Final Report

Mushroom supply chain best practice management

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Public summary

The Australian mushroom industry has a strategy to improve the presentation, storage, and shelf life of mushrooms through R&D initiatives, in collaboration with retail and supply chain partners. As a result, this project was developed to review postharvest factors affecting mushroom quality, better understand the issues occurring in Australian mushroom supply chains and share best practice information with supply chain stakeholders.

A global literature review was conducted to provide recent information on how mushrooms should be handled to maximise postharvest quality. The review identified several research gaps for future work, and key findings were used to develop the best practice guide.

Supply chain monitoring was undertaken with three suppliers and the three major retailers, tracking batches of mushrooms using real-time temperature and location tracking loggers. Temperature and quality were monitored from the packhouse to nine retail distribution centres (DCs), and then out to 26 retail stores in Australian cities and regional towns.

The majority of supply chains monitored had average pulp and air temperatures below 5°C. However, some supply chains were higher than this target, and in many supply chains there were periods where temperatures exceeded 5°C. Temperatures frequently exceeded 5°C at retail stores, and in some cases prior to dispatch from the packhouse.

Differences of up to 2°C were identified within consignments, different positions on a pallet, or location in the truck.

Supply chains varied considerably in length, often a result of time in distribution centres, with some product moving out of the DC within a few hours, while in other cases product remained at the DC for 2 days.

Quality of mushrooms at the best before date was acceptable in 11 out of 14 supply chains assessed. In two cases, significant time at temperatures well above 5°C was the likely cause of the quality decline.

Information gathered from the literature review, industry consultation and supply chain monitoring were used to develop a supply chain best practice guide. The guide presents the procedures to best maintain quality through the mushroom supply chain and printed and electronic copies are available to all Australian mushroom supply chain stakeholders via the *MushroomLink* website.

Supply chain monitoring results and the best practice guide were presented to supply chain stakeholders through online webinars, and meetings with major retailers.

Through the new resources developed, the project has increased supply chain stakeholders' awareness of the procedures required to maintain mushroom quality. Engaging suppliers and retailers in supply chain monitoring activities has contributed to businesses making changes that will improve the presentation, storage, and shelf life of mushrooms. This will ultimately ensure mushrooms more consistently meet consumer expectations, reducing rejections at retail distribution centres and helping to grow the category as a whole.

Keywords

Mushroom; Agaricus bisporus; supply chain management; temperature; quality; postharvest

Introduction

The Australian mushroom industry is facing dual challenges of increasing input costs and low prices. Consumption of mushrooms is stable at 2.78 kg/pp annually, and export of mushrooms is minimal. To improve grower returns, the industry aims to increase consumption to 4 kg (Hort Innovation, 2022).

The industry invests more than $3 million in marketing annually. However, no marketing campaign will be successful if quality is not what the consumer expects. Moreover, consistently presenting high quality, clean and white mushrooms to consumers at retail is a way to increase purchases.

The Mushroom Strategic Investment Plan outlines a strategy to improve the presentation, storage, and shelf life of mushrooms through new, focused R&D initiatives in collaboration with retail and supply chain partners.

What is causing quality issues and rejections by retailers?

Identifying and managing the factors that impact mushroom freshness and colour at retail is clearly critical. Temperature is a key factor. Delivery delays, spatial temperature variability within a truck, and inaccurate measurement by retail QC staff using poorly calibrated probes can result in temperature related rejections at retail DC. There is often little tolerance for consignments arriving at DCs above the recommended temperature. However, it is unclear whether transitory temperature variations significantly impact the quality and safety of whole mushrooms.

Initial quality, freedom from pathogens, rapid cooling after harvest, and packing method are likely to have greater impact on quality than minor temperature increases just before delivery. It is also likely that the conditions under which mushrooms are held after they arrive at the DC – i.e. transport to stores, back of store handling and retail display are having a significant impact on the consumer experience. There is a need to better understand what happens after mushrooms arrive at the DC and the potential impacts on quality.

What is needed to improve quality at retail and reduce rejections?

This project has addressed two key gaps to help the industry deliver good quality mushrooms to the consumer and at the same time reduce rejections.

- **Supply chain monitoring** to clearly understand where the issues are occurring in the commercial supply chains.
- **Availability of best practice information** to inform supply chain participants on best practice for each part of the chain. There also needs to be an extension effort to inform everyone handling mushrooms, including the retailers, about what they should be doing to present high quality mushrooms to consumers. This will maximise retail sales and prices.

The project aimed to help industry improve the handling and storage of mushrooms within the value chain, from farm gate and transportation to retail. This will reduce rejections at distribution centres, improve retail quality, minimize waste and ensure food safety. The project collated information on existing best practice management in handling and storage of mushrooms, informed by a global literature search. This information was used to develop a Best Practice Guide for growers, transporters and retailers of mushrooms.

Methodology

Review of global literature related to handling and storage of mushrooms

A literature review was carried out to collate the most up to date information about how mushrooms should be handled to maximise quality and minimise any food safety risks. The review included scientific, peer-reviewed literature, Hort Innovation reports, State Government reports and fact sheets, books and conference proceedings. The AMGA member's area, which includes newly digitised material and other "grey literature" was also accessed for material not included in refereed scientific journals, conference papers and commercial literature.

The review included all available Australian and international information on factors relating to mushroom handling and storage, encompassing as wide a range of information as possible. There was a strong emphasis on highlighting new information (i.e. 2017-current) and current/recently completed trials, which industry members are unlikely to have previously encountered. AHR used international abstracting services including Commonwealth Agricultural Bureau (CAB) abstracts, Web of Science Core Collections and Google Scholar searches. The review team also contacted international mushroom researchers and experts working around the world directly to make sure unpublished and 'grey literature' was included in the review.

Industry consultation and supply chain monitoring

The project team engaged with three major mushroom suppliers in different states to track sliced and whole mushroom temperature and quality throughout the supply chain from supplier to retail store. Project team members directly engaged with staff at each supplier to thoroughly understand on-farm practices, current issues being faced in the supply chain as well as barriers to the adoption of best practice. A small comparison of each supplier's vacuum cooler efficiency was also carried out. The tracking of mushroom loads from supplier to retail store was coordinated with the three major retailers, as well as tracing loads going to an independent retailer's DC and a wholesaler's warehouse.

Pulp and air temperature dataloggers, Frigga model M1E and V5C respectively, with GPS tracking were added to at least three loads from each supplier. The dataloggers were dispersed throughout different pallets and locations within each pallet. A sample of mushrooms from the same batch was taken and stored in a refrigerator at the project team's facility under optimal conditions until the best before date. The pulp temperature dataloggers were retrieved from each retailer's DC by a project team member. While at the DC, the project team member observed QC receival procedures and storage conditions in the DC.

The air temperature dataloggers were allowed to continue through to retail stores, while being traced via GPS. Once a datalogger reached a retail store, whenever possible a project team member retrieved it from the store, as well as purchasing 3 punnets of the mushrooms from the load. Pulp and air temperatures were measured on the retail display. The mushrooms were transported back to the project team's facility in an insulated container, followed by storage at optimal conditions until their best before date (Figure 1).

