EXCLUSION IS A VITAL COMPONENT OF A MUSHROOM FARM'S IPDM PROGRAM

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INTRODUCTION

When we think of exclusion principles on a mushroom farm, we immediately think of grow room doors and seals (Figure 1). And for good reason, as grow room doors and seals are the major physical barrier used to keep flies and dust away from the mushroom crops. But doors and seals are not the only exclusion principles that are applied on mushroom farms. In this article we will look at further methods of exclusion appropriate for mushroom farms, how to apply them and why they are applied.

Pest and disease management on a mushroom farm is achieved by an integrated pest and disease management (IPDM) program, a system of complimentary and coordinated activities, which, when performed correctly, suppress pest and pathogen populations in a cost-effective and environmentally sound manner. An effective mushroom farm IPDM program (Figure 2) embraces a range of control and good agricultural practice options including:

- practising stringent general farm hygiene
- providing a highly selective compost for the mushroom mycelium
- applying appropriate grow room environmental management
- encouraging biocontrol agents
- using appropriate pesticides as required.

In addition to controlling pest and disease outbreaks, an effective mushroom farm IPDM program – sometimes referred to as whole farm hygiene or holistic farm hygiene – has the additional benefits of reducing reliance on expensive pesticides, which in turn lowers the health risk to farm staff, reducing the threat to the environment, and eliminating the risk of resistance developing in mushroom pests and pathogens.

Figure 1. Damaged door frames give poor physical exclusion. Image: J Allan

WHAT DO WE MEAN BY 'EXCLUSION'?

The term 'exclusion' implies an external source of infection. Although an external source is possible for the initial introduction of pests and pathogens onto the farm, the enclosed and tightly controlled environment of modern mushroom farms means the source of infection is often from within the farm. However, external sources cannot be ignored, particularly considering the increasing practice of preparing compost in bulk at one location and transporting it to use in another. It has been widely demonstrated internationally that the trend to bulk compost handling has been implicated in the development and expression of both *Trichoderma aggressivum* (compost green mould) and Mushroom Virus X (MVX) Syndrome. Effective exclusion must therefore minimise the risk of introducing infection from outside the farm as well as reducing the chances of infection from within the farm.

One of the most efficient and cost-effective infection control measures in a mushroom farm IPDM program is to physically exclude pests and pathogens from the mushroom grow room. After all, in the absence of a pest or pathogen, there is no disease. Physical exclusion is achieved by:

- establishing physical barriers where they do not yet exist
- ensuring physical barriers are appropriate to exclude the target pest / pathogen and its vectors
- maintaining the integrity of existing physical barriers

In addition to physical exclusion strategies, there are also many farm practices, such as traffic management, farm gate inspections, and cleaning which do not present a physical barrier to pests and pathogens but still result in their exclusion from the crop.

MUSHROOM FARM IPDM

GENERAL FARM HYGIENE

1. Grow room hygiene
- cookout
- removal of organic material
- soap and water wash
- sanitise / disinfect

2. Foot dips

3. Monitoring
- sticky fly traps
- counts of diseased mushrooms
- signage

4. Sanitation of tools

5. Sanitation of machinery
- filling line
- casing line

6. Sanitation of facilities
- including floors
- may include fogging

7. Sanitation of contact surfaces

8. Process scheduling
- emptying and filling done at different times

9. Strict glove policy enforced

10. Clean clothing daily

EXCLUSION/CONTAINMENT

1. Vector control
- door seals
- fly mesh
- sticky fly traps
- foot dips
- signage
- 'traffic control'

2. Dust control
- door seals
- air filtration

3. Spot treatment

4. Disease monitoring & recording

5. Pest monitoring & recording

6. Harvester training
- keep beds clean
- recognise symptoms
- indicate / isolate
- report

7. Strict glove policy enforced

8. Signage

ELIMINATION

1. Highly selective compost

2. Cultural practices

3. Spot treatment

4. Fly control
- electronic fly 'zappers'
- sticky yellow fly traps

5. Pesticide application
- insecticides
- flies
- mites
- nematodes
- fungicides
- dry bubble
- cobweb
- green mould
- adoption of biorayionals

6. Efficient waste disposal protocol

Figure 2. Components of a mushroom farm IPDM program

WHAT ARE WE TRYING TO EXCLUDE?

