 include Croatia, Greece, Romania and Switzerland. Before the current conflict, Ukraine was also a significant mushroom producer and user of peat casing.

There is usually a plentiful supply of peat in Canada for the North American mushroom industry. However, there have been recent disruptions in supply and peat shortages due to restrictions in transportation imposed during the Covid pandemic and adverse weather conditions for peat harvesting (Zoom 3). Previously, most peat for casing in Mexico was obtained from Canada but the largest producer, Hongos, now imports the casing from Poland and Russia (H. Leal Lara).

Most peat in Australia is imported European ready-mixed wet-dug peat and sugar beet lime casing. Some blond peat is imported from the Baltic states and Canada and blended with wet-dug peat casing for use on tray farms (Zoom 3). In New Zealand, imported European wet-dug peat is mainly used although local peat is used on some farms, particularly for brown strains.

Peat-casing accounts for around 30% of the Chinese button mushroom production (Cai Weiming) which according to Singh et al. (2020) is 2.48M tonnes annually. Peat for this year-round industrial-scale mushroom production is mainly obtained from Northeast China. The main mushroom growing provinces are Fujian and Zhejiang in Eastern China (Cai Weiming), although production is moving to northern provinces due to the proximity of raw

materials (Royse et al. 2017). Japan is the world's second largest mushroom producer, but this is almost entirely of species that do not require a casing layer; button mushroom production represents a very small percentage of the total (Singh et al. 2020). India produces around 200,000 tonnes of button mushrooms annually but this is predominantly with non-peat casing (CR Meera; Singh et al. 2020). Iran produces around 100K tonnes of mushrooms annually (Singh et al. 2020) using local peat casing such as Fatir in Khouzestan. Other Asian countries using smaller quantities of peat casing not shown in Table 1 include Indonesia, Kazakhstan, Malaysia and the UAE.

In Africa, South Africa is the largest user of peat casing. Previously this was from local sources but this is no longer permitted so it is now imported (Zoom 6). There are also mushroom farms in North African countries which import small volumes of European peat for casing, not included in Table 1.

The Brazilian button mushroom industry is still small – most mushrooms consumed are canned and imported from China. About 90% of the mushroom farms use peat casing, and of these, around 95% obtain it from the company +Terra located in Southern Brazil. The remaining 5% of peat casing is imported using German wet-dug peat (DC Zied). South American countries using smaller quantities of peat casing and not shown in Table 1 include Argentina and Chile (Singh et al. 2020).

3.2 Future regulations on the extraction of peat in different countries including remediation requirements/incentives

Peatlands are an important carbon sink as well as an important habitat for endangered species. Peat extraction therefore results in the release of carbon dioxide and loss in biodiversity. The regulatory situation regarding peat extraction and use in different countries is very dynamic and is likely to change periodically in the next few years. The supplies of German peat are secure for another four years but there is increasing political pressure in Germany to stop the extraction of peat. The German government has set targets for reducing peat in the hobby and professional sectors to 30% and 70% by 2030. In Norway, the government has set targets for phasing out peat in the hobby and professional sectors by 2025 and 2030 respectively. In Switzerland, the government target is 5% peat use in the professional sector by 2030 (Hirschler et al. 2022). The possibility of exemptions for the continued extraction of peat in support of mushroom producers is tenuous (Zoom 1). The supply of peat from Estonia, Lithuania, Finland, Sweden and Russia (Kaliningrad area) is more secure (Zoom 1). It may be more difficult in the future to get extraction licences in Poland and Latvia.

Peat extraction in Ireland (IRL) has virtually ceased since Bord na Mona, who predominantly supplied the energy and horticulture growing media sectors, stopped

extraction activities in 2021. This was precipitated by legislation governing planning permission and licencing of peat extraction. For mushroom casing producers, the pathway to regulatory compliance requires the dual consent of both authorities and it remains as yet untested. A 'Horticultural Peat (Temporary Measures) Bill 2021' is making its way through parliament that aims "to make exceptional provision for peat extraction for the purpose of horticulture for a temporary period…" but it is still being debated. Currently most of the peat in mushroom casing supplied by manufacturers in Ireland and Northern Ireland is now obtained from bogs in Northern Ireland (UK), which is governed by different legislation (Zoom 8). As of August 2022, a proposal to ban peat growth media/compost in Northern Ireland by 2025 has been removed from the Northern Ireland Peatland Strategy 2022-2040 of the Department of Agriculture, Environment and Rural Affairs (DAERA). Action 11 of that strategy now commits to conducting a review on "peat extraction and the use of peat and peat products by 2023" and any recommendations will be taken forward (https://www.daera-ni.gov.uk/sites/default/files/consultations/daera/NI%20Peatland%20Strategy%20-%20Copy%20for%20EQIA%20Consultation.%20%208-8-2022.%20PDF_0.PDF). About 60% of Irish peat casing is exported, and of this, 40% is for the British market.

In Great Britain, the government department Defra has prohibited the sale of peat in garden products from 2024 and will impose a ban on professional use in 2026. A partial exemption on the use of peat for mushroom casing until 2030 is being considered, including restrictions on the allowed depth of peat casing and/or the percentage volume of peat inclusion in casing. Imports of mushrooms into Great Britain will need to meet the same regulatory requirements.

The Dutch horticultural industry is still heavily dependent on peat and there is also a large growing media industry. It is therefore unlikely that supply of peat products in the Netherlands will end in the near future as a result of intervention by the Dutch government (Zoom 2 & 5). The 'Responsibly Produced Peat' (RPP) Foundation is a non-profit organisation that oversees the certification of peat production for growing media, which was financially supported by the Dutch Government (https://www.responsiblyproducedpeat.org). It offers a route to more sustainable peat extraction and a certification scheme that incorporates: 1, Legal aspects, 2, Good governance, 3, Site selection, 4 Site preparation and peat extraction, 5 After-use and rehabilitation, and 6, Chain of custody and RPP labelling. Media producers in the Netherlands and Germany embrace this system and see it as a way forward. Twenty-two companies are certified for RPP products. In terms of mushroom casing, most of the peat is imported from Germany from RPP sites which produce high quality peat. There are also RPP sources in Finland, Sweden and Estonia, but they are of poorer quality in terms of mushroom casing (Zoom 1).

In Australia and South Africa, extraction of peat stopped in the early 2000s. Since then, all peat casing and/or peat has been imported from Europe or North America (Zoom 5). In New Zealand, there are peat bogs in the South Island supplying peat for mushroom casing. This is mainly a sphagnum peat but the quality for mushroom casing is poorer than that of imported European sphagnum peat casings and is used mainly for brown mushrooms. There is currently no environmental pressure in New Zealand to close the South Island peat bogs (Zoom 4). The peat bogs in the North Island are mainly reed and sedge peat and some is blended with other peat sources for mushroom casing.

3.3 Future legislation on the use of peat in mushroom casing in different countries

Currently, there is no government legislation against the use of peat in professional horticulture, even in countries where the local extraction of peat is not permitted such as South Africa (Zoom 6) or is permitted under licence, such as in Ireland. In several countries, this situation will change in the next few years. There is also considerable pressure against the use of peat for casing is from multiple retailers, (supermarkets) particularly in Western Europe (Zoom 2). The approval of peat in organic products is currently under review by the Soil Association, the regulatory organisation for organic products in the UK (H. Blogg, Soil Association). There is no equivalent pressure against the use of peat from retailers in North America; the interest in alternative casings there has been driven by the shortage of peat due to unfavourable weather conditions for extracting peat in Canada (Zoom 3; Samp & De Santis 2022).

4. Peat alternative casing materials

4.1 Comparison of peat and alternative materials

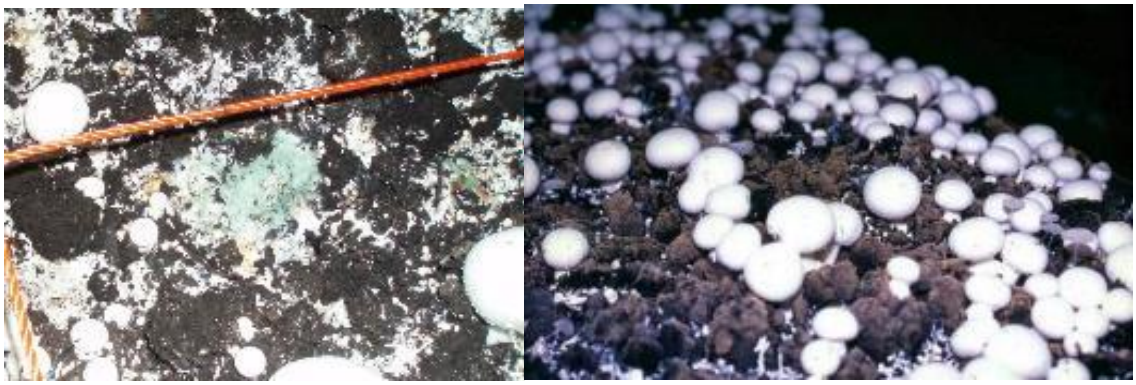
A systematic review of the scientific, peer-reviewed literature between 1970 and 2021, comparing peat casings with those containing alternative ingredients is underway by Teagasc (G. Young et al 2024). The review paper will be published in 2024 and circulated to the AMGA when available. This section presents a summary of the most important scientific developments. A summary of the main peat alternatives available in Australia, and their advantages and disadvantages, is outlined in Table 2.

Early work on peat alternative casings in the UK and Ireland focused on the use of bark (Allen 1976; Staunton 1982) and paper production by-products (Hayes et al. 1978). Although moderate mushroom yields of that era and comparable with those from milled peat and chalk casings in the same experiments were obtained, they were substantially lower than those currently obtained from wet-dug peat casing blends using high yielding mushroom strains and spawn-run (Phase 3) composts. A significant disadvantage of plant

fibre materials such as bark, wood fibre, paper by-products and coir are their tendency to encourage the growth of green moulds and other competitor fungi (Noble 2011).

Table 2. Some main advantages and disadvantages of peat alternatives available for mushroom casing. Alternatives generally have lower water holding capacity, either at saturation and/or under applied suctions (matric potentials) than sources of sphagnum peat.