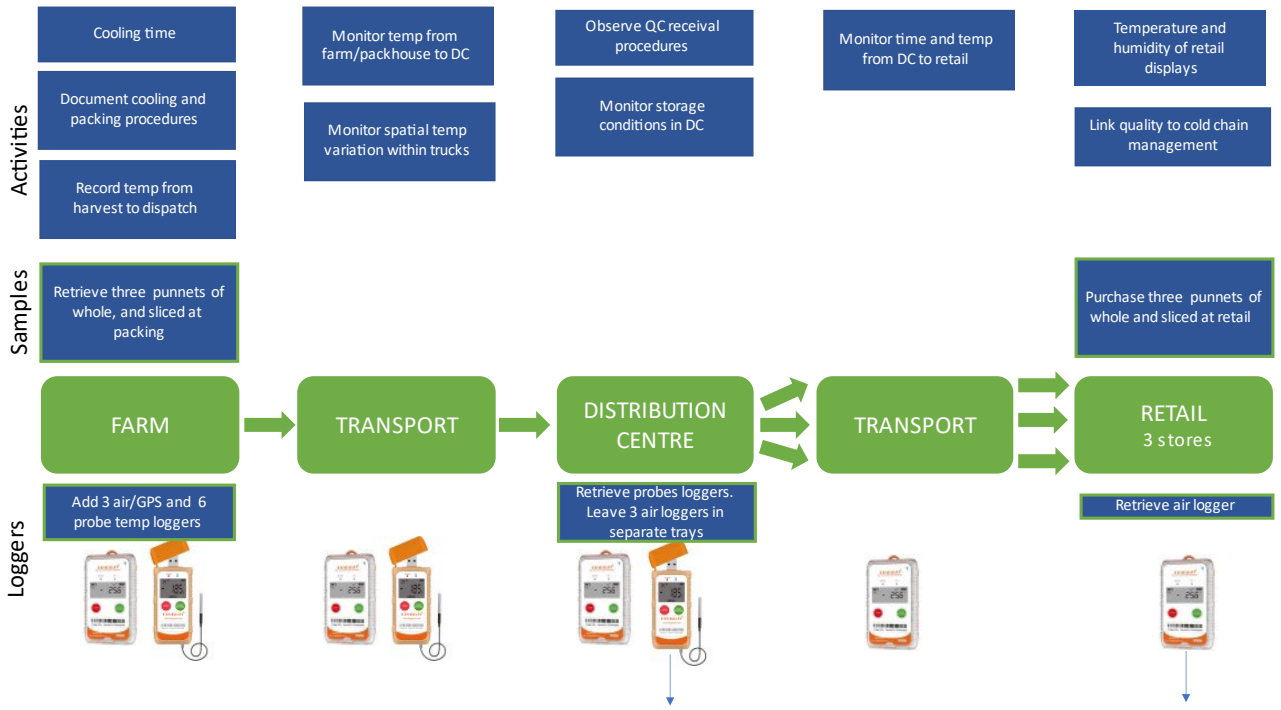

Figure 1. Supply chain monitoring activities conducted. Each batch was monitored from the farm through to the retail distribution centre and out to three retail stores.

Upon reaching their best before date, the quality of store purchased mushrooms and retention samples was compared. Whole mushrooms were assessed using a color meter to assess cap colour and a spherical tip durometer to measure cap firmness. Whole mushrooms were deemed unacceptable when the sum of the cap colour's RGB values was below 500 or if cap firmness fell below 29 shore units. Sliced mushrooms were evaluated solely based on flesh colour using a colour meter and were considered unacceptable if the sum RGB was below 500.

A total of 36 individual supply chains were monitored between January 2024 and April 2024 with mushrooms originating from three different states (NSW, VIC and SA). Mushrooms were sourced from a different grower in each state. Monitored mushrooms were sent to three major retailers, one minor retailer and one wholesaler.

The results were confidentially communicated back to the suppliers as well as to the participating retailers.

Best practice guide

Using the information gathered from the literature review, industry consultation and supply chain monitoring, a best practice guide was developed to encompass each stage of the supply chain.

The guide was reviewed by the project reference group prior to publication.

The best practice guide covered the following sections:

- Pre-harvest: growing room environment, irrigation, managing disease
- Harvest and packing: bruising at harvest, trimming, processing, packaging, library trays (reference trays)
- Cooling: room cooling, forced air cooling, vacuum cooling
- Storage: cold room efficiency, storage temperature, managing the store room
- Transport: loading at the farm, temperature management on trucks, monitoring temperature during transport
- Distribution Centre: Measuring temperature, assessing quality, mushroom storage
- Retail: receival and storage, shelf display and handling
- Calibrating probe thermometers

Industry extension

A variety of extension methods were used to share project findings and engage with supply chain stakeholders. These included:

- Retailer engagement meetings with the three major retailers. At these meetings, a presentation was held to discuss the project's activities and how it will benefit them. Key findings from the literature review were presented, and discussions on critical control points in the supply chain, and actions that could be taken to improve supply chain management.
    - Subsequent meetings were held with two of the major retailers (offered to all three) following the completion of the supply chain monitoring to discuss results and present them with the relevant sections of the supply chain best practice guide.
- Face-to-face workshop with staff from a major Australian mushroom producer to communicate on farm best practice ranging from pre-harvest to post-harvest to ensure quality. Workshops have been offered to two other major Australian mushroom producers who participated in the project supply chain monitoring.
- Webinars – presenting sections of the best practice guide for various supply chain stakeholders
- Magazine articles and a factsheet – articles outlining findings throughout the project in the *MushroomLink* magazine
- Best practice guide – distributed to supply chain stakeholders
- Literature review – a review of global research focused on topics which affect post-harvest mushroom quality. An emphasis was placed on contemporary research (post-2017).

Links to the best practice guide, factsheet, literature review, magazine articles and webinar recordings are available in the outputs section of this report.

Results and discussion

Literature review

A literature review of research into post-harvest treatment of mushrooms was compiled, resulting in a 48-page document which cited 151 papers, unpublished articles and industry reports. A focus on contemporary research (post-2017) was applied when conducting the review.

The literature review covered a wide range of topics which affect post-harvest quality, beginning with pre-harvest practices. The pre-harvest factors explored included the growing environment, casing and compost, irrigation, pinning, disease and crop health, nutrition and supplements, as well as the choice of variety and breeding.

The literature review then delved into research concerning harvest timing and method, handling during harvest and packing, followed by cleaning and washing.

Postharvest treatments were then covered, focusing on postharvest dips, edible coatings, fumigation in packaging, ethylene removal and 1-MCP, irradiation and pulsed light, as well as other methods of extending storage life.

Cooling and storage temperature was explored, looking at cooling method and temperature, storage temperature, effect of temperature on respiration rate, effect of temperature on water loss, and monitoring temperature in supply chains.

Finally, packaging and storage atmosphere was investigated with a focus on package design and materials, and modified atmosphere packaging.

The review identified a number of research gaps for the industry to address in the future. These are detailed in the recommendations section of the report.

Supply chain monitoring and industry consultation

Industry consultation with the participating mushroom farms revealed they had been experiencing issues with temperature rejections by the retailers with the frequency of the rejections increasing in the summer. The mushroom suppliers expressed an interest in supply chain monitoring to identify where the cool chain breakdowns were occurring. They also expressed an interest in knowing the conditions mushrooms experience after receival at a retailer DC. Consultation with three retailers revealed that they were also interested in discovering any weak points present in the cool chain, offering their assistance with coordinating DC visits and sample collections from retail stores.

Air temperature was monitored in a total of 36 individual supply chains, while pulp temperature was monitored to the DC in 27 individual supply chains. Several supply chains were not able to be monitored all the way to the retail stores due to the dataloggers being mistakenly removed by distribution centre (DC) staff. Due to the length of some supply chains monitored, the project team were not able to visit every store that received monitored batches of mushrooms. The project team visited 14 out of 26 retail stores that received monitored batches of mushrooms. Display conditions were recorded at the retail stores visited, and samples of mushrooms from the monitored batch were purchased for quality assessment.