The most common fungal pathogens of commercial mushroom cultivation in Australia, *Lecanicillium fungicola* (dry bubble), *Cladobotryum mycophilum* (cobweb), *Mycogone perniciosa* (wet bubble) and *Trichoderma* spp. (casing green mould), can all start new infections from spores and individual hyphal cells. But as fungi have no means of mobility, spores and hyphal cells must be carried from the site of infection, often an older crop, to a clean site in a new room. Similarly, the virus particles causing Mushroom Virus X Syndrome (MVX) and La France disease in Australia are not mobile. They must also be carried to sites of new infection as the particles cannot survive outside host *Agaricus* hyphal cells and spores (**Allan 2020a** and **Gill 2020a**). The most common carriers, or vectors, of these pathogens are farm dust (see box below), people, and most significantly, sciarid and phorid flies.

While nematodes and mites are both capable of movement, their range is restricted by their size. In addition to being a common component of farm dust and attaching to people, both pests characteristically form a phoretic association with flies, allowing them to relocate to new rooms and establish new infections (**Gill 2020b** and **Allan 2020b**).

Flies are small and highly mobile; they are attracted to the smell of actively growing mycelium in the mushroom compost over large distances and can quickly establish large populations on-farm if left unchecked. While they can impact mushroom crops in their own right, the greatest impact of flies on mushroom quality and yield is their ability to vector pests and pathogens from older to newer crops. This ability is particularly important in the spread of pathogens with sticky spores such as *Trichoderma* and *Lecanicillium,* which are carried on the legs of flies (Figure 3). Consequently, exclusion plays a significant role in managing fly populations (**Allan 2017**) and is crucial for both crop health and farm profitability.

Effective exclusion is not just targeted at specific pests and pathogens. The vectors and carriers of the pests and pathogens must also be excluded from areas where they will carry infection to the crop.

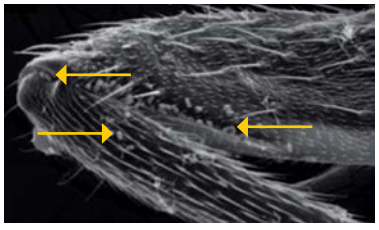

Figure 3. Sticky *Lecanicillium* (dry bubble) spores (examples arrowed) trapped in the knee joint and adhering to the leg and leg hair of a sciarid fly.
Image: Courtesy A Shamshad

WHAT IS 'DUST'?

Dust occurring on-farm is mainly composed of soil from roadways, bare ground, and surrounding fields. But significantly for disease management, farm dust also contains organic material originating from mushroom cultivation.

Sources of on-farm dust include compost and casing dropped onto the ground during filling operations and compost, casing and mushroom debris dropped onto the floor during harvest, and spot treatment, or spread to the floor by watersplash during irrigation (below). This organic matter accumulates under trays and shelves and collects in cracks and joins in the floor. When it dries out, the organic matter becomes airborne through foot traffic, sweeping and air movement.

Grow room organic matter may include:

- spores and mycelium of fungal pathogens and *Agaricus*
- casing and compost, which may or not be contaminated with pathogens and/or colonised by *Agaricus*
- mushroom debris, which may or may not be contaminated with pathogens
- dead flies and the mites, pathogens and *Agaricus* spores and cells they may carry
- mites and the pathogens and *Agaricus* spores and cells they may carry
- dried resistant nematode larvae

In the 'Grogan Experiment', Helen Grogan demonstrated that grow room dust was able to cause dry bubble at the same rate as a low concentration of pure Lecanicillium spores (**Gill 2021**).

GROW ROOM DOORS

The most effective physical barrier to dust and flies is a well-sealed, closed, grow room door. Fortunately, integrity of the door and seals is relatively easy to test – see the box below. Depending on the building design, some door seals may be difficult to access. It is particularly important that these seals are inspected regularly as it is less likely that damaged, difficult-to-access seals will be detected during the everyday work routine.

The most effective door is a closed door. Even a perfectly fitting door with new seals cannot exclude dust and flies if it is constantly open. Do not leave doors open unless necessary and use smaller personnel doors instead of the main door whenever possible. Ensure the doors on newly filled rooms are closed when dirty operations such as room emptying or harvesting in an old room are being performed elsewhere on the farm.

Figure 4. Damaged door seals prevent effective exclusion. Image: J Allan

Shelf farms are at a disadvantage when it comes to filling as the entire back wall is removed during the process and the aroma of actively growing *Agaricus* mycelium in the spawn-run compost are very attractive to flies. With the filling machinery in place, it may not be possible to shut the door even when the production crew takes a break. For these farms, dust must be managed (**Gill 2021**) before and during the process while adult flies will need to be treated once the room is filled and the door closed to prevent them laying eggs in the beds.