Material	**Advantages**	**Disadvantages**	**Some major references**
Organic			
Bark (compost fines)	availability	green mould, competitor uses	Allen 1976, Staunton 1982 Noble & Dobrovin-P 2005
Biochar	?	cost, availability	Young et al. 2023
Coir	water holding	cost, competitor uses	Labuschagne et al. 1995
Cormo			https://cormogroup.com
Green waste compost	water holding, availability, cost	contaminants, EC, variability	Noble & Dobrovin-P 2016a Goldwater 2021
Hydra-fibre	low bulk density	water holding	Samp & De Santis 2022
Miscanthus	low bulk density water holding	cost	Mushroom Supply & Services, PA, USA
MykoDeck			https://ikts.fraunhofer.de
Newfoss			https://newfoss.com/
Paper waste by-products	water holding, availability	contaminants moulds	Hayes et al. 1978 Dergham et al. 1991
Recycled casing	water holding availability, cost	EC, separation, needs cooking-out	Zied et al. 2020 Taparia et al. 2021
Recycled rockwool	water holding cost	sticks to mushrooms	Noble & Dobrovin-P 2016a
Spent coir	water holding, availability, cost	root material, moulds	Noble & Dobrovin-P 2016a
SMC	water holding, availability, cost	EC, leaching needs re-composting	Barry et al. 2008 Rowley & Burdon 2019
Sphagnum moss	water holding	availability, cost	Taparia et al. 2021
Wood fibre	low bulk density availability	low water holding moulds	Noble & Dobrovin-P 2016a
Inorganic			
Bentonite clay	water holding	cost, bulk density, EC	Buchanan & Barnes 2003
Filter cake clay	availability, cost	bulk density	Noble & Bareham 2002
Ground limestone	availability	cost, bulk density	Nair & Bradley 1981
Perlite	low bulk density	cost, C footprint, sticks low water holding	Polat & Onel 2021
Sugar mill mud	availability, cost	bulk density	van Jaaresveld & Korsten 2008



Peat casings substituted with bark (left) and paper waste (right) colonised with green mould and cinnamon mould respectively

Materials such as vermiculite and rockwool can tend to stick to caps (left);
materials with low water retention produce leggy mushrooms which open early (right)

Composted SMC was previously used in the USA at Creekside (formerly Moonlight Mushrooms). The material was composted for two years; steam treated in an auger mixer for 1 minute at 57°C and mixed with blond peat (B. Driessen). There has since been a large amount of research into recycling spent mushroom compost (SMC), also known as spent mushroom substrate (SMS), into fresh casing, most notably by Barry et al. (2008). Cooked-out composted material was used to avoid contamination with pests and diseases, and the SMC contained peat from the previous crop. When used at 18% v/v, they found that leaching composted SMC from an EC of 11 to 4 mS/cm was required to reduce the salt content to an acceptable level to obtain mushroom yields comparable with fresh casing. Similarly, Mirzadeh (2022) describes a method for leaching and recycling SMC in casing. Samp & De Santis (2022) indicate that a leaching period of between 3 months and 1 year is needed to remove excess salts and make SMC reusable as a casing ingredient, with a maximum inclusion of 25 to 30%. Work in Iran has shown that leaching to reduce EC from 7.7 to 1.7 mS/cm can improve the suitability of SMC for casing, although the process requires 3.5 to 4

m^3 water per tonne of SMC (Riahi et al. 1998; Rowley & Burdon 2019). Obtaining sufficient fresh water and disposal of the leachate may be problematic in Australia and other countries.

Work in the UK on commercial mushroom farms (Noble & Dobrovin-Pennington, 2016a) showed that several materials could be blended at 25% by volume with peat casing with no significant effects on yield or quality. The most promising materials were composted pine bark fines, granulated rockwool slabs (a by-product from the glasshouse vegetable industry), separated spent mushroom casing and filter cake clay (a by-product from quarries). Subsequent experiments (unpublished) showed that increasing the rate of spent mushroom casing to 33% resulted in a small mushroom yield loss, although Taparia et al. (2021) incorporated 50% of recycled casing into fresh peat casing without a significant effect on mushroom yield or quality. Experiments (Noble, unpublished) showed that mushrooms could be grown on 100% vermiculite, bark or recycled rockwool, with about 80% of the yield of peat casing.

Composted green wastes produced to the UK PAS100 standard were added to peat casing at 25% with no significant effect on yield (Noble and Dobrovin-Pennington, 2016a). However, the levels of permitted contaminants in PAS100 compost in terms of glass and plastic would not be sufficiently rigorous for use as mushroom casing. Sturgeon (2007) applied for a patent on the use of green waste compost as a casing material. Experiments in Australia (Goldwater, 2021) have shown that composted green waste incorporated in peat casing at 50% reduced yield by around 11% while complete replacement of peat with composted green waste reduced yield by 31%.

Spent growing media such as bark, wood fibre, rockwool and coir from other horticultural sectors can be a significant disposal problem but could be used in mushroom casing. Granulated rockwool slabs following cucumber production were added to peat casing without loss in mushroom yield although there was a reduction in mushroom quality in terms of size and cleanness (Noble & Gaze 1995; Noble & Dobrovin-Pennington 2016a). Spent coir growbags were used as a component in peat casing material but there were problems with green mould and other pathogens (Noble & Dobrovin-Pennington 2016a). A patent application for a method to resolve these problems has been made following a recent Innovate UK project: https://gtr.ukri.org/projects?ref=10003816

There have been numerous patents on peat alternative casing materials although none has yet proved to be commercially successful longer-term. Stoller (1978, 1979) and Rettig et al. (2001) describe casings prepared from either shredded newspaper or by-products from the paper producing process. Yamashita (1989) and Starkey et al. (1995) describe casings prepared from rockwool and lignite. Polat & Onel (2021) describe a casing in Turkey prepared from vermicompost and perlite. Noble & Bareham (2002) describe a casing containing fine particle tailings (multi-roll filter cake) from the mining and quarrying

industries. Around 30,000 m^3 of 20% multi-roll filter cake (MRF) casing was marketed by Tunnel Tech to the UK mushroom industry. The MRF was mixed with a local dry brown peat and was used by about 10 farms where it compared favourably with wet dug peat casing (Noble 2003). The demise of the coal mining industry and closure of local peat bogs ended the availability of the raw materials. A similar casing prepared from Canadian peat and filter-cake clay from a sand quarry was developed by Grange Growing Solutions near Sydney in 2006 but the low price of imported ready mixed wet-dug peat casing ended further development.

Large flats grown on a Canadian milled peat and filter cake casing in Australia 2006

In Northern Ireland (AFBINI) trials have been conducted with composted bark, coir, wood fibre, coal tailings and road tailings. Reasonable results were obtained with 30-50% peat substitution although the casings tended to dry out quicker than peat. Blends of alternative materials are more likely to be successful than individual materials (M. Kilpatrick). Casing materials based on locally available by-products such as Mabu casing from sugar cane bagasse (fermented sugar cane pith) and Fibregro from wattle bark (a by-product of the tanning industry) in South Africa, were produced on a small scale (Booyens, 2012; Dave Dobson, personal communication). Mabu casing was texturally similar to peat but was not fully commercialized. Raw bagasse contains too much soluble sugar and must be composted before use in casing. However, the bagasse and wattle bark materials were not pasteurised and there were problems with mould contamination (Zoom 6). Trials have also been conducted with a filter-cake by-product from sugar mills in South Africa (Zoom 6).

In Israel, a casing made from anaerobically digested cattle manure was developed, but the feedstock became unavailable (Zoom 6).

Cropping trials in 1993 at Melbourne Mushrooms did not show a significant difference between Canadian milled peat and coir casings although mushroom yields of around 13 kg m^{-2} in eight weeks were small by today's standards (Ewan Harper, presentation at 1993 AMGA Conference). The addition of 5% bentonite to a 50:50 peat: coir casing did not significantly affect mushroom yield in these trials but a 5% zeolite addition slightly reduced yield. A 70:30 coir: filter cake casing was also developed by Grange Growing Solutions in 2006 and produced similar mushroom yield and quality to a milled peat casing but was discontinued due to cost.

Chalk or lime sources are normally added to peat in casing at 5 to 20%v/v. Noble et al. (1999) found that mushroom yield was slightly higher using sugar beet lime than with ground chalk but there was no difference in yield between using 9 or 25% v/v. Barry et al. (2008) found mushroom yield was slightly higher when ground lime instead of sugar beet lime was added to brown peat but no significant difference when added to black peat. Huerta et al. (2001) showed that high rates of sugar beet lime (70%) reduced mushroom yield only slightly. The volumetric cost of sugar beet lime or chalk is around double the price of peat and together with cost of transporting a dense material would make casing significantly more expensive if used at high rates. The current commercial rate of sugar beet lime and/or ground limestone in casing is around 6-10% v/v (Harte Peat). However, there has been recent interest in increasing the rate of limestone in casing in the USA to offset the shortage of peat (Samp & De Santis 2022).

The use of water absorbent polyacrylamide gels in mushroom casing was investigated in the 1990s. However, mushroom casing is kept wetter than potting media so there is less problem of drying out and rewetting. The German product 'Stockosorb' was briefly marketed for use in mushroom casing but no beneficial effects were reported.

As well as reductions in mushroom yield and quality, a disadvantage of several peat alternatives has been a delay in cropping of 4-5 days compared with peat casing (Zoom 2). On some farms using peat-reduced casing, a lower mushroom yield in three flushes is accepted so the compost filling rates are lower and the cropping cycle is extended (Zoom 4).

4.2 Current use and development of non-peat casing materials in different countries

In France and Spain where limestone clay (marl) and mineral soils were traditionally used for casing, these have now almost been completely replaced by peat casings (A Pardo, Zoom 4). Small quantities of untrimmed mushrooms for specialist markets are still grown in French caves using the traditional 70% marl: 30% milled peat casing. Small quantities of mineral soils are used for casing in Brazil (DC Zied). In China, seasonally produced mushrooms (about 70% of the total production) are grown on casing made from rice husks and dredged

river ‘mud’. However, the mushroom yield from this casing is significantly lower than from Chinese peat casing (Cai Weiming). In India, a blend of coir and composted cattle manure is used for casing (CR Meera).

4.2.1 Near-to-market casing products

In Ireland, Monaghan Mushrooms have developed a peat alternative casing (undisclosed) that produces good quality mushrooms but the yield is not yet comparable with peat (Zoom 8). Harte Peat have successfully trialed 30 and 50% peat blends and are now focusing on developing a 100% peat free blend (undisclosed).

4.2.2 Recycled spent mushroom compost and casing

Recycled separated spent mushroom casing has been used on a farm in South Africa for about one year. The cooked-out material is rewetted and mixed at 40% with 60% new imported peat casing. This is repeated for 12 cropping cycles with the proportion of recycled material gradually reduced to 30%. The mushroom yield and quality have been the same as from 100% peat casing (B. Driessen). Separated spent casing is also mixed with fresh peat casing on farms in New Zealand and Israel (Zooms 4 and 5). However, in the Netherlands and some other countries, crops are no longer cooked out due to the energy cost; the SMC or separated casing must therefore be pasteurised separately if it is to be reused. Some of the casing producers do not think this is economically viable (Zooms 2 and 5).

In the Netherlands, separated spent compost is filled in an aerated bunker system. It self-heats to around 80°C (or a small amount of nitrogenous activator is added) and after 10 days looks like black humus. This material is added at 30% to fresh casing without negative effects on mushroom yield and quality (B. Driessen). Other tests have shown that higher rates result in yield losses. The material can be sold off-site at 25 €/tonne; the bulk density is 600 kg/m^3 so the volumetric cost is 15 €/m^3.