Temperatures in supply chains

In 28 out of 36 supply chains the average pulp temperature was maintained within the optimum range of 0-5°C. However, pulp temperatures often fluctuated within a range of more than 3°C (Figure 2). In eight supply chains average pulp temperature exceeded the optimum range, and most of these were in supply chains of two retailers.

Similar to pulp temperature, the average air temperature was maintained well in the majority of supply chains (Figure 3). However, air temperatures fluctuated significantly, and more so than pulp temperature. In one case air temperature went below 0°C, risking the freezing of the product. Moreover, air temperature was not a good predictor of pulp temperature, with cases where pulp was higher than air, and vice versa where air was higher than pulp.

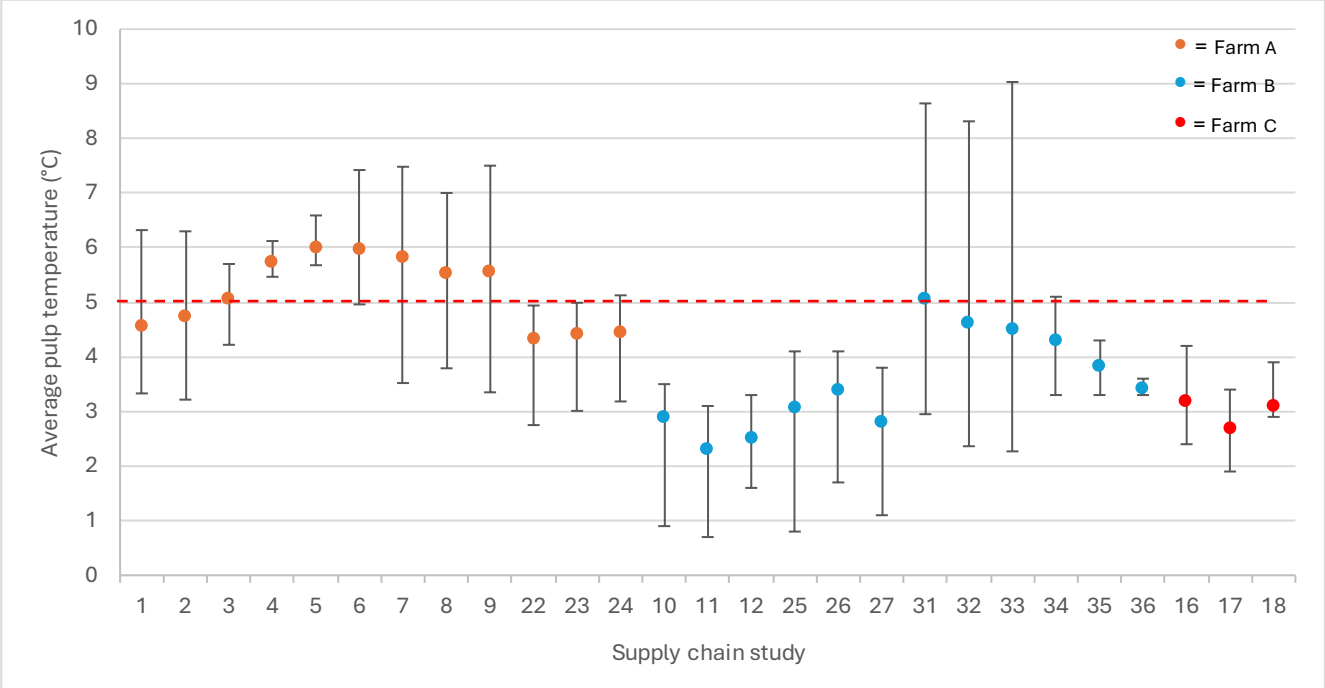

Figure 2. Average pulp temperatures of mushrooms from the packhouse to the retailer DC. Bars represent maximum and minimum temperatures recorded. The red dotted line is the maximum optimal temperature. Supply chain studies are grouped by supplying farm.

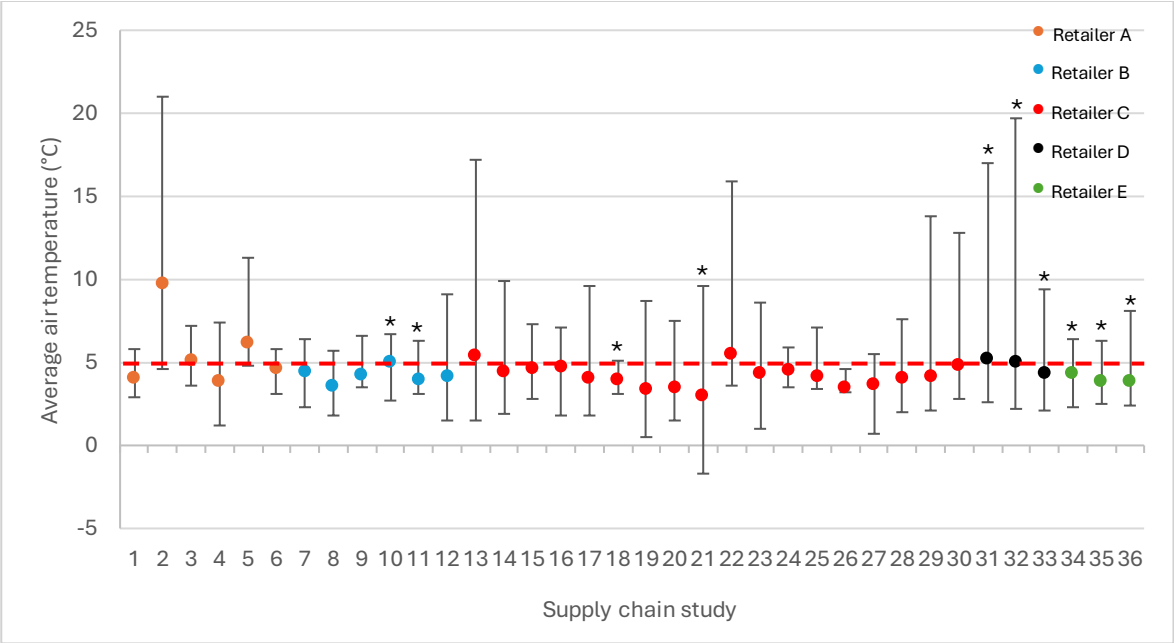

Figure 3. Average air temperatures of mushrooms with measurements starting at the packhouse. Asterisks above data points indicates supply chains in which the dataloggers were removed at the DC. All other supply chains were monitored through to the retail store. Bars represent maximum and minimum temperatures recorded. The red dotted line is the maximum optimal temperature.

Temperatures by stage of supply chain

Issues of high pulp temperatures (>6°C) were identified at the packhouse and at retail stores. Pulp temperatures were maintained reasonably well during transport and in the retail distribution centre (Figure 4), although there is room for improvement with approximately 20% of supply chains operating at an average of 5-6°C. Note that of the samples above 5°C at the farm, 57% remained above 5°C through to the retail DC. This highlights the difficulty of removing heat from mushrooms during transport, and the importance of keeping air temperatures low throughout the supply chain to prevent further warming.

The pulp temperature of mushrooms on display in retail stores is an area for improvement, with 61% of samples tested exceeding 5°C (Figure 4). This highlights inadequacies in storage and display temperatures in retail stores.