On tray and block farms, the grow room door is usually left open to allow spawn-run compost to be loaded into the grow room from the set back or spawn run room. For farms filling from an internal corridor, fly pressure will come primarily from older crops while dust is less of an issue. For tray farms that fill from an external door, dust will need to be managed before and during filling and flies can be treated once the room is filled and the door closed.

HOW TO TEST THE INTEGRITY OF GROW ROOM DOORS AND SEALS

Enter the grow room, shut the door, and turn off the room lights.

Look around the entire outer edge of the door and check there are no patches of light showing through.

If you do see light, examine the pattern of the light. If the light is in unusual shapes and in definite but separate areas, it is most likely that the seals are damaged (Figure 4).

The light entering the room may be caused by an ill-fitting door. If the light patch more or less evenly increases or decreases in size as you look up and down the sides, or along the top and bottom, then the door may not be hanging correctly and the mounting gear will need adjustment.

An ill-fitting door may result in unusual wear in the door seals and these will need to be re-inspected once the door has been adjusted.

Examine the door frame and make sure the edge of the frame is true. Contact with machinery such as forklifts and pallet trucks as they pass in and out of the grow room can damage the frame and prevent a tight seal forming (Figure 1).

Look for other signs of seal and joint failure around the room. For example, wherever external water can enter a room, unfiltered air will also be able to enter (below).

FILTRATION

Irrespective of the air handling system on the farm, filtration of incoming air to the grow rooms is crucial to exclude infective dust, flies, and other pests from the crops. Filtration requirements are unique to each site and are determined by variables such as cultivation process, building configuration, air speed and load. We will confine our comments in this article to ways of attaining effective filtration against mushroom pests and pathogens.

Filters intended for removing bacteria are too fine and too expensive for use in a growing room and are more likely to be used in compost tunnels and Phase II cool down. Because of the very small pore size, bacterial filters clog up very quickly with dust and spores, increasing resistance. This results in increased running costs and will alter the airflow within the grow room to the detriment of the crop.

Because air travels along the path of least resistance, it is important that the main filter sits snugly against the mounting gasket within the filter box to create an airtight seal, forcing all contaminated air through the filter and preventing flies from bypassing it. Because main filters are expensive to replace, their lifespan can be extended by using a coarse pre-filter to capture large dust particles, pests, and other insects before they reach the main filter and clog the fine pores. Coarse filters not only entrap particles in their fibres, but they also retain particles by electrostatic attraction.

The ducting of incoming air systems must be regularly inspected for leakages. Regularly check:

- for holes in the ductwork
- that nuts and bolts are secure and are tight against the steel
- to ensure bolt heads fit snugly in the hole drilled for them and that there is no gap around the bolt head
- that there are no stresses, such as vibration, on the ductwork that would cause a bolt hole to 'stretch'
- that the gaskets (if fitted) in the flexible joints are in good condition and have not perished
- on external fan units that the pipework hasn't degraded or perished

FLY MESH

Many washable filters are quite porous to flies, particularly phorids, and although they are not able to fly against overpressure to enter rooms, they can walk through the filter (Figure 5), and once out of the main airstream, fly as usual. Flies can be prevented from entering grow rooms through vents and other wall penetrations by fitting a quarantine mesh (maximum aperture size of 0.3mm) over the hole. When installing quarantine mesh, be aware that the fly mesh:

- must fit tightly over the opening being screened as flies are strongly attracted to the smell of fresh compost and they will find any small gaps (Figure 6)

Figure 5. Flies can penetrate some washable fibrous pre-filter material. Image: J Allan

Figure 6. Badly fitted fly mesh does not protect the crop. Note the fly mesh pulling away from the frame (arrow). Image: W Gill

- may make it harder for air to exhaust so the exhaust may need to be increased to ensure that the air circulation in the rooms is not compromised

Consider placing fly mesh over the drains, particularly if drains are shared between rooms. While preventing flies from entering a room, this will also prevent the flies escaping to other rooms when steam is introduced at cookout.

FLY TRAPS

The most commonly available fly traps are electronic 'zappers' with an attractant UV light (Figure 7a) and yellow sticky traps (**Gill 2020c**) which can be purchased as either a long and wide strip (Figure 7b) or small individual squares (Figure 7c). As monitoring tools, these traps are extremely useful provided they are inspected at regular time intervals and fly numbers are noted, so that the number of flies in a specific location can be recorded over time. An increase in flies recorded in the traps is advanced warning of disease incidence inevitably increasing.