4.2.3 Cormo (Switzerland)

Cormo (https://cormogroup.com/) have developed a growing medium ‘TEFA’ which is processed from corn stems (stover). They use a separation technology to obtain the fibrous part of the stalk. The annual production is around 3,500 m^3 for various horticultural uses including casing. TEFA casing alone produces around 80% of the mushroom yield of a peat casing although it is best used as a partial peat replacement (Anonymous 2019). It is currently being tested on several farms in Europe although it is still not fully commercially available (Peters 2021). Mostly it is used at 20% with blond dry peat but the aim is to use only 20% peat, and ultimately to dispense with the peat. It is more difficult to mix with wet peat. It is anticipated that Cormo TEFA casing will become commercially available in 2024. There is no market price yet but transport cost may exceed product price. It is currently

produced in Alsace, France but the objective is to produce Cormo TEFA casing internationally from local maize crops to reduce transport costs (Zoom 6).

4.2.4 Newfoss (Netherlands)

A growing medium based on processed plant fibres (e.g. mown grass) has been developed by Newfoss (https://newfoss.com/) with a patent application (Van Boekel and Van der Horst 2020). It is currently being tested in the EU funded project BIOSCHAMP. Results indicate that it works better as a partial peat replacement than as a peat-free casing (J. Baars). Taparia et al. (2021) showed a 7% mushroom yield loss when Newfoss was incorporated at 50% in peat casing; complete replacement of peat was not investigated in the report.

4.2.5 MykoDeck

A research project 'MykoDeck' is being conducted at the Fraunhofer Institut of Ceramic Technologies, Dresden, Germany. A combination of pulping, homogenization and composting is being used to convert various sources of biomass (green wastes, straw, hardwood residues, SMC) into a peat alternative casing. Mushroom cropping trials at five mushroom farms in Germany are underway. https://www.ikts.fraunhofer.de/en/blog/peat-free-casing-soils-for-sustainable-mushroom-cultivation.html

4.2.6 Hydra-fiber and Wood Fibre Products

A by-product of the timber industry in North America, Hydra-fiber (https://www.hydrafiber.com/) is made by Profile Products from processed pine bark and wood fibre in Conover, North Carolina. The raw material is fed into a digester and is then steam treated to form a thin fibrous material (Samp & De Santis 2022). Trials have indicated that the best ratio is 20-30% Hydra-fibre, 20-25% SMC and 50-60% peat. In Ireland, a-wood fibre product is being tested as a casing component at a 30% inclusion by Walsh Mushrooms.

4.2.7 Sphagnum moss

Sphagnum moss is a renewable material harvested from the surface of formerly mined and degraded peatlands, produced by companies such as Biolan (Finland) and Premier Tech Horticulture (Canada) (https://www.pthorticulture.com/en/sustainable-development/). The surface sphagnum moss layer is harvested at 3-6 year intervals (Pouliot et al. 2015; Taparia et al. 2021) or longer. The process of producing sphagnum moss is still under development, for example the Innovate UK project Sphagnum Farming UK and Sphagnum Moss Farming in Canada (Pouliot et al. 2015). When compared with other peat alternatives, water holding characteristics of sphagnum moss are quite similar to those of peat, and in a mushroom

crop, sphagnum moss added at 25% produced the same yield as peat casing (Taparia et al. 2021). The effect of a 100% sphagnum moss casing was not investigated and the total availability and cost of the material are unknown. Hirschler et al. (2022) state that sphagnum moss is currently not relevant to the growing medium industry and requires a considerable amount of further research and development.

4.2.8 Biochar and hydrochar

Biochars are produced by a process of pyrolysis, wherein feedstock materials (typically lignin-rich 'woody' biomass) are heated (350-750°C) for a set period of time, in oxygen-limited conditions (Mumme et al. 2018). The resultant 'char' is a carbon-rich material, which because it doesn't readily decompose, stores this carbon on a long-term basis (Shackley et al. 2016). Biochar amendments to horticultural growing media can enhance water retention, aid in cation exchange, and can negate the requirement for additional liming (Prasad et al. 2017).

The physiochemical attributes of biochars however can vary considerably depending on the initial feedstock material used as well as the conditions of temperature, pressure and residence time under which it was pyrolysed. Developments on the use of biochars in horticulture are predominantly focused on its use in plant production and there is little information on the use of biochar in mushroom cultivation, for example: https://wsmbmp.org/biochar-a-helpful-tool-for-mushroom-growers/

As with coal tailings, the black colour and often dusty nature may be an issue for both mushroom cleanness and handlers.

The cost of biochar production can vary, depending on the process and the feedstocks used in its production. The global mean cost per kg of biochar was calculated by Ahmend et al. (2016), to be $2.65. Current cost of biochar is around $300/$m^3$. However the scale of production varies considerably worldwide, with current production in North America is around 70,000 tonnes. The largest producer in Australia is Green Man Char, Preston, Victoria.

Hydrochar is produced in a process of hydrothermal carbonization (HTC) also known as 'wet' torrefaction. HTC takes place in a close-system in the presence of water at temperatures between 180-250°C and as such this process is well suited to transformation of high-moisture content feedstock materials such as agricultural sludges and residues, digestate, food-processing by-products and municipal waste (Dalias et al., 2018; Jackowski et al., 2020). Hydrochars have textural properties similar to those of peat (Farru et al., 2022). However according to Dalias et al. (2008) hydrochars concentrate phenolic compounds to a greater extent than biochars, which are shown to have a phytotoxic or inhibitory effect in plants. As a result it's acknowledged that HTC may require feedstock pre-conditioning and/or

post-production treatment to extend the use of hydrochars as a growth media constituent (Dalias et al., 2018; Farru et al., 2022). Scaled production of hydrochars is limited worldwide, with most being produced currently at pilot-scales. As with biochar, there is a lack of information on suitability of use for mushroom casing.

4.2.9 Perlite

Perlite has been used in a casing formulation in Turkey (Polat & Onel 2021). However, heat is required in manufacture and supplies from countries such as Greece are not completely secure in the long term.

4.2.10 Miscanthus grass and pellets

Dust from miscanthus grass straw processing, which can also be formed into pellets, has been used as a casing component in the USA (David Iaconi, personal communication). Tests with 25 and 50% mixes containing a blend of dust and pellets with peat have produced better results than wood fibre. Competition for animal bedding still makes the material too expensive for casing.

4.3 Current and recent research projects on casing

Current and recent research projects on peat alternative casings are shown in Table 3. The largest current project that involves peat substitution in casing is BIOSCHAMP, a €4M EU Horizon project involving 11 partners from 6 countries. The main peat alternative being investigated by them is a grass fibre product from a biorefining process developed by Newfoss (https://newfoss/producten/). The project aims to have a 30% peat-reduced (30% circular) casing using locally available raw material on the commercial market in 2024. Full growing tests have now taken place. Although Poland is the largest user of peat for mushroom casing, there is currently no Polish government funded work on peat alternative casings. Some privately funded research is being conducted on mushroom farms in Poland (Zoom 2). Similarly in the Netherlands, there has been little publicly funded work on peat substitution (Zoom 8). In other countries, trials on peat alternatives are being conducted in-house by several European commercial companies including BVB and Legro (Netherlands), Cormo (Switzerland) and Monaghan Mushrooms and Harte (Ireland) (Zooms 4 and 7).

At Penn State University, the inclusion of wood fibre products into peat casing has been investigated. At 25% inclusion, there was no significant effect on mushroom yield, but yield was reduced at higher inclusion rates. Green mould infection was observed on wood fibre treatments (J. Pecchia).

Table 3. Current and recent projects on mushroom casing

Project	Materials	Main Partners
Beyond Peat	Various	Teagasc (IRL) AFBINI (NI)
Bioschamp	Newfoss processed grass fibre, Sphagnum moss	ASOCHAMP, CTICH, IRNASA-CSIC, Fertinagro, Eurochamp, Innovarum (ES), INAGRO (B), Wageningen Research, Kekkilä-BVB, Newfoss (NL), University of Oxford (GB), University of Perugia (I), UGLK (PL), EKOFUNGI (RS)
Cormo	Cormo TEFA	Cormo (CH) Mushroom farms in France and Germany
Flanders Government	Various	INAGRO (B)
MykoDeck	Various biomass	ITKS Fraunhofer Institut, Dresden (D) Mushroom farms in Germany
Peat-Free	Various	Microbiotech (GB), Gs Fresh (GB) Waitrose (GB)
S-Transit	Various	Teagasc (IRL), UCD (IRL), Microbiotech (GB)
Turkey	Perlite and vermicompost	University of Akdeniz
Mexico	Coffee and paper wastes	Facultad de Química, UNAM (MEX)
AMI	Wood fibre and SMC	Penn State Univ (USA)

4.4 Characterisation of casing materials and relationships with mushroom cropping

A scientific paper on the physical characterisation of peat and alternative casing materials has been prepared and submitted by Noble and Dobrovin-Pennington (2023). The paper has been submitted for publication and circulated to the AMGA when available. The air and water holding characteristics, bulk density, pH and EC of casings were considered. A range of peat types and lime sources, and 18 alternative materials obtained from different countries were included. After drainage from saturation or at matric potential -1 kPa, peat casings generally had higher water volumes than alternative materials except bentonite, coir and paper waste; pine bark fines and used granulated rockwool had higher water volumes than the other alternatives. At matric potential -15 kPa, bentonite had the highest water volume, followed by some of the peat casings, and paper waste; one source of green waste compost had a water volume equivalent to the other peat casings. Mushroom yield from peat casings normally declines when the electrical conductivity (EC) is ≥1.5 mS cm^{-1} and all the alternatives had ECs below this value. However, for alternatives which retain less water than peat casing, this threshold EC may be lower.

Electronic sensors have been used to monitor the water status of casing during mushroom cropping. Electronic tensiometers have provided more useful information on water availability in casing than volumetric moisture sensors since the output is not influenced by the physical properties of the casing. Solid-state foam-based tensiometers

have been used in growing media and mushroom casing. Although they are more robust than water-filled tensiometers, they do not detect the full decrease in casing matric potential during a flush of mushrooms which can go down to -40 kPa or lower.

5. Economics and sustainability of alternative casing materials

5.1 Availability and costs of alternative materials in Australia and other countries

Imported European casing consists of an organic material (wet-dug peat) and a mineral material (sugar beet lime). Over a range of least 5 – 25% v/v, the rate of sugar beet lime in peat casing has only a small or insignificant effect on mushroom yield. Alternative materials for both the organic and mineral fractions in casing should therefore be considered.

5.1.1 Organic materials

Growing Media Europe estimate that there will be a 200% increase in demand for peat and wood fibre and 400% increase in demand for coir if the current increase in demand for growing medium components continues. The professional growing media sector must also compete with the hobby gardening sector and energy industry for raw materials (Zoom 8). In Norway, the production of bark is 400,000 m^3 but 80% of this is used for bioenergy (Alfredsen et al. 2018). A review by Hirschler et al. (2022) in Germany suggests that the resource supply does not generally indicate a limitation to an extended use of alternative growing media constituents (bark, green waste composts, wood fibre, coir) in Europe.