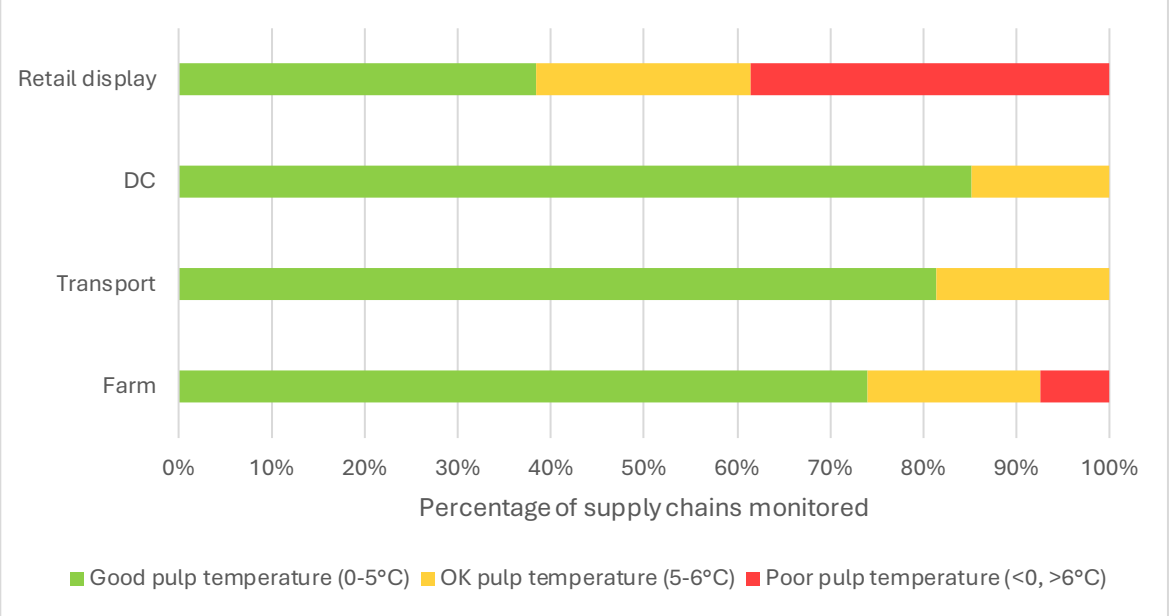

Figure 4. Average pulp temperature of mushrooms at stages in the supply chain (n=27, retail display n=14).

Temperature management was an issue for all three major retailers at some point from the DC to retail store (Figure 5). This may be a result of poor airflow or cooling capacity in coolrooms/trucks, cooling set points intentionally set above optimal to accommodate temperature-sensitive items within a mixed load, overcrowding of the truck/coolroom, or heat emitted by other items in mixed loads. Large fluctuations in temperature were measured during transport and at the retail stores and this is likely to cause condensation on the inside of packaging, reducing mushroom quality.

Temperature management in retail stores was poor for two of the three major retailers. It must also be noted that there were often extended delays at all retailers when the mushrooms were unloaded from the truck and placed in the coolroom. This delay allows the mushrooms to warm rapidly, as well as develop condensation once they are placed in the coolroom.

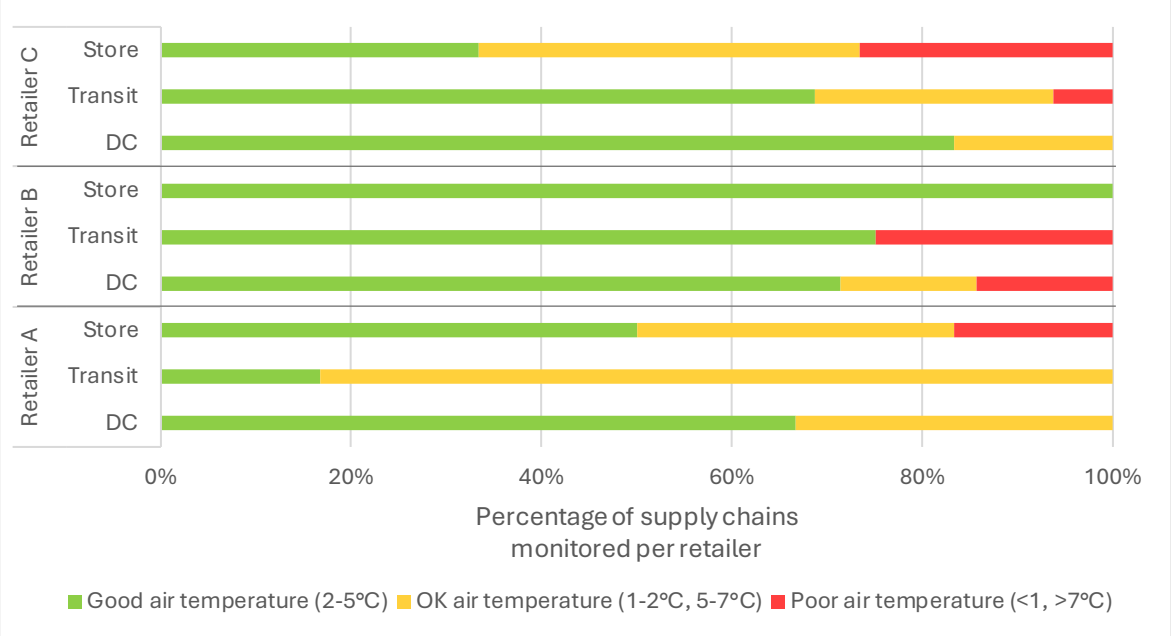

Figure 5. Average air temperature at stages in the mushroom supply chain, broken down by retailer (Retailer A n = 6, 6, 6 (DC, Transit, Store); Retailer B n = 6, 4, 4; Retailer C n = 18, 16, 15).

Temperature by position in trucks/pallets

Differences of up to 2°C were identified in pulp temperatures of mushrooms at different locations within a pallet and between different pallets in the same consignment (Figure 6). Differences were most pronounced during transport and are likely a result of differences in airflow due to positions of the pallets on the truck, and position of the mushrooms on the pallet. Without adequate airflow, respiratory heat may build up within the punnet, carton, or pallet, further increasing respiration in a positive feedback loop.