When fly populations are low, fly traps can be useful in vulnerable areas of the farm to keep the population down to controllable levels. But when the fly population escalates in summer, fly traps are not very effective as a method of exclusion. Unlike other agricultural industries which use similar traps to control flies, mushroom farms hold hundreds of tonnes of compost in a warm and moist environment – ideal conditions for breeding flies. The number of flies caught in these traps will have little impact on the rate of reproduction or the population at its peak. When fly populations flourish, growers will need to an apply alternative IPDM tool – hit the population hard with appropriate biological or chemical insecticides to reduce fly numbers to a level that can be maintained by fly traps.

FOOT DIPS

Standard cultivation practices such as harvesting and watering spread pests and pathogens from infected beds onto the floor in dropped casing, in mushroom debris, and by watersplash. Consequently, the grow room floor is a significant reservoir of disease which can easily be transferred onto the beds and spread around the farm on footwear (Figure 8, p34). Well-maintained and suitable foot dips (**Gill 2019**) are therefore an important component of an effective farm exclusion strategy. There are many proprietary foot dip designs available but not all are appropriate for use on mushrooms farms; furthermore, one design may not be suitable for all on-farm situations.

Some considerations for effective foot dips are:

1. Safety
    - foot dip has a reservoir with a non-slip base and low sides
    - use a non-slip disinfectant if possible when the foot dip is on a painted concrete floor
2. Cleanliness
    - wash out the foot dip and totally replace the disinfectant at least daily in high traffic volumes

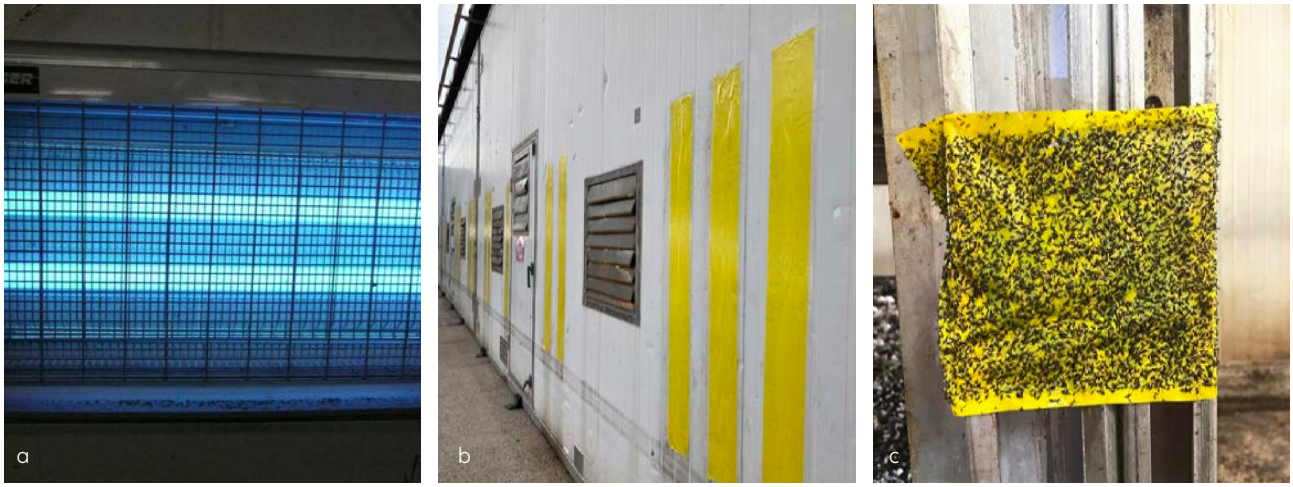

Figure 7. Examples of fly exclusion methods a) electronic fly 'zapper' b) long lengths of wide yellow sticky paper positioned around known fly entry points c) individual fly traps require frequent replacement especially when fly populations are high. Images: J Allan

- do not 'top up' the reservoir – this dilutes and diminishes efficacy of the disinfectant
- dispose of the dirty disinfectant in compliance with local environmental guidelines

3. Suitability – the foot dip is appropriate for the situation
    - while perhaps suitable for a smaller farm, a moulded foot bath (Figure 9a) is not appropriate for a larger farm. In areas of high traffic volume, the organic content builds up quickly and activity of the disinfectant is very reduced
    - use a large mat-type foot dip (Figure 9b) or disinfectant mat (see next section) in grow room doorways
    - the foot dip reservoir must be deep enough to cover the soles of footwear

In addition to being an effective exclusion tool, foot dips are also a constant reminder to staff that they are working in a vulnerable area and that they need to be mindful of hygiene at all times. Once a foot dip is no longer in use, it must be cleaned and put away out of sight and not left dirty and abandoned in plain view (Figure 9c).