Bark

Bark is Australia's main ingredient for potting media. Around 400,000 tonnes are produced annually by sawmills from softwood trees (*Pinus* species). About 55% of this bark is burnt for energy production, about 10% is used for woodchip and the remaining 35% is disposed of. The main production states are NSW, Victoria, Queensland and SA (Lock & Whittle 2018). The bark is ground, screened and composted with a nitrogen source (urea or ammonium nitrate) before use in horticulture. The quality of composted bark can be variable depending on the age of the bark and length of the composting process (Nursery & Garden Industry Australia, Technical Nursery Papers, September 2010, No. 8). The main threat to supply is the energy industry which will affect the price. The price will also depend on whether current horticultural grades of bark are suitable for casing, or whether additional grinding, screening and/or composting are required. Main suppliers of horticultural bark include BioGro (part of ICL group) and Australian Growing Solutions (part of Klasmann-Deilmann):
https://icl-sf.com/global-en/article/from-bark-to-potting-media-without-shortcuts/
https://klasmann-deilmann.com/en/klasmann-deilmann-expands-in-australia/

Wood by-products

Wood fibre is produced from hardwood (eucalypts) and softwood (pine) sources in Australia and is widely used in plant growing media. Hardwood wood fibre has a more rapid nitrogen draw-down than softwood wood fibre making it less suitable for plant growing media, but the relative suitability for mushroom casing is unknown. The fibre is sterilised at 150°C at 6 bar pressure before mechanical refining. Cost factors will be similar to those of bark. Suppliers include Australian Woodfibre and Australian Growing Solutions:
www.australianwoodfibre.com.au
www.agsolutions.net.au

Green waste compost

Composted green wastes produced to Australian composting standard AS 4454.2012 are used in some Australian plant growing nurseries (Nursery & Garden Industry Australia, Technical Nursery Papers, September 2010, No. 8). It has been used experimentally for mushroom casing in Australia and elsewhere as described in Section 4.1. Green waste compost from the landscape sector was used due to the lower EC (and potentially lower contamination) than in compost from household collections (Goldwater 2021). It is likely that a higher standard for compost would be required for casing than the above AS standard (or equivalent European standards) and it is unclear whether this could be achieved commercially. There is no competition for composted green wastes from the energy sector (although there may be competition for some of the feedstocks), and costs will be lower than for bark or wood fibre products. Composted green wastes have a higher bulk density than bark or wood fibre and transport from composting sites is likely to be a major cost element. Information on the availability of composted green wastes in Australia can be found from the Australian Organics Recycling Association (AORA): www.aora.org.au.

Coconut fibre (coir)

Coir fibre dust is widely used in Australian plant growing media at 10-15% v/v and for soft fruit and tomato growbags. More recently, chopped coconut husk has also been included in growing media (Nursery & Garden Industry Australia, Technical Nursery Papers, September 2010, No. 8). Mushroom casing trials were conducted at Melbourne Mushrooms in the 1990s (see Section 4.1). Unlike bark, wood fibre and composted green waste, coir is an imported material and the cost is significantly higher than that of peat. Suppliers in Australia include:
Galuku (https://galuku.com/coir-substrate-australia/)
Fernland (www.fernland.com.au)
Global Axis (www.globalaxis.com.au).

Recycled horticultural growing media

Spent growing media such as peat, bark, coir and rockwool are produced in quantity by the glasshouse industry and other horticultural sectors and have been used in mushroom casing (Noble & Gaze 1995). Around 30,000 tonnes (300,000 m^3) of spent coir are produced from the glasshouse berry and vegetable industry in Australia annually (Blaesing 2019). In the UK, around 70,000 m3 are produced by the berry fruit industry. An Innovate UK project consortium has examined this material and applied for a patent on a method that produces a mushroom casing from this material.

Re-composted or leached SMC

The recycling of casing into fresh casing has recently been examined in Australia by The Growth Drivers (TGD) consultancy (Scott Needham et al.) in a Hort Innovation funded project. Australia produces around 300,000 tonnes of SMC annually so there is sufficient material to completely replace peat. However, as mentioned in Section 4.1, there are significant issues of high EC and potential contamination with pathogens and pests. Cost will depend on capital and on-going reprocessing costs, water supply and disposal of leachate.

New materials

For casing materials based on locally available by-products, such as Cormo's TEFA casing ingredient based on bioprocessed maize stems and Newfoss's NFF ingredient based on bioprocessing of grass and other agricultural plant residue streams, the transport costs may exceed the product costs (Zoom 6). The raw materials for these casings are available in Australia; commercial availability will depend on the success of current mushroom cropping trials in Europe. Other options may include acquiring the patented technologies developed by these companies to bioprocess similar local materials at a local level.

5.1.2 Mineral materials

To have sufficient water-holding capacity for mushroom casing, mineral materials need to have a small particle size such as clays and filter-cakes from mining and quarrying. Filter-cakes are the fine particle residues left after dewatering (usually with a flocculant and subsequent filtering) sludges from these industries. Larger particle particles such as silts and sands also risk making the mushrooms 'gritty'.

Lime

Powder grade agricultural lime containing high calcium and low magnesium is widely available in Australia. Lime and cement kiln dusts may be useable in casing depending on

analysis, particularly with respect to (high) calcium and (low) magnesium contents and freedom from heavy metals and hydrocarbons (https://www.dpi.nsw.gov.au/agriculture/soils/guides/soil-acidity/best-lime). However, if other by-products have sufficiently high pH values (8 or above), the requirement for lime in casing may be negated.

Sugar industry by-products

Sugar beet lime, a standard component of European casing is not available in Australia because only cane sugar is produced. Since the withdrawal of EU sugar beet quotas, the area of sugar beet in the EU and UK has declined (CEFS Statistics 2021) and increasing proportion of sugar (more than 80%) is imported cane sugar. Sugar beet lime is also a significant cost in mushroom casing ($40/tonne). It is usually added at 10-15% by volume, although rates in peat casing of between 10 and 30%v/v have only small effects on mushroom yield and quality (Noble et al. 1999; Huerta et al. 2001; Barry et al. 2007).

Matured sugar beet lime

Cane sugar refining in Australia produces two useable by-products: bagasse (fermented cane pith) and mill mud (a fine particle filter-cake). Most of the bagasse is used by sugar mills for energy generation but the mill mud is disposed of as a soil conditioner and could be available (H. Cook). It has a moderate to low EC (around 0.85 mS/cm) and a pH of 7.9-8 making it a potential replacement for sugar beet lime. Transportation from the cane sugar mills in Queensland would be the major cost. Around 57Kt are produced annually by a single sugar mill (C Wood). As with sugar beet lime, the material would need maturation for several months.

Mining and quarrying by-products

Fine particle filter-cakes are produced by sand and gravel quarries, as well as coal and other mineral mines. Silt-grade (<63 μm) particulates are washed from the larger aggregate (sand/gravel) fraction at the mining site. This by-product represents approximately 20% of all material quarried in the UK (Mašková et al. 2019) and there is an abundant supply of such material in NSW. It is typically collected in a settlement pond/lagoons, wherein flocculant can be added to aid in settlement. However, due to the combined pressure on quarry/mine sites for space and environmental compliance, filter-press infrastructure is favoured over settlement ponds. These facilities occupy a smaller area and separate fine-particulates from water by means of mechanical screening. The resultant material resembles potter's clay (although not typically comprised of clay minerals), known as 'filter-cake'. Filter-cakes from sand quarries are more suitable than those from coal mining due to the paler colour and are therefore less likely to stain mushrooms. They are also typically non-hazardous and inert, although this would likely require assessment on a site-to-site basis especially in instances where the bedrock geology is likely to contain heavy-metal containing minerals. Sand quarry filter-cake was used in producing an Australian peat-based mushroom casing (Grange Growing Solutions) in 2006. The pH of the filter cake was 8.4 so that no lime was required in a peat casing mix.

5.2 Carbon footprint and environmental impact of alternative materials

The United Nations Environment Assembly (UNEA) resolution 16, on 'Conservation and Sustainable Management of Peatlands' was adopted by all UN member states (2019). This resolution recognises, the environmental and climatic services provided by peatlands which are acknowledged with respect to the implementation of the 2030 UN Agenda for Sustainable Development. Peatlands are the most effective store of organic soil carbon on Earth, accounting for 600 Gt worldwide (Limpens et al., 2008). Where peatlands remain intact they actively and continually sequester atmospheric CO_2 however this functionality is lost once peat-soils decompose in the presence of oxygen once drained for peat extraction (Waddington et al., 2015). Each cubic metre of peat extracted releases between 110 and 220 kg CO_2 (Bos et al. 2011).

Intact and even semi-degraded peatlands, fens and wetlands are considered unique and important habitats with global importance in the prevention of biodiversity decline (Tanneberger et al., 2021). Furthermore in a report to the IUCN (UK), Allot et al. (2019) notes that intact peatlands may act to buffer the release of surface water into streams and rivers, thus helping to mitigate flooding.

All the organic materials that have been considered for peat alternatives in mushroom casing are by-products of other processes rather than virgin materials and have

lower carbon footprints than peat. The other main environmental benefit of peat alternatives is preventing the loss in biodiversity of peat bogs. However, there are environmental risks such as the spread of invasive pests, diseases and plants from re-processed plant materials. Pollution can result from leachate from composted materials (Moyland 2020).

A move from peat to alternative casings will affect several factors that could both reduce and increase the carbon footprint of button mushroom cultivation and food production generally (Table 4). From this review, it can be assumed that this move would result in a mushroom yield loss, a longer production cycle, and more watering due to a lower water holding capacity of peat alternative casing. If the production of alternative materials requires significant energy (milling, heating, transport etc.) this could partly or completely negate any carbon footprint reduction over peat casing. Similarly, a reduced efficiency or delay of mushroom cultivation will increase the requirement of composts, and heating or cooling of cropping rooms to achieve the same level of production. Full life cycle analysis (LCA) taking all these factors into account will be necessary to compare casing blends derived from alternative ingredients with each other.

Table 4. Potential effects of moving from peat to alternative casing on the carbon footprints and other environmental impacts of mushroom cultivation and food production generally

Moving from peat to alternative casing: Reduced carbon footprint or impact	**Moving from peat to alternative casing: Increased carbon footprint or impact**
Avoids extraction of peat from bogs and release of CO_2	Energy requirement for processing alternatives
Shorter transport of local raw materials	Reduced efficiency of cropping composts
	Additional heating of cropping rooms
	More and greater frequency of watering
	Washing and disposal of leachate
	Higher mushroom prices; switch to meat
	Less recycling of straw and manures

If mushroom prices rise due to poorer yields and/or lower efficiency of production, this may encourage consumers to switch to meat products and will reduce the recycling of organic wastes (straw and manures) into food production. If the raw materials for alternative casings can be sourced locally, this will reduce carbon footprint of casing compared with imported materials. However, shipping of casing from Europe to Australia is usually in return shipping containers which offsets their carbon footprint. Therefore, unless the peat alternative casing results in a similar efficiency of mushroom production to peat casing and

does not involve significant energy consumption in production or transport, the overall reduction in carbon footprint may be small. Similarly, if the alternative casing requires significantly more irrigation water and/or involves washing and disposal of leachate (for example from washed SMC), the environmental benefits may negate the benefits of peat replacement. The tangible environmental benefits of alternative casing materials are the avoidance of peat bog ecosystem destruction, the preservation of their carbon sinks and biodiversity and longer-term sustainability.