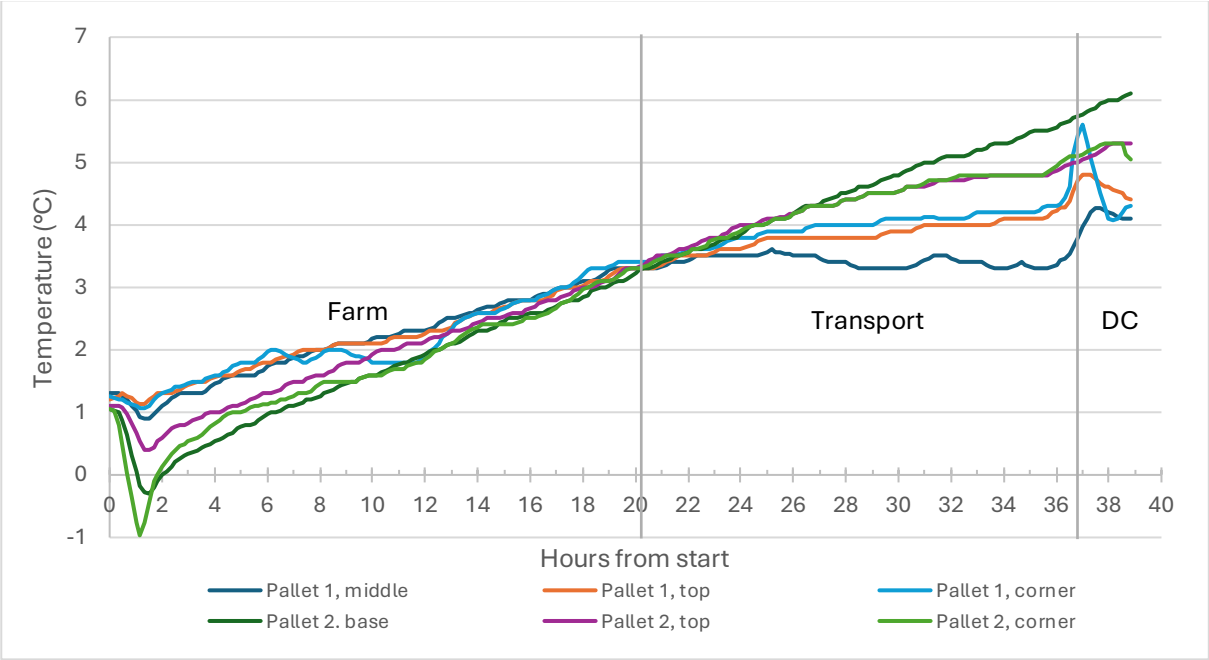

Figure 6. Pulp temperatures measured in the supply chain between a mushroom farm and retail distribution centre (DC).

Time in the supply chain

There was considerable variation in the length of supply chains monitored across each retailer. One major retailer had consistently shorter supply chains than the others (Figure 7). This is due to the very fast turnaround time of the mushrooms at this retailer's DC, spending less than half the time in the DC as the other two retailers (Figure 8). While there was little difference in mushroom quality between the retailers at the best before date, a shorter supply chain is likely to result in longer storage life after purchase.

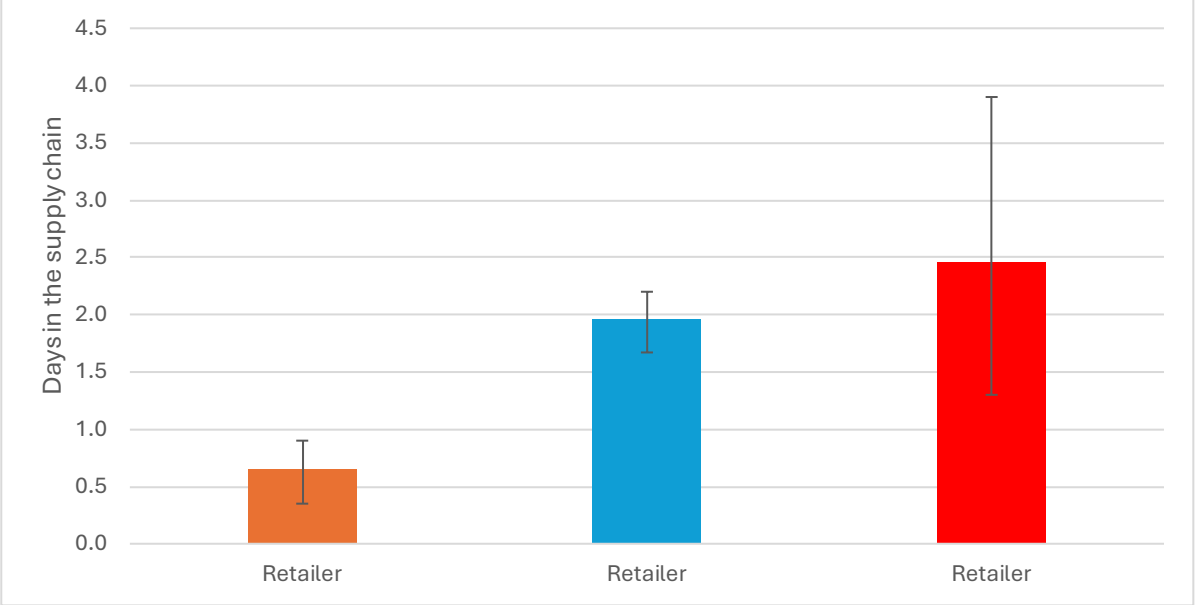

Figure 7. Days from departing the packhouse to arrival at the retail store. Bars represent the maximum and minimum from supply chains monitored for each retailer.

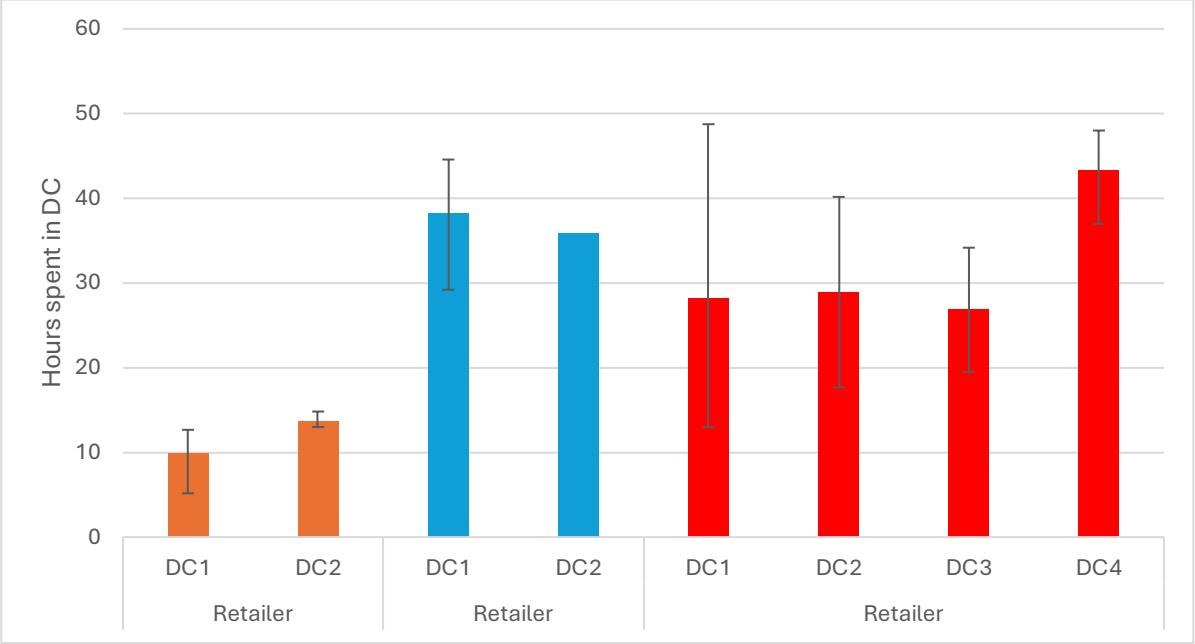

Figure 8. Time mushrooms remained in the retail distribution centre (DC) before dispatch. Bars represent the maximum and minimum of three different cartons.

Quality

Of the 14 mushroom samples that were purchased from retail stores, all but 3 of them were of acceptable quality when assessed on their best before date (Figure 9). Acceptability was defined as having a colour with total sum RGB greater than 500 as well as having a cap firmness of over 29 shore units. All three of the unacceptable samples were sliced mushrooms and failed in respect to browning rather than firmness. Of the samples that were of unacceptable quality, one was displayed at retail at room temperature, one was subjected to a multi-hour blackout in store, while the other did not

appear to have been subjected to any temperature abuse based on datalogger recordings. The cause of the third sample's poor quality is unclear, it is speculated that it was removed from the vicinity of the datalogger and kept at room temperature for an extended period prior to being returned to cool storage. Of the unacceptable samples, all were sold in the same city, two were from the same supplier and sold through the same retailer, through a short supply chain. The third sample was subjected to interstate transport and sold through a different retailer, in a medium length supply chain.