To be an effective exclusion tool, it is critical that foot dips are closely monitored and maintained particularly on high traffic days. Organic matter severely reduces the killing power of disinfectants and published studies have demonstrated that in environments with a high organic load, footwear can actually become contaminated from the foot dips if they are not cleaned and the disinfectant replaced routinely. Given the potential for floor-borne pathogens to infect mushroom crops, the resources required for foot dip maintenance is a good investment. Clean and well-maintained foot dips ought to be located at every grow room door irrespective of the cropping cycle and at the entrance to the facility so visitors and tradespeople do not track infection in from outside.

DISINFECTANT MATS

Disinfectant mats are particularly useful for excluding pests and pathogens on tray farms, where forklifts travel in and out of new rooms. Disinfectant mats can be carpet offcuts or lengths of artificial turf which are impregnated with a disinfectant and laid across the entire grow room doorway (Figure 10). The offcut must be long enough to span the whole doorway and it must be wide enough to allow the largest vehicle wheel a full rotation in contact with the mat to ensure disinfection. The formula to calculate how wide the mat must be for your vehicles has been published previously (**Gill and Allan 2015**).

There are a number of benefits in using disinfectant mats instead of foot dips:

- they do not have side walls as foot dip reservoirs do (trip hazard), so they are much safer for staff
- they are stable and do not move on the floor even if laid over painted concrete

Figure 8. Examples of transmission routes of pathogens from grow room floor to mushroom bed a) shelves are sometimes used to climb on during crop inspections b) mushrooms along the outer edges of trays are sometimes knocked by harvesters' feet overhanging picking trolleys. Images: J Allan a); W Gill b)

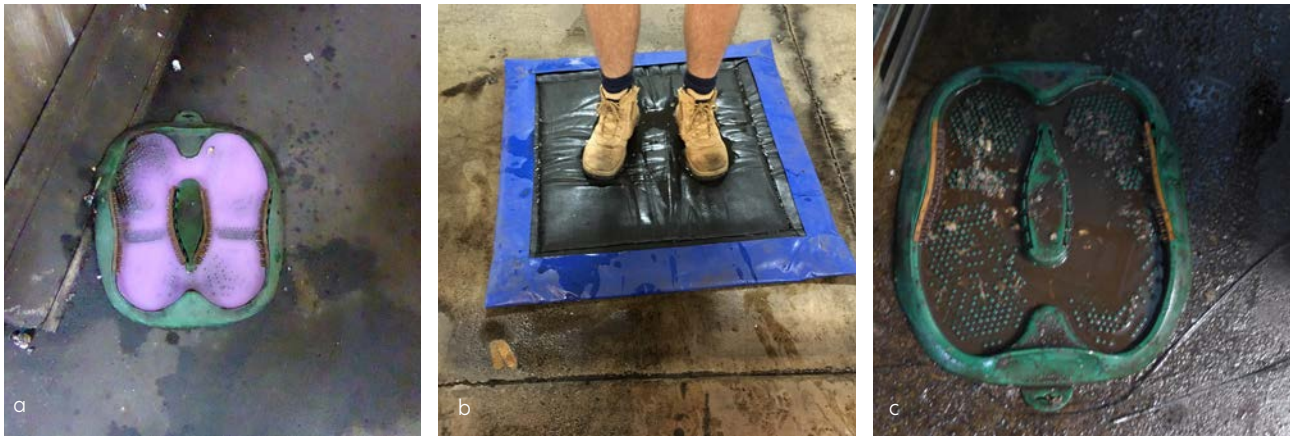

Figure 9. Foot dip qualities a) moulded foot dips are not suitable for high traffic areas such as rooms being harvested b) a low-sided mat-type foot dip is safe and better suited to wheeled equipment c) make sure unused foot dips are cleaned and stored out of sight when not in use. Images: J Allan

- laden forklifts can drive directly onto a mat and make a turn without disturbing it
- all wheeled vehicles and equipment used in a grow room get their wheels disinfected every time they pass over the mat
- small, wheeled equipment such as box trolleys and pallet jacks can be pushed over the mat very easily
- harvesters cannot avoid disinfectant mats as they can foot dips

Figure 10. A disinfectant mat in front of a grow room doorway to disinfect staff footwear and the wheels of vehicles, trolleys , and other wheeled equipment. Image: W Gill

'TRAFFIC' MANAGEMENT

Traffic management cannot be strictly considered physical exclusion as it is not a tangible object that prevents pests and pathogens from entering mushroom crops. But good traffic management plays an important role by excluding the potential infections carried by staff and their equipment from older crops.