An analysis of sustainability of peat alternatives was undertaken by Bek at al. (2020). Green waste compost and bark were considered to be the most sustainable materials. Since bark is a by-product of the timber industry, supply will depend on the production of timber, particularly for building. Wood fibre can involve significant energy consumption (47 kWh m^{-3}) if it is extruded but can be produced by sieving and milling which are less energy demanding. Coir processing involves significant water use and transport from coconut growing areas. Global production, mainly from India and Sri Lanka is currently around 10Mm^3, but based on the global area of coconuts could increase to 50Mm^3. With the exception of green waste compost, the price of peat alternatives in the UK and Ireland is 2 to 6 times higher than of peat (Bek et al. 2020).

6. Changes in mushroom cultivation needed in response to non-peat casing

6.1 Changes in casing water measurement and irrigation

Watering of the casing is usually based on pre-determined watering schedules (volumes and timing) and adjustments made on the ‘feel’ of the casing (den Ouden 2016). Water is then applied through mobile watering ‘trees’ or through sprinklers fixed into the shelves. Such systems are suited to peat casing where a reservoir of water can be established and no further water needs to be applied before the first flush, thereby reducing the risk of bacterial blotch. Attempts have been made to install automated drip irrigation systems in mushroom growing beds to compensate for the lower water holding capacity of peat alternative casings. The aim is to avoid applying water to developing mushrooms by sub-irrigating through perforated pipes that are buried into the casing at application. Systems have been developed by Netafim in Israel (Danay et al 2016; Raz et al 2016) and in an Innovate UK project (Noble et al 2017). In the latter project, mushroom yields and quality from the submerged pipe system and conventional sprinklers were not significantly different, although the comparisons were done with a standard 5 cm depth layer of wet-dug peat casing. It is possible that there may be benefits from using a submerged pipe irrigation system when using shallower casing layers and/or alternative materials (Zoom 6). A drawback of the

submerged pipes has been the time required to install, extract and sanitize the irrigation system between mushroom crops, particularly as many crops are now not cooked-out.

Reducing the depth of the casing from 4.5 or 5cm to 2.5 or 3 cm normally reduces the mushroom yield (Kalberer 1986; Noble et al. 1997). It may be possible to reduce the depth of the casing layer without affecting mushroom cropping by adjusting the water applications (B. Driessen). In North America, the casing depth was reduced from 4-5cm to 3-4 cm during the peat shortage (Samp & De Santis 2022).

6.2 Mushroom strains

Mushroom strains have been selected for performance on peat casing, except in China where predominantly mineral soil casing has been used. Pardo et al (2010) measured the mushroom yield and various quality parameters of white, off-white and mid-range hybrid mushrooms strains when grown on four different mineral soil and peat casing mixtures. Although they found significant differences in yield and quality between strains and casing materials, there was no interaction between the two factors, i.e. the 'best' strain was the same for all four casings and vice versa. Tests in the UK, Ireland and New Zealand have shown that mushroom yields and quality on alternative casings are more comparable with wet-dug peat casing when using brown strains (e.g. Amycel Heirloom, Sylvan Tuscon) than when using white strains (e.g. Sylvan A15). This is probably due to the higher yielding capacity, and therefore higher water requirement of white strains compared with browns. It is also easier to water brown strains than white strains closer to harvest with less risk of staining and bacterial blotch. This reduces the disadvantage of lower water retention of peat alternatives and can enable casing to be washed off caps since dirtiness can be a problem with some alternatives. White strains also tend to have rougher caps than brown strains making it more difficult to obtain clean mushrooms. There is a need for new white strains that have a lower water requirement, can be watered closer to harvest without risk of blotch or staining and have smooth caps that are suited for use with peat alternatives.

Brown mushroom strains are more suited to milled sphagnum peat and alternative casings than current white mushroom strains

6.3 Preparation and mechanical blending of non-peat materials

Until the introduction of wet-dug peat casing, most farms mixed and wetted their own casing from baled dry sphagnum peat and chalk (Atkins 1974). Milled peats were wetted and blended in screw-auger mixers such as the Traymaster or rotating paddle mixers such as the Adelphi (Bunt 1976) and Winget Turbomixer (Atkins 1974). However, such machinery was unsuitable for wet-dug peats which depend on their microporous structure for high water holding capacity, which is lost after heavy compression or partial drying out (den Ouden 2016). Following the introduction of wet-dug peats, blending of bulk materials was done with front-end bucket loaders by specialised casing producers located near to the sources of wet-dug peat (or connected through a bulk shipping canal system as in the Netherlands and northern Germany). The casing is then transported ready mixed to mushroom farms. Peat casing that is exported may undergo some drying out and compression to reduce transport costs (den Ouden 2016). However, for peat alternatives such as bark and composts which are resilient to structural breakdown, heavy and thorough mixing is essential to achieve a good blend. The above types of screw augers and paddle mixers may then be more suitable. Localised mixing and wetting of dry casing ingredients, close to mushroom farms, may be a more viable option. In the west USA, most farms mix their own casing from raw materials whereas on the east coast, it is more common for farms to have it delivered ready-mixed (Zoom 3).

Due to the dependence on imported ready-mixed casing, the casing mixing infrastructure that was previously in Australia and other countries has largely been dismantled (S. Grange). This would need to be reassembled if casings were to be prepared from locally available materials.

7. Regulatory impacts on the recycling of materials into casing

7.1 Waste regulations concerning the recycling of materials into casing

The Australian Environment Protection Agency (EPA) has a waste classification system (Waste Classification Guidelines – Part 1: Classification of Wastes). Various chemical contaminant thresholds (CT) are set for wastes. The by-products considered for use in mushroom casing would be classified as general solid wastes (non putrescible) ≤CT1 unless they have an exemption. There are several exemptions for the re-use of materials in agriculture and other applications. These include: biosolids, bulk agricultural crop waste, coal washery rejects, compost (pasteurised at 55°C), and recovered quarry fines. It is also possible to apply for an exemption for a specific waste material.

The compost waste exemption requires materials to be composted at 55°C for at least three turns or given an equivalent pasteurisation treatment (for example in an in-vessel

composting system). There is no specific exemption for classification of SMC. In the UK (except Northern Ireland) SMC is classed as a waste and cannot be sold commercially as a growing medium component, although it can be spread on to fields under an exemption. In the Netherlands, separated spent compost is composted at 80°C which means that it passes sanitary tests and the material can be exported. It can be sold as a casing ingredient, or if composted with ammonium sulphate from air scrubbers, as a fertilizer (B. Driessen).

7.2 Food regulations concerning growing mushrooms on recycled materials

Food standards in Australia are regulated by the Food Standards Australia New Zealand. Unlike leafy vegetables, berries and melons, there are no primary production standards for mushrooms. However, in these other crops, inputs of soil amendments, fertiliser and water must be recorded. Microbiological limits in food are set under Standard 1.6.1. Limits for pesticide residues in agricultural products are set by the Australian Pesticides and Medicines Authority. In the EU, there are specific limits for heavy metals in mushrooms. In South Africa, food accreditation (Act 26) is required for a casing material to be used for mushroom cultivation (Zoom 6).

8. Future requirements to produce mushrooms and non-peat casing in Australia

8.1 Future availability of imported peat

As outlined in section 3, due to regulatory changes, the availability of peat from European countries that produce the best quality wet-dug peat for casing is both tenuous and dynamic. However, there are still peat extraction licences in Germany, Ireland and Northern Ireland to enable a plentiful supply of wet-dug peat for mushroom casing for several decades. Even if peat casing is no-longer permitted for use in Europe, all the major European casing producers confirmed that they still had viable businesses supplying wet-dug peat casing to the Southern Hemisphere. This will also depend on the shipping costs from Europe to the Southern Hemisphere.

In Canada, the supply of peat can be erratic. The current situation regarding the availability of peat in Australia described in this report is therefore likely to change periodically in the next few years. The AMGA should regularly update the information on the future availability of peat and alternative casing materials. In any event, the development of a long-term sustainable casing strategy for the Australian mushroom industry is prudent.

8.2 Future research and development requirements

8.2.1 Watching brief on availability of peat and alternatives for casing

The AMGA should regularly update the information on the availability of peat from different countries. The progress of peat alternatives in other countries such as the use of SMC, Cormo and Newfoss should also be followed. However, further development of these

alternatives in Australia should wait until they have been shown to be viable on a commercial scale elsewhere since peat is likely to be available for at least a decade and probably decades.

8.2.2 Casing materials

From this review, there are several organic and mineral materials in Australia that are currently in sufficient quality and quantity and at potentially low cost to be considered for use in mushroom casing. These are:

- Composted pine bark fines
- Heat expanded woodfibre (softwood pine and hardwood eucalypts)
- Re-composted SMC (if leaching can be avoided)
- Spent growing media from other horticultural production
- Mill mud from sugar cane processing
- Filter cakes from sand quarries

Advantages and disadvantages of these materials are outlined in Table 2. Since there is currently significant research effort in Europe and North America examining partial and complete replacement of peat with bark, woodfibre, SMC and coir, with no commercial mix yet available, repeating this work in Australia is unnecessary. The risk of wet-dug peat casing being unavailable in Australia is much lower than in Europe. Mixtures of peat and organic peat alternatives such as bark, wood-fibre and coir should be avoided since if peat is available at a viable cost, it will still be the best material, particularly if performance can be improved by adding mineral materials. If it is banned or becomes too expensive, it will not be available for mixtures either. Also, the risk of green mould is increased by mixing peat with organic materials.

The following areas should be examined, in each case using wet-dug peat and sugar beet lime casing as a control material:

(a) Replacement of the 10-15% imported sugar beet lime in casing with up to 30% of local materials (mill mud in Queensland and filter cakes elsewhere). This would have several advantages:
    (i) increase the amount of wet-dug peat that can imported for the same shipping cost
    (ii) avoid the cost of adding sugar beet lime to the casing
    (iii) reduce the amount of wet-dug peat needed by substitution with mill mud or filter cake
    (iv) keep the peat acidic during shipping, reducing the risk of moulds and nematodes.

The main disadvantages would be the need for mixing facilities and the transport cost of the mill mud or filter cake within Australia.