Figure 9. Examples of mushroom quality at best before date. (a) Mushrooms of acceptable quality. (b) Mushrooms at the limit of acceptability. (c) Mushrooms of unacceptable quality.

Output

Table 1. Output summary

Output	Description	Detail
PRG meeting minutes	Three sets of meeting minutes were written following PRG meetings.	The PRG minutes for the PRG meetings held on 3 August 2023, 3 November 2023, and 6 December 2023 were provided to the PRG by the project team.
Literature review	A 48-page literature review covering 151 pieces of literature concerning the postharvest management of mushrooms.	The literature review is available on the MushroomLink website here.
Best practice guide	A 35-page Australian supply chain best practice guide.	The best practice guide is being printed at the time of writing and posted to a distribution list of 130 stakeholders including all Agaricus growers, mushroom packer and wholesale operators, input suppliers, AMGA and the three major retailers. An additional 70 copies will be held for future distribution to Australian mushroom industry stakeholders, such as at the October 2024 Mushroom Conference to be held in NZ. The guide is also available on the *MushroomLink* website here. The guide will also be available in the AMGA

		Document library.
MushroomLink articles	Three magazine articles providing high level and easily accessible coverage of key project work.	The MushroomLink article 'Best Practice for the Mushroom Supply Chain' was provided as an introduction to the project in the Autumn 2023 issue here. The MushroomLink article 'Best Practice in Mushroom Supply Chains' is available in the Summer 2023 issue here. The MushroomLink article 'Cold Mushrooms are Quality Mushrooms' is available in the Autumn 2024 here. All articles were distributed physically to all *MushroomLink* mailing list recipients, and are available on the *MushroomLink* website.
Factsheet	Factsheet detailing how to accurately measure temperature of mushrooms.	The 'Measuring temperature' factsheet was made available online on the *MushroomLink* website here.
Workshops and webinars	In person workshop and online webinars	29 January 2024 – In person workshop with mushroom farm on postharvest management of mushrooms. Two further workshops have been offered to other mushroom farms who assisted with this project. 19 June 2024 – Industry webinar – presenting key findings from supply chain studies. Webinar was recorded and is available here. 3 July 2024 – Industry webinar – presenting the new mushroom supply chain best practice guide. Webinar was recorded and is available here. . 19 June 2024 – Online meeting with a major retailer to review results from the supply chain studies and present the retail sections of the supply chain best practice guide. 24 June 2024 - Online meeting with a major retailer to review results from the supply chain studies and present the retail sections of the supply chain best practice guide.
Supply chain monitoring reports to suppliers	Reports with detailed results on the supply chain monitoring conducted. The reports identified opportunities to improve supply chain management.	Supply chain monitoring reports were sent to the participating suppliers and are confidential. Deidentified information from these reports is provided in the best practice guide, and in the results section of this final report.
Supply chain monitoring reports to retailers	Reports with detailed results on the supply chain monitoring conducted. The reports identified opportunities to improve supply chain management.	After obtaining approval from the relevant suppliers, confidential supply chain monitoring reports were sent to each of the three major retailers.

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Supply chain stakeholders have increased awareness of the procedures required to maintain mushroom quality	Outcome 2. Industry supply, productivity, and sustainability. Strategy 3: Improve the presentation, storage and shelf life of mushrooms through new, focused R&D initiatives in collaboration with retail and supply chain partners. KPI: availability of new knowledge to improve shelf life and shelf appeal of mushrooms.	All outputs developed, including the postharvest literature review, magazine articles, factsheet, supply chain study reports, and best practice guide have, and will continue to increase awareness of procedures required to maintain mushroom quality.	QA staff at three major mushroom supply businesses have worked with the project team to undertake the supply chain monitoring and reviewed results with consideration of quality and supply chain best practice. Major retailers have participated in meetings focused on supply chain best practice . A meeting was held with all three major retailers prior to conducting the supply chain monitoring. Online meetings were held with two of the three major retailers (offered to all three) to present the monitoring results in their supply chains, and the new best practice guide. Feedback was positive, with staff from both retailers mentioning they were not previously aware of some best practice recommendations. Industry members have read the MushroomLink articles and factsheet. There were 98 views of the temperature factsheet. All industry members have access to the two webinars, and were able to watch live or via the recordings linked earlier in the report The recording of the first webinar has been watched 42 times in the first 2 weeks following the presentation. The recording of the second webinar has been watched 30 times in the first week

			following the presentation. This will increase awareness of issues in Australian mushroom supply chains, and best practice to better maintain quality. Surveys completed (see M&E) by farm owners, growers and employees following the webinars revealed that most respondents found the information useful to their business, improved understanding of factors which affect the quality of mushrooms in supply chains and improved understanding of best practice in mushroom supply chains. The best practice guide clearly presents the procedures required to best maintain quality of mushrooms. Copies of the guide will be distributed to at least 200 industry stakeholders.
Suppliers and retailers make changes that will improve the presentation, storage, and shelf life of mushrooms	Outcome 2. Industry supply, productivity, and sustainability. Strategy 3: Improve the presentation, storage and shelf life of mushrooms through new, focused R&D initiatives in collaboration with retail and supply chain partners. KPI: availability of new knowledge to improve shelf life and shelf appeal of mushrooms.	Worked with three major mushroom suppliers to review their current postharvest and supply chain practices, and identified opportunities for improvement. Meetings were held with the major retailers to ensure they were engaged with the project, and open to making changes in their supply chains. Retailers were provided with a summary of the monitoring results in their supply chains, and these will be reviewed with consideration of best practice. Suppliers requested a standardised temperature measurement and	One supplier is using the data collected in this project to select the transport company with the best temperature control in their supply chains. It was identified at one packhouse that their vacuum cooling system was running for a set period of time, rather than based on the probe temperature of the mushrooms. This was raised as an issue, and the supplier is looking into changing this. A major retailer has adjusted their DC receival temperature specification – this may be partly due to evidence provided by this

		calibration method. This was developed and a factsheet provided to the industry will help ensure all suppliers and retailers measure temperature consistently.	project. As a result of the project a major retailer advised they would follow up and check their coolrooms in their stores are operating correctly, A major retailer was also taking action to ensure that sliced mushrooms are no longer displayed at ambient, after this was identified by the project. A major retailer passed on the best practice guide to their operations team who will look at incorporating some of the content on their back of store poster. Industry stakeholders will use the best practice guide as a future resource to influence changes to improve the presentation, storage and shelf life of mushrooms.