Harvesters are the most significant vectors of mushroom pests and disease, second only to flies. Consequently, staff rosters and cropping cycles must be coordinated to prevent harvesters from picking an older room – which will naturally have a greater probability of higher pest and pathogen populations – then moving to pick a younger room. Harvesters must wear freshly laundered clothes daily as the first pick must be from the newest crop. This is to prevent the pests and pathogens encountered in the older rooms at the end of the previous day's shift from being carried on the previous day's clothing to the new crop.

Staff working in clean areas such as filling and casing must also begin their shift in freshly laundered clothes as the crop at this stage is highly vulnerable to contamination. Because of some of the biological properties of mushroom pests and pathogens, clean area staff must not share facilities with harvest staff for the well-founded fear of transferring pathogens, particularly *Lecanicillium* and *Trichoderma*, to the casing and fill line.

There are a number of other practices that harvesters are trained to follow to ensure pests and pathogens are excluded from mushroom crops. Some examples of these practices are:

- understand and follow the farm's glove policy
- ensure knives and buckets are thoroughly cleaned and disinfected at the end of each shift
- ensure picking equipment is thoroughly cleaned and disinfected at the end of shift
- recognise disease symptomology and report it correctly so that the affected mushrooms can be marked and other harvesters avoid touching them

AT THE FARM GATE

All goods and services which pass through the farm gate must at least be visually inspected as a minimum before they are delivered to sensitive areas on the farm. Off-site personnel such as tradespeople and company reps must be signed in to comply with current on-site WHS policy upon arrival. This is a good opportunity to determine if previous jobs involved agricultural properties or other mushroom growing sites. Deliveries should be inspected at the office for contaminants and organic material before being sent onto the farm. Incoming trucks need to be inspected, particularly those coming directly from other mushroom farms or agricultural sites, and cleaned, if necessary, before entering the farm. To prevent potential sources of infection from entering the farm (Figure 11) and affecting the crop, check that:

- spawn and casing materials are examined carefully on arrival and immediately before use. Even commercial spawn makers get infections (Figure 12)
- re-usable crates and boxes are clean and free of biofilm, insect larvae, and mouldy mushroom material
- re-usable crates are disinfected before they are introduced into cropping rooms
- pallets used to transport inward goods are free of organic material
- cardboard boxes from inward goods have not become wet and mouldy
- signage to direct tradespeople, company reps and casual visitors to the office before entering vulnerable areas is clearly visible
- tradespeople account for their previous service visit when signing in at the office e.g., nursery? Farm?
- clean foot dips or disinfectant mats are located at the entrance to vulnerable areas of the farm
- incoming delivery and waste removal vehicles are assessed, particularly if they are servicing multiple farms.
    - do they need to be cleaned before entering the property?
    - can they be restricted to a specific area of the farm away from growing rooms and vulnerable procedures?

Figure 12. A *Penicillium* infection (green growth) beneath a filter patch in a bag of commercial *Agaricus* spawn. Image: W Gill

Figure 11. Sources of potential infection carried across the farm gate a) spent compost in the back of a delivery truck which had arrived from another mushroom farm b) compost packed into the wooden pallets following a peat delivery from another mushroom farm c) mouldy cardboard box used to deliver mushroom farm supplies. This box originated from overseas. Images: W Gill

A NOTE ABOUT CONTAINMENT

When a disease outbreak occurs on-farm, we respond by **containing** the pathogen or pest to the affected grow room. It is no coincidence that many of these containment measures, such as air filtration, foot dips, secure doors and seals are the same as our exclusion measures. This is because the enclosed nature of mushroom growing facilities means that the restriction of pests and pathogens in one direction (exclusion) is equivalent to the restriction of pests and pathogens in the other direction (containment). This overlap is acknowledged and reflected in the mushroom farm IPDM system diagram (Figure 2).

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