(b) Use of brown or blond dried milled peats from Baltic States, Scandinavia, Canada (and possibly New Zealand peat) in combination with small particle materials (sugar mill mud, filter cake clays) to increase casing density and improve water holding characteristics.

Small scale trials followed by larger scale tray and shelf trials will be needed to determine the optimum blends of materials and how they compare with wet-dug peat and sugar beet lime casing. Suitable mixing equipment will be needed for wetting and blending raw materials.

8.2.3 Watering regimes

Methods for watering before the first flush without causing blotch discoloration will be needed to maximize yields from dry milled peat casings. New casing blends will need to be characterized for physical properties using methods described in Section 4.4. Electronic tensiometers can measure the effect of casing materials and watering regimes on moisture availability in the casing layer.

8.2.4 Strain selection

As outlined in section 6.2, the difference between wet-dug peat and dry milled peat casings is smaller when using brown strains of mushrooms than white strains. There is a requirement for white mushroom strains that perform equally well in terms of yield and quality on wet-dug peat and dry milled peat casings. Strains that are tolerant of watering before the first flush and that have smooth caps would also be beneficial for dry milled peat casings. Work is needed on the water use efficiency of brown and white mushroom strains in different casing materials and under different watering regimes.

8.2.5 Assessments

In assessing the suitability of new casing blends, the following factors need to be considered:

- Mushroom yield and crop duration
- Mushroom quality, particularly size, opening, cleanness, blotch and shelf life
- Effects on mycelium growth and initiation of primordia
- Watering requirement
- Occurrence of moulds and fungal diseases, particularly green mould (*Trichoderma* sp,), Cinnamon mould, Dry bubble (*Lecanicillium fungicola*).

8.3 Future commercial equipment and infrastructure requirements

Full scale commercial development will require input from suppliers of raw materials, casing or growing medium manufacturers, mushroom farms, spawn producers, scientists, and retailers. Large-scale mixing and wetting facilities for preparing blends of casing materials will be needed. As mentioned in Section 6.3, equipment is likely to be different than that used for preparing ready-mixed peat casing.

It is likely that casing blends suitable for tray and shelf farms will be different. Intermediate scale cropping facilities will be needed for conducting replicated experiments before the most promising blends are tested on a fully commercial scale.

9. Conclusions

1. A casing layer is essential for button mushroom fruitbody production in quantity; peat as well as many other materials can stimulate the formation of fruitbody initials.
2. Annually, the global button mushroom industry uses about 4M m^3 of peat for casing; the largest volumes of peat casing are used in Poland and the USA.
3. Mushroom casing currently represents about 10% of the peat extracted for growing media and about 5% of the total peat extracted globally; peat extraction for energy continues to decline which will tend to increase the latter percentage.
4. Australia uses around 85K m^3 of peat casing annually, about 2% of the global total; most of this peat is imported from Europe with a smaller volume from Canada.
5. The regulatory situation regarding peat extraction and professional use in different European countries is dynamic and is likely to change periodically in the next few years.
6. In Europe, it is becoming increasingly difficult to obtain new permissions for peat extraction and several countries now have phase-out plans for the use of peat in professional horticulture, starting in 2026; there is also pressure from multiple retailers to stop using peat in casing.
7. There is sufficient wet-dug peat from bogs with extraction licences in Europe to supply the mushroom industry for several decades; even if the use of peat casing is banned in Europe, the major casing producers expect to have viable businesses supplying the Southern Hemisphere with peat casing; this will depend on shipping costs.
8. Although the supply of peat from Baltic States, Finland, Sweden and Russia is secure, the quality of the blond peat is less suitable for mushroom casing than the wet-dug black peats from the island of Ireland, Germany and Poland.

9. The supply of peat in North America has been erratic due to unfavourable harvesting and transport conditions rather than environmental pressure.
10. There are no 100% peat alternatives which have been shown to produce the same mushroom yields and quality in the same timeframe as wet-dug peat casings; the discrepancy can be largely attributed to poorer water retention, higher salinity (electrical conductivity) and/or susceptibility to mould growth of peat alternatives.
11. Globally and in Australia, there is currently a plentiful supply of potential peat alternatives for casing, such as bark and wood fibre products and imported coir but the demand for bioenergy and alternative horticultural uses will increase prices and may lead to shortages.
12. There is a large supply of recycled growing media in Australia such as spent peat, bark, coir and rockwool from other horticultural sectors which could be re-used as mushroom casing.
13. Developments such as Cormo's TEFRA from maize stalks, Newfoss's NFF from bioprocssed grass and sphagnum moss are undergoing mushroom cropping trials in Europe; all these raw materials are or could be available in Australia in sufficient quantity for casing.
14. The carbon footprints of peat alternatives are smaller than of peat, even if the energy required for processing and transport for some materials is considered; however, reductions in mushroom production efficiency and recycling of organic wastes into food production and increase in demand for water (e.g. for leaching and irrigation) will negate environmental benefits of peat substitution.
15. Mushroom substrates (casing and/or compost) have been recycled to produce new casing in some countries although leaching to reduce salinity to an acceptable level would be a significant challenge in Australia.
16. In Australia, there are large supplies of filter-cakes from the quarrying and cane sugar industries which could replace sugar beet lime and some of the wet-dug peat in a casing blend.
17. Green wastes composts have been used experimentally in mushroom casing and they could form a component in a casing blend; however, current quality standards are not sufficiently rigorous for use in mushroom casing.
18. In the recycling of wastes or by-products into casing in Australia, the waste classification and application for a waste exemption from the EPA should be considered.
19. Research and development for casings in Australia should concentrate on replacing sugar beet lime in imported casing with larger volumes of locally available mineral

materials: filter cakes from quarries and sugar mills; the use of these materials with dry milled peat and New Zealand peat should also be examined.

20. There has been a large research effort in recent years into peat 'reduction' rather than complete replacement; this now seems less relevant since a peat ban will make it unavailable for use in mushroom casing; research into 100% peat replacement is a new challenge and will require an evolution of the mushroom production system.
21. Mixing peat (acidic which favours green mould) with organic materials that are susceptible to green mould (bark, green waste compost, coir, wood fibre) increases the risk of green mould; it is better to keep peat and alternatives apart.
22. Current brown mushroom strains are more suited than white strains to dry milled peat and peat alternative casings due to a lower water requirement, less risk of blotch or staining by watering close to harvest and smooth caps which do not attract specks of casing; there is therefore a need for white strains bred for use on dry milled peat and peat alternative casings.
23. Due to the dependence on imported ready mixed casing, the casing mixing infrastructure that was previously present in Australia and other countries has been dismantled; this would need to be reassembled if casings are to be prepared from locally available materials.

References

Ahmed MB, Zhou JL, Ngo HH, Guo W (2016). Insight into biochar properties and its cost analysis. *Biomass and Bioenergy 84*: 76-86.

Alfredsen G et al. (2018) Secondary raw materials from wood-based value chains in Norway. Norsk Institutt for Biookonomie, Vol. 4, Number 93, 39pp.

Allen PG (1976) Casing variables – plastic tunnels. *Mushroom Journal* 37: 22-29.

Anonymous (2019) A new peat substitute. *Mushroom Business*: 94.

Atkins FC (1974) Guide to Mushroom Growing. Faber and Faber, London, 122 pp.

Barry J, Grant J, Doyle O, Grogan H (2008) Partial substitution of peat with spent mushroom substrate in peat-based blends. Science and Cultivation of Edible Fungi XVII (Part 1) pp. 388-410.

Bek D, Lennartsson-Turner M, Lanari N (2020) Towards peat-free horticulture in the UK: an assessment of policy, progress, opportunities and barriers. University of Coventry, 93pp. https://hta.org.uk/uploads/assets/219d3ce6-e9a2-4659b0a52d7a1bd6dd1e/FINALCOVNTRYUNIREPORT-HTAGMAFinalCoversauthors29Sept20-1.pdf

Bels Konig HC (1950) Experiments with casing soils, water supply and climate. *Mushroom Science* I: 78-84.

Betts R (2021) What's the Potential for Mushrooms to Cause Bacterial Food Poisoning? https://www.rapidmicrobiology.com/news/what-39-s-the-potential-for-mushrooms-to-cause-bacterial-food-poisoning

Blaesing D (2019) Coir waste management for hydroponics in berries. Final Report MT17016, Hort Innovation Australia.

Blok C, Eveleens B, van Winkel A (2021). Growing media for food and quality of life in the period 2020-2050. Acta Horticulturae, 1305, 341-355. https://doi.org/10.17660/ActaHortic.2021.1305.46

Booyens, N (2012) Mushroom industry has the option to stop depleting natural resources. https://www.engineeringnews.co.za/article/mushroom-industry-has-the-option-to-stop-depleting-natural-resources-2012-08-10

Bos MG, Diemont HW, Verhagen A (2011) Sustainable peat supply chain. Wageningen University, The Netherlands, Altera Report 2167.

Buchanan PK, Barnes J (2003) The Mushroom Industry in New Zealand. http://www.hri.ac.uk/isms/article16.htm.

Bunt AC (1976) Modern potting composts. George Allen & Unwin, London.

CEFS Statistics (2021) https://cefs.org/wp-content/uploads/2022/04/CEFS-Statistics-2020-2021.pdf

Clancy G, Horton PR (1981) Laboratory and field testing of graypete as a substitute for sphagnum peat moss casing in the cultivation of Agaricus bisporus. *Mushroom Science* XI (Part 1): 441-452.

DAFM (2022). Working Paper to address challenges related to peat supply in the Horticulture Sector. https://www.gov.ie/ga/foilsiuchan/39315-working-paper-to-address-challenges-related-to-peat-supply-in-the-horticulture-sector/

Dalias P, Prasad M, Mumme J, Kern J, Stylianou M, Christou A (2018) Low-cost post-treatments improve the efficacy of hydrochar as peat replacement in growing media. *Journal of Environmental Chemical Engineering* 6: 6647-6652.

Danay O, Van den Berg P, Raz D, Engel Y, Kobi E, Barski I, Levanon D (2016) From Theory to Practice - Success in Implementing Drip Irrigation in Commercial Mushroom (A. bisporus) Cultivation. Science and cultivation of edible and medicinal fungi: Mushroom Science XIX. Proceedings of the 19th Congress of the International Society for Mushroom Science, Amsterdam, The Netherlands, 30 May–2 June 2016. International Society for Mushroom Science. Amsterdam: 27-29.

Den Ouden M (2016) Mushroom Signals: A Practical guide to optimal mushroom growing. Roodbont Publishers BV, Zutphen, The Netherlands. 153 pp.

Eastwood DC, Herman B, Noble R, Dobrovin-Pennington A, Sreenivasaprasad S, Burton KS (2013) Environmental regulation of reproductive phase change in *Agaricus bisporus* by 1-octen-3-ol, temperature and CO_2. *Fungal Genetics and Biology* 55:54-66.

Edwards R, Flegg PB (1953) Cropping experiments on casing soil. Report of the Mushroom Research Association 1952: 20-29.