Monitoring and evaluation

Table 3. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
1. To what extent has the project achieved its expected outcomes?	There is already evidence of increased awareness of procedures to best maintain mushroom quality, as well as changes made to improve quality. These outcomes will be further met after the project, as the best practice guide is used and adopted by the industry. Across two surveys conducted at the end of each webinar, 11 out of 12 respondents indicated the information presented improved their understanding of best practice or quality management in mushroom supply chains. In a survey from the second webinar, 4 out of 5 grower/QA respondents indicated they would consider making changes in their operations to improve mushroom quality, as a result of the project. Refer to Table 2 'Outcomes summary' for examples of changes made by suppliers and retailers to improve quality.	It will be important for the best practice guide to continue to be shared with industry members after the project is completed. This can be achieved through the Mushroom Communications project.
2. How relevant was the project to the needs of intended beneficiaries?	The project was relevant to the needs of suppliers and retailers who are all working to improve mushroom quality. Across two surveys conducted at the end of each webinar, all respondents (n=12) indicated that the information presented was useful to their business.	There is a future need to address other needs of beneficiaries, which include the impacts of temperature management on food safety of mushrooms.
3. How well have intended beneficiaries been engaged in the project?	Three major suppliers and retailers were engaged with, particularly during the supply chain monitoring. All beneficiaries have been engaged with during general project communication and extension.	If possible in the future, engage more with smaller suppliers.
5. What efforts did the project make to improve efficiency?	The team regularly reviewed time spent on the project, and wherever possible tried to ensure this was directed efficiently at the project activities.	Where possible minimise changes to the project to reduce administrative costs.

Recommendations

Research needs from the literature review included:

- Examine whether calcium added to casing can increase calcium uptake in the fruiting bodies.
- Investigate use of moisture probes to optimise irrigation and test use of drip irrigation to quantify quality benefits (if any)
- Examine the effects of different supplements on postharvest quality and storage life. Test whether adding supplement to casing (instead of compost) increases effects on quality.
- Independently review whether new harvesting and packing systems affect storage life and quality of mushrooms.
- Examine whether the delay between harvest and cooling, and postharvest weight loss, affect susceptibility to bruising. Test whether mushrooms bruise more easily when cold or warmer, and examine the effect of firmness on bruising susceptibility.
- Determine which dip treatments are worthy of further investigation. Consider whether they could be applied pre-harvest in irrigation water rather than as a postharvest dip.
- Determine whether mushrooms are sensitive to ethylene. If so, test whether the exposure times and concentrations that could occur within commercial supply chains are likely to be reducing storage life. Also determine whether the ethylene inhibitor 1-MCP is likely to provide commercial benefits for mushrooms.
- Determine the effects of transitory temperature fluctuations (as can occur during loading or unloading) on quality of punnetised / cartonised mushrooms and suggest critical limits for significant damage. Examine whether such a fluctuation is likely to impact the microbial safety of sliced mushrooms.
- Test the effect of biodegradable packaging options on storage life, quality and temperature management of mushrooms.

Future supply chain work:

- Improve temperature management of mushrooms in supply chains, with a focus on retail
- Survey mushroom temperature, quality and shelf life at retail stores to determine how frequently purchased mushrooms fail customer expectations
    - Survey should include major and independent retailers
    - Reports provided to retailer and packhouse
    - Traceback on “fail” samples to identify where problems may have occurred

References

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Intellectual property

No project IP or commercialisation to report

Acknowledgements

The project team acknowledge the three suppliers and major retailers who were involved in the supply chain monitoring, taking time away from their everyday operations. Also to those who contributed their time and provided advice as members of the project reference group.

Appendices

1. MushroomLink magazine articles
2. Factsheet – measuring the temperature of mushrooms
3. Australian mushroom supply chain best practice guide
4. Mushroom supply chain reports (confidential)
5. PRG minutes (confidential)
6. Literature review

BEST PRACTICE FOR THE MUSHROOM SUPPLY CHAIN

Even the most polished or targeted marketing campaign will not work if the mushrooms on the supermarket shelf look old, brown, and unappealing. The same applies through the whole supply chain; effort spent on growing, picking and packing the best possible mushrooms will be wasted if they are not well managed after.

As production costs continue to rise, increasing consumption is key to improving grower returns. Although the industry invests well in marketing, impact depends on mushrooms having high quality at retail and acceptable storage life. Ensuring mushrooms consistently meet consumer expectations will help to grow the whole category.

Many pre-harvest and postharvest factors can affect mushroom quality. While some have been reviewed, more detailed information is needed about the effects of postharvest handling and temperature management in Australian supply chains.

To address this knowledge gap, a new levy funded project has commenced that aims to improve quality of mushrooms at retail, develop more efficient management of supply chains, and reduce rejections of mushrooms at retail distribution centres (DC).

"We really want to take this project to the people directly involved," project leader Dr Jenny Ekman said.

"To get industry on board, the project team aims to monitor a range of Australian supply chains, then examine quality and shelf life. This will allow us to identify problematic areas, as well as ensure the proposed solutions are logistically possible and financially viable," Dr Ekman added.

No amount of marketing will sell more mushrooms if they don't look good at retail.

Information collated through existing literature and on the ground 'field work' (de-identified) will be summarised and combined to create a Mushroom Supply Chain Best Practice guide.

In developing the guide, the project seeks to answer three key questions.

1. What is causing quality issues and rejections by retailers?

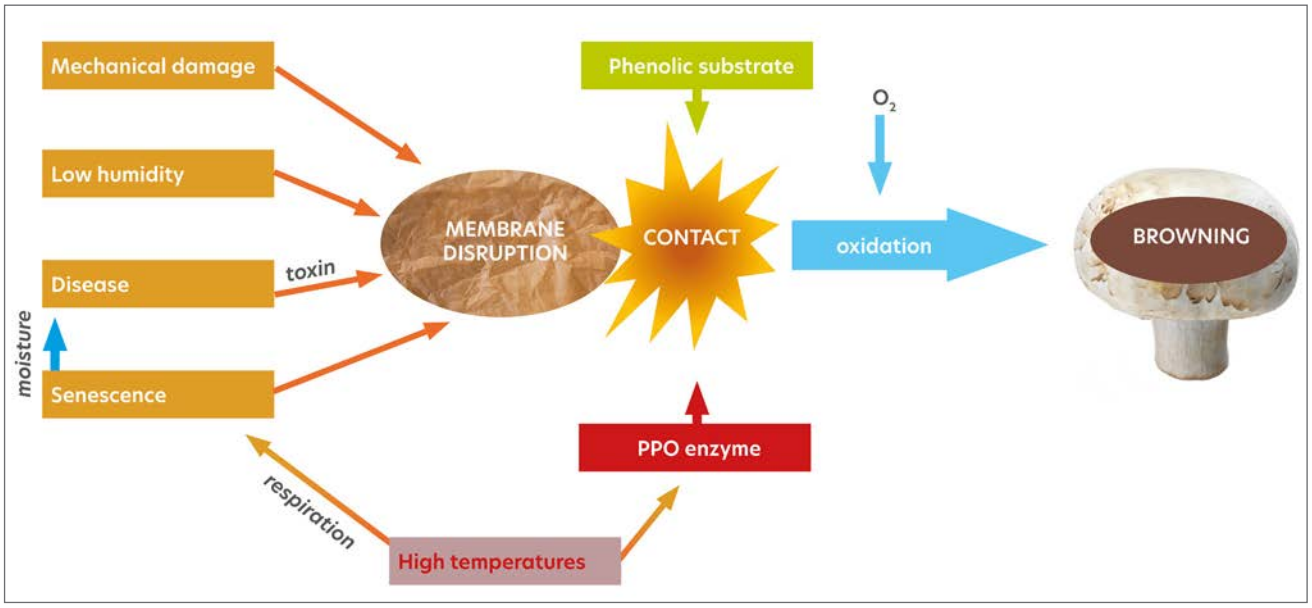
Identifying and managing the factors that impact mushroom freshness and colour at retail is clearly critical.

Key factors include cooling delays, storage and transport temperature, delivery delays and spatial temperature variability within a truck. Rejections could also be due to poorly calibrated probes or thermostats. These factors can all lead temperature related rejections at retail DC, which have little tolerance for consignments arriving above the recommended temperature.