Farru G, Dang CH, Schultze M, Kern J, Cappai G, Libra JA (2022) Benefits and limitations of using hydrochars from organic residues as replacement for peat on growing media. *Horticulturae*, *8*(4), p.325.

Femia N (2022) Grower Stories: SA Mushrooms in Australia. https://bvbsubstrates.videomarketingplatform.co/grower-story-sa-mushrooms-australia

Fermor T, Lincoln S, Noble R, Dobrovin-Pennington A (2000) Microbiological properties of casing. *Mushroom Science* 14: 447-454.

Flegg PB, Wood PB (1985) Growth and fruiting. In: The Biology and Technology of the Cultivated Mushroom. PB Flegg, DM Spencer, DA Wood (eds), John Wiley & Sons, Chichester, pp. 141-178.

FSA (2003) ACM/655 Advisory Committee on the Microbiological Safety of food, Raw mushrooms: Consumer Advice. Food Standards Agency (UK).

Gallagher PA (1976) Peat in protected cropping. In: Peat in Horticulture (eds) DW Robinson & JGD Lamb. Academic Press, London, pp. 133-145.

Genders R (1969) Mushroom growing for everyone. Faber & Faber, London, 216 pp.

Goldwater, A (2021) Recycled organics as an alternative to peat in mushroom casing trials. *Australian Mushroom Journal* 2: 34-36.

Hayes WA, Nair NG (1974) Effects of volatile metabolic by-products of mushroom mycelium on the ecology of the casing layer. Mushroom Science IX (Part 1): 259-268.

Hayes WA, Randle PE, Last FT (1969) The nature of the microbial stimulus affecting sporophore formation in Agaricus bisporus (Lange) Sing. *Annals of Applied Biology* 64: 177-187.

Hayes WA, Yeo SG, Cresswell PA, Jakeman KJ (1978) Paper and pulp mill by-product as a casing medium for mushroom culture. *Mushroom Journal* 62: 38-44.

Hirschler O, Osterburg B, Weimar H, Glasenapp S, Ohmes M-F (2022) Availability of bio-based alternative materials. Thuenen Working Paper 190. Braunschweig and Hamburg, Germany.

Huerta F, Spalding T, Kelly (2001) Investigations on casing soil with a high mineral content. *Mushroom News* 49(1) 4-9.

Jackowski, M., Niedzwiecki, L., Lech, M., Wnukowski, M., Arora, A., Tkaczuk-Serafin, M., Baranowski, M., Krochmalny, K., Veetil, V.K., Seruga, P. and Trusek, A., 2020. HTC of wet residues of the brewing process: Comprehensive characterization of produced beer, spent grain and valorized residues. *Energies*, *13*(8), p.2058.

Kalberer PP (1986) Influence of the depth of the casing layer on water extraction from casing soil and substrate by the sporophores, on the yield and on the dry matter content of the fruit bodies of the first three flushes of the cultivated mushroom *Agaricus bisporus*. *Scientia Horticulturae* 27: 33-43.

Labuschagne P, Eicker A, van Greuning (1995) Casing mediums for *Agaricus bisporus* cultivation in South Africa: A preliminary report. *Mushroom Science* XIV (Part 1): 339-346.

Limpens J, Berendse F, Blodau C, Canadell JG, Freeman C, Holden J, Roulet N, Rydin H, Schaepman-Strub G (2008) Peatlands and the carbon cycle: from local processes to global implications–a synthesis. *Biogeosciences*, *5*: 1475-1491.

Lock P, Whittle L (2018) Future opportunities for using forest and sawmill residues in Australia, ABARES, Canberra, November. CC BY 4.0. https:/doi.org/10.25814/5bdfaee303b64

Magan N, Challen M P and Elliott T J (1995) Osmotic, matric and temperature effects on in vitro growth of Agaricus bisporus and A. bitorquis strains. In: Elliot, T.J. (ed.), Science and technology of edible mushrooms. Rotterdam, Balkemaar, pp. 773-780.

Maskova L, Simmons RW, De Baets S, Moran Montero E, Delmer A, Sakrabani R (2019) Assessment of silt from sand and gravel processing as a suitable sub-soil material in land restoration: A glasshouse study. Chemosphere 219: 58-65. https://doi.org/10.1016/j.chemosphere.2018.11.155

Miller N, Gillespie JB, Doyle OPE (1995). The involvement of microbiological components of peat casing materials in fructification of Agaricus bisporus. In: Mushroom Science XIV: 313-322.

Mirzadeh M (2022) Spent mushroom compost as casing. https://ahr.com.au/blog/t48616mfrz7539k9lll4u1skc41748?rq=mushroom%20casing

Mishurov NP, Selivanov NP, Devochkina NL, Rubtov AA (2021) High-tech production of edible mushrooms on an industrial basis in the Russian Federation. IOP Conf. Series: Earth and Environmental Science 723 (2021) 032080 IOP Publishing doi:10.1088/1755-1315/723/3/032080

Moyland E (2020) Forslag til plan for overgang fra bruk av torvbaserte til torvfrie produkter in Nowegian). Proposal for a plan for transition from the use of peat-based to peat-free products. Norge Miljo-Direktoratet, Rapport M-1673, Trondheim, Norway.

Mulholland B, Watson A (2019) Transition towards responsibly sourced growing media within UK horticulture. Final Report AHDB Horticulture Project CP 138.

Mumme J et al. (2018) Toxicity screening of biochar-mineral composites using germination tests. Chemosphere 207: 91-100. https://doi.org/10.1016/j.chemosphere.2018.05.042

Nair NG, Bradley JK (1981) Recycling waste plant products as casing materials in mushroom cultivation. Mushroom Science XI (Part 2): 147-152.

Noble R (2003) Peat substitution makes mushroom casing more eco-friendly. *Mushroom J.* 638: 20-21.

Noble R (2011) Mushrooms: Desk study/literature review of the potential alternative materials to peat in mushroom casing. AHDB Report M 55.

Noble R, Gaze RH. (1995) Properties of casing peat types and additives and their influence on mushroom yield and quality. Science and Cultivation of Edible Fungi (ed.) TJ Elliot, Balkema, Rotterdam. pp. 305-312.

Noble R., Bareham L. (2002) Casing material and its use in crop cultivation. European Patent Number EP(UK) 1372374; South African Patent No 2003/7476; Australian Patent No. 2002241097 B2; US Patent USP83684. International Patent WO2002076185 A1

Noble R (1999) Determining the causes of mushroom water stress symptoms. HDC Final Report M 35.

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

Noble R., Dobrovin-Pennington A (2016a) AHDB Report M 60 Developing alternatives to peat in casing materials for mushroom production. Final Report, AHDB Horticulture, Kenilworth, UK.

Noble R, Dobrovin-Pennington A (2016b) Peat and alternative materials for mushroom casing. AHDB Factsheet 15/15. AHDB Horticulture, Kenilworth.

Noble R, Dobrovin-Penninton A (2023) Physicochemical characterisation of peat and alternative casings. Submitted to *Scientia Horticulturae*.

Noble R, Dobrovin-Pennington A, Evered CE, Mead A (1999) Properties of peat-based casing soils and their influence on the growth of the mushroom (*Agaricus bisporus). Plant and Soil* 207: 1–13.

Noble R, Rama T, Dobrovin-Pennington A (2000) Continuous measurement of casing soil and compost water availability in relation to mushroom yield and quality. *Mushroom Science* 14: 433-440.

Noble R, Rama T, Miles S, Burton KS, Stephens TM, Reed JN (1997) Influences of compost and casing layer depths on the mechanical properties of mushrooms. *Annals of Applied Biology* 131: 79 - 90.

Noble R, Fermor TR, Lincoln S, Dobrovin-Pennington A, Evered C, Mead A, Li R (2003) Primordia initiation of mushroom (*Agaricus bisporus*) strains on axenic casing materials. *Mycologia.* 95: 620-629.

Noble R, Dobrovin-Pennington A, Hobbs PJ, Pederby J, Rodger A (2009) Volatile 8-carbon compounds and pseudomonads influence initiation of *Agaricus bisporus* primordia. *Mycologia* 101:583-591.

Noble R, Goodchild M, Jenkins D, Burton K, Walker D, Moorhouse E (2017) Precision Irrigation of Mushrooms Using a Novel Dielectric Tensiometer. *Mushroom News* 65 (10): 8-17.

Pardo A, de Juan A, Alvarez-Orti M, Pardo JE (2010) Screening of Agaricus bisporus (Lange Imbach) strains and the casing variables for quality mushroom production in Spain. HortScience 45: 231-235.

Peters J (2021) Searching for the holy grail (peat-free casing soil). *Mushroom Business* 108.

Polat E, Onel O (2021) An alternative new casing material in the production of Agaricus bisporus. Mediterranean Agricultural Sciences 34: 261-266.

Pouliot R, Hugron S, Rochefort L (2015) Sphagnum farming: A long term study on producing peat moss biomass sustainably. *Ecological Engineering* 74: 135-147.

Prasad M, Tzortzakis N, McDaniel N (2018) Chemical characterization of biochar and assessment of the nutrient dynamics by means of preliminary plant growth tests. *Journal of Environmental Management* 216: 89-95.

Pryce S (1991) The Peat Alternatives Manual. Friends of the Earth, CAB Direct.

Puustjarvi V, Robertson RA (1976) Physical and chemical properties. In: Peat in Horticulture (eds) DW Robinson & JGD Lamb. Academic Press, London, pp. 133-145.

Rainey PB (1985) A Study of Physical, Chemical and Biological Properties of the Mushroom Casing Layer. MSc Thesis, University of Canterbury, New Zealand.

Raz D, Danay O, Van den Berg P, Engel Y, Kobi E, Barski I, Levanon D, Van Der Meij P (2016) Drip Irrigation in Mushroom Cultivation should be Aligned with Common Practice. Science and cultivation of edible and medicinal fungi: Mushroom Science XIX. Proceedings of the 19th Congress of the International Society for Mushroom Science, Amsterdam, The Netherlands, 30 May–2 June 2016. International Society for Mushroom Science. Amsterdam: 30 -34.

Rettig B, Lelley J, Jaeger R (2001) Casing material for stacks and sitting-out areas in mushroom culture. US Patent No: US 6,205,703 B1.

Riahi H et al. (1998) The first report of spent mushroom compost (SMC) leaching from Iran. Acta Horticulturae 469: 473-480.

Robinson DW, Lamb JGD (1975) Peat in Horticulture. Academic Press, London.

Rowley C, Burdon J. 2019. Using spent mushroom compost as a casing amendment. Aust. Mushroom J. 2019: 37-41.

Royse DJ, Baars J, Qi Tan (2017) Current overview of mushroom production in the World. In: Edible and Medicinal Mushrooms, Technology and Applications (eds) DC Zied, A Pardo), John Wiley & Sons, London, pp. 5-13.

Salmones D, Gaitan-Hernandez R, Mata G (2018) Cultivation of Mexican wild strains of Agaricus bisporus, the button mushroom, under different growth conditions in vitro and determination of their productivity. *Biotechnol. Agron. Soc. Environ.* 22(1): 1-9.

Samp R, De Santis G (2022) Peat shortfall and how to deal with it. Mushroom Business, November 2022, No 115, pp. 26-31.

Shackley, S., Ruysschaert, G., Zwart, K. and Glaser, B. (2016). Biochar in European soils and agriculture. Science and practice. Routledge, London.

Singh M, Kamal S, Sharma VP (2020) Status and trens in world mushroom production-III World production of different mushroom species in the 21st century. Mushroom Research 29(2): 75-111. DOI:10.360/MR.29.2.2020.113703

Soylu MK, Kang M (2016) Mushroom cultivation in South Korea. *Turkish Journal of Agriculture* 4: 225-228.

Starkey NG (1996) A method for the production of fungi. International Patent Application Number WO 96/33602.

Staunton L (1982) Mushrooms. In: Horticulture Research Report, An Foras Taluntais, Dublin, p.21.

Stoller B (1978) Synthetic casings for mushroom beds. US Patent No: US 4,079,543

Stoller B (1979) Synthetic casing for mushroom beds. US Patent No: US 4,170,842.

Sturgeon C (2007) Growth medium for fungi. GB Patent Application 2450346A.

Tanneberger, F., Moen, A., Barthelmes, A., Lewis, E., Miles, L., Sirin, A., Tegetmeyer, C. and Joosten, H., 2021. Mires in Europe—Regional diversity, condition and protection. *Diversity 13*(8): 381.

Taparia T, Hendrix E, Nijhuis E, de Boer W, van der Wolf J (2021) Circular alternatives to peat growing media: A microbiome perspective. *Journal of Cleaner Production* 327: https://doi.org/10.1016/j.jclepro.2021.129375

UNEP. Resolution Adopted by the United Nations Environment Assembly on 15 March 2019. 4/16. Conservation and Sustainable Management of Peatlands (2019). Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/28480/English.pdf?sequence=3&isAllowed=y (accessed on 03 April 2023).

Van Boekel GHC, Van der Horst HC (2020) Production process and composition of casing material for growing mushrooms. European Patent Application EP3593631A1.

Van Gils JJ (1988) Cultivation. In: The Cultivation of Mushrooms (ed LJLD van Griensven). Darlington Mushroom Laboratories pp. 263-306.

van Jaarsveld LP, Korsten L (2008) Chemical and physical properties of alternative casing media in commercial production of button mushrooms [*Agaricus bisporus* (Lange)]. In: Science and Cultivation of Edible Fungi XVII (Part 1) pp.310-332.

Vedder PJC (1978) Modern Mushroom Growing. Tjeenk Willink-Noorduijn N.V., The Netherlands.

Visscher HR (1988) Casing soil. In: The Cultivation of Mushrooms (ed LJLD van Griensven). Darlington Mushroom Laboratories pp. 73-89.

Waddington, J.M., Morris, P.J., Kettridge, N., Granath, G., Thompson, D.K. and Moore, P.A., 2015. Hydrological feedbacks in northern peatlands. *Ecohydrology* 8: 113-127.

Yamashita K (1989) Nutrition agent for artificial cultivation of mushrooms. Japan Patent No.: JP401080227 A

Young G, Gernon D, Grogan H, Walsh L, Schmidt O, Tracy S (2023) Supporting a sustainable transition away from peat-use in mushroom cultivation. Poster at 2023 Mushroom Days Exhibition, Den Bosch, The Netherlands.

Zied DC, Sanchez JE, Noble R, Pardo-Gimenez A (2020) Use of spent mushroom substrate in new mushroom crops to promote the transition towards a circular economy. Agronomy 10, 1239. https://doi.org/10.3390/agronomy10091239.

Appendix I: List of persons consulted in this review and their affiliations

Consultee	Affiliation	Country
Antanasov, Neno	Gs Fresh	Great Britain
Armstrong, Kiri	Meadow Mushrooms	New Zealand
Baars, Johan	Wageningen University	Netherlands
Badgery, Phillip	Legro	Australia
Blogg, Hugh	Soil Association	Great Britain
Breukers, Henryk	Sterckx	Belgium
Buis, Ted	Legro	Netherlands
Cai Weiming	ZAAS, Hangzhou	China
Callisto, Carmine	Global Axis Pty Ltd	Australia
Chambers, Craig	Mercer Mushrooms	New Zealand
Checel, Marcin	Wokas	Poland
Cook, Hywel	Sugar Research Australia	Australia
Cuddy, Ciaran	Harte Peat	Ireland
Dams, Ellen	Legro	Netherlands
Danay, Ofer	Champignon Farm	Israel
Driessen, Bart	Mycosupport Consulting	Netherlands
Flanagan, Mike	Walsh Mushrooms	Ireland
Garfield, Emma	Gs Growers	Great Britain
Gernon, Donal	Teagasc	Ireland
Gheysens, Kristof	INAGRO	Belgium
Goldwater, Adam	Australia Horticulture Research	Australia
Grange, Simon	Grange Growing Solutions	Australia
Hansen, Kirsten	Tvedemose Champignon, Lungby	Denmark
Iaconi, David	Mushroom Supply & Services Inc	USA
Leal Lara, Hermilo	Facultad de Química, UNAM	Mexico
Jones, Jacqui	TNZ	New Zealand
Kilpatrick, Mairead	AFBINI	Northern Ireland
Korsten, Lise	University of Pretoria	South Africa
Martin, Geoff	Dr Mush Advisory	Australia
Martinez-Carrera, Daniel	COLPOS, Puebla	Mexico
McCarthy, Adrian	Australian Growing Solutions	Australia
McCourt, Martin	McDon	Northern Ireland
Meera, CR	Dept. Microbiol. St Mary's College,	India
Moll, Volkert	BVB Substrates	Netherlands
Moyland, Elisabeth	Norwegian Environment Agency	Norway
Mutsy, Arpad	Bio Fungi Ltd	Hungary
Nedels, Hans	BVB Substrates	Netherlands
Oosterkamp, Elsje	Wageningen University	Netherlands
Pardo, Arturo	CIES	Spain
Pawlowski, Piotr	Wokas	Poland
Pecchia, John	Pennsylvania State University	USA
Piecarski, Miroslaw	Wokas	Poland
Polat, Ersin	Akdeniz University	Turkey
Pyck, Nancy	INAGRO	Belgium
Rabiańska, Luiza	Bio-Mycel	Poland
Raz, Dubi	Netafim	Israel

Appendix I (Cont.): List of persons consulted in this review and their affiliations

Consultee	Affiliation	Country
Sargeant, Peter	Gs Fresh	Great Britain
Smith, Christine	Lambert Spawn	USA
Stoknes, Ketil	Lindum	Norway
Szumiga, Joanna	INWARZ	Poland
Thaler, Matthias	Cormo	Switzerland
Theron, Lou	Australian Wood Fibre Ltd	Australia
Trzcińska, Ewa	Wokas	Poland
Van Berckel, Guss	International Peatland Society	Germany
Van der Meer, Arjen	Wageningen University	Netherlands
Van Greuning,	Sylvan Spawn Inc	South Africa
Vermunt, Ronald	Legro	Netherlands
Vernooij, Eric	Champfood	Netherlands
Wilson, Jude	Monaghan Mushrooms	Ireland
Wood, Craig	ISIS Central Sugar Mill Co Ltd	Australia
Wysocki, Karol	Agaris	Poland
Zied, Diego Cunha	Universidade Estadual Paulista	Brazil

Appendix II Template of invitation email to Zoom meetings

From: secretariat@isms.biz <secretariat@isms.biz>

Sent: xxxxxxxx

To: xxxxxxxx

Subject: Invitation to Participate in a Zoom Workshop to discuss the Future of Casing

Hi xxxxxxx,

The International Society for Mushroom Science (ISMS) is seeking your help for a project on the future of casing in agaricus mushroom production.

ISMS is organizing series of workshops on Zoom with researchers and technical experts from institutions and commercial companies in the global mushroom industry during December 2022 and January 2023.

The workshops are designed to capture relevant information on a range of topics related to casing. Participants will be given the opportunity to speak via ppt presentation for 3- 5 minutes if they wish or simply participate in the discussions. Participants are encouraged to present information in areas where they have knowledge/expertise in relation to any of the topics to covered in the Review (see Table of Contents attached).

Following the contributions by workshop participants, the Principal Authors will ask specific questions of the group for discussion. The authors may follow-up with individual participants to get further detail after the workshops are completed.

The project team is inviting you would to participate in a 1-1.5 hour workshop to be held on:

Date: xxxxxxx at Time: xxxxxxx (London time)

Please advise by return email [secretariat@isms.biz] if you are willing to participate at the date and time advised.

ISMS will email a Zoom meeting invitation to participants soon after we receive your confirmation email.

If you are unable to make the meeting, or prefer to respond in writing, we would appreciate if you would email your information to secretariat@isms.biz with "casing information – your name" in the subject box. The objective of the workshop is to hear and discuss what you know about casing.

The following questions and the Table of Contents for the Review (attached) will provide guidance on the type of information the Principal Authors are seeking. It is **not** expected that participants will respond to all issues but anything you can contribute will be appreciated. Questions of interest are:

Peat Availability and Supply

1.What is the annual volume of peat currently extracted for all purposes?
2.Is there any plan and time schedule for the phasing out of peat extraction?
3.Will there be any exemptions for extraction and use of peat for particular horticultural sectors?

Peat in Mushroom Casing
1.What volume of peat is currently used for mushroom casing?
2.From which countries is the casing obtained?
3.Are any other materials used for mushroom casing?
4.What is the typical price of mushroom casing per cubic metre?
5.What are the main problems of using peat alternative casings?
6.Is the mushroom industry in your country under competition from countries which will continue to use peat casing? If so, which countries?

Examples of on-farm trials/ techniques that have been tried in the past for reducing or eliminating peat from casing soils. What problems were encountered?

Research and Commercial Development
1.Have you or are you conducting any research and development projects on peat alternative casings?
2.Are you aware of any published reports or articles on casing research (not published in peer reviewed Journal)? Where can they be sourced
3.Are you able to provide any information on new developments?
4.If not, when do you expect this information to be made available?
5.What do think are the main requirements for future research and development of casing materials?

The information collected during the meetings and via email will support the writing of a comprehensive Review Paper of the future of casing. The final paper will be made freely available to the international mushroom industry via the ISMS website in May 2023. All Zoom workshop participants will be acknowledged as contributors in the Review Paper.

The Principal Authors of the Review Paper are Dr Helen Grogan and Dr Ralph Noble. The paper is part of a project being funded by the Hort Innovation Mushroom Fund and the Australian Mushroom Growers Association. The workshops are being facilitated by ISMS.

Yours Sincerely,
Greg Seymour
President, ISMS
on behalf of the ‘Future of Casing’ project team.