While temperature fluctuations potentially increase food safety and quality risks for sliced mushrooms, the extent to which small changes in temperature impact whole mushrooms is less clear. "It really depends on whether the mushrooms get wet, and stay wet, as that is going to increase browning," suggests Dr Ekman.

Slicing makes it even more challenging to maintain mushroom quality and safety through the supply chain, but is increasingly popular with consumers.

Initial quality, freedom from pathogens, rapid cooling after harvest, and packing method are likely to have greater impact on quality than transitory temperature changes just before delivery.



Summary of potential causes of mushroom browning.

2. What happens after mushrooms arrive at the DC?

Temperature monitoring should not stop at the DC but continue through to retail. The conditions under which mushrooms are held during transport to stores, back of store handling and retail display are highly likely to have a significant impact on the consumer experience.

There is also some evidence that mixing mushrooms with ethylene producing crops, as can occur in trucks and back of store cool rooms, may reduce quality. "Ripening avocados, mangoes, passionfruit and stonefruit release significant amounts of ethylene," comments Dr Ekman, "but we just don't know what impact this may be having on mushrooms stored in the same environment".

Third flush mushrooms 9 days after harvest

Untreated

+ Calcium

Previous trials at the MLMRU have confirmed that adding $CaCl_2$ to irrigation water improves mushroom firmness and retains whiteness during storage, with the greatest effects on third flush mushrooms.

3. What is needed to improve quality at retail and reduce rejections?

The project team will use two strategies to address this question.

- **Innovate at critical control points**: Once we understand where issues are occurring, we will test solutions. These will be done in conjunction with industry partners to ensure they are consistent with commercial practice. They will also draw on past and present research, such as that currently conducted at the MLMRU.
- **Develop a best practice guide and training materials**: A concise, easy to understand best practice guide will be developed which is suitable for all supply chain participants, from grower to retailer. To encourage adoption, matching training materials and extension activities will be conducted to promote new information and resources.

The outcomes of this project will help industry improve the handling and storage of mushrooms within the value chain, from farm gate and transportation to retail.

"If we can manage the supply chain properly, we reduce rejections at distribution centres, improve retail quality, minimise waste, and ensure food safety," Dr Ekman said.

"That's a win for everyone"

KEY POINTS

- A new project aims to improve quality of mushrooms at retail by improving supply chain management
- Improved handling and storage will reduce rejection of mushrooms at distribution centres
- Industry engagement is planned into the project to ensure outcomes are both financially and commercially viable.
- Outcomes of the project will be summarised into a best practice guide for the industry

Hort Innovation Strategic levy investment | MUSHROOM FUND

This project has been funded by Hort Innovation using the mushroom research and development levy and funds from the Australian Government. For more information on the fund and strategic levy investment visit horticulture.com.au

BEST PRACTICE IN MUSHROOM **SUPPLY CHAINS**

"I learned the truth at seventeen, that love was meant for beauty queens...." *- Janis Ian, 1975*

by Dr Jenny Ekman

Fortunately, most people believe that beauty is more than skin deep. However, for mushrooms, looks are everything. Good looking mushrooms will soon waltz off the shelves. Meanwhile, their less appealing counterparts remain unloved, unwanted, and unsold.

Recently contracted project MU22011 is developing guidelines for best practice management within mushroom supply chains, from farm to retail store. The project aim is to ensure that shoppers are presented with fresh, unbruised, and all-round glamorous mushrooms every time they go shopping (Figure 1). With many, if not most, purchases decided in store, good quality is a key strategy to reverse recent drops in sales.

The project plan will identify the critical control points affecting mushroom quality and safety. Using data on temperature and quality, the team will work with both growers and retailers to develop a Best Practice Guide for the Australian industry. Online workshops and training materials will be rolled out in parallel.

The first step in the project was to review what we already know about factors affecting mushroom quality. These are some highlights:

PRE-HARVEST EFFECTS ON POSTHARVEST QUALITY

The room environment

Temperature, humidity and airflow in growing rooms have a huge impact on mushroom quality. Mushroom formation is triggered by 'airing', i.e. reducing CO_2 levels within the growing room. This also allows the release of accumulated 1-octen-3-ol from the substrate. This volatile compound suppresses formation of the primordia which develop into fruiting bodies, so removal is essential[1].

Figure 1. Well presented, good quality mushrooms practically sell themselves.

High CO_2 levels can result in stipe elongation, stretched veils and smaller caps[2]. Managing CO_2 accurately and uniformly within the room is difficult without adequate airflow. However, rapid airflow stimulates formation of melanin, the brown compound also responsible for bruising and browning of cut surfaces[3].

Airflow also needs to be balanced against the metabolic heat produced by developing mushrooms. So, for example, air flow may need to be higher when approaching Flush 1 compared to Flush 3.

Avoiding overpinning is clearly essential for good quality mushrooms. Overpinning can occur if CO_2 levels drop rapidly. Conversely, dropping CO_2 too slowly may reduce yield. Pinning is also affected by the casing material, with clumped, wet casing reducing pinning compared to granulated material kept moist.

Their lack of a true skin means mushroom quality is strongly affected by humidity and air movement. Mushrooms grown at low relative humidity (<85%) may not only be 'scaly' (Figure 3), but also more susceptible to bruising compared to mushrooms grown at high RH (92%), with effects most pronounced in early flushes[4].

It's hard to have your cake and eat it too, so improvements in quality must sometimes be balanced against yield. For example, mushrooms grown at lower temperatures (11–13°C) were firmer and contained more calcium than mushrooms grown at 17–19°C, but yield was reduced[5]. Similarly, growing conditions that improve dry matter are associated with increased shelf life, but decreased yield[6] (Figure 4).

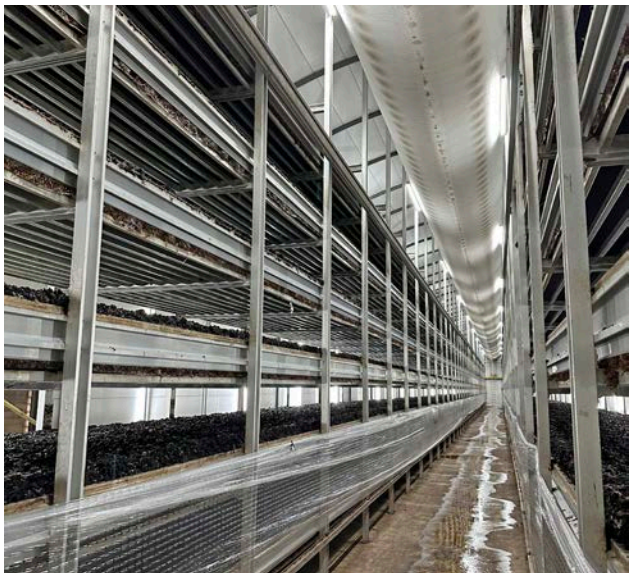


Figure 2. Monaghans Mushrooms in the UK uses perforated plastic wrap to reduce airflow over the lower bed, as well as a soft air delivery system to distribute air evenly through its 70m long growing rooms.

Figure 3. Slight scaling due to increased airflow on the outer edge of the bed; inner mushrooms are not affected.

Substrates and additions

When it comes to casing, black peat appears to be a clear winner at producing the best quality mushrooms. Brown and golden peats can also provide very good results.

Many trials have tested peat blended with ingredients such as coal tailings, spent compost, coconut fibre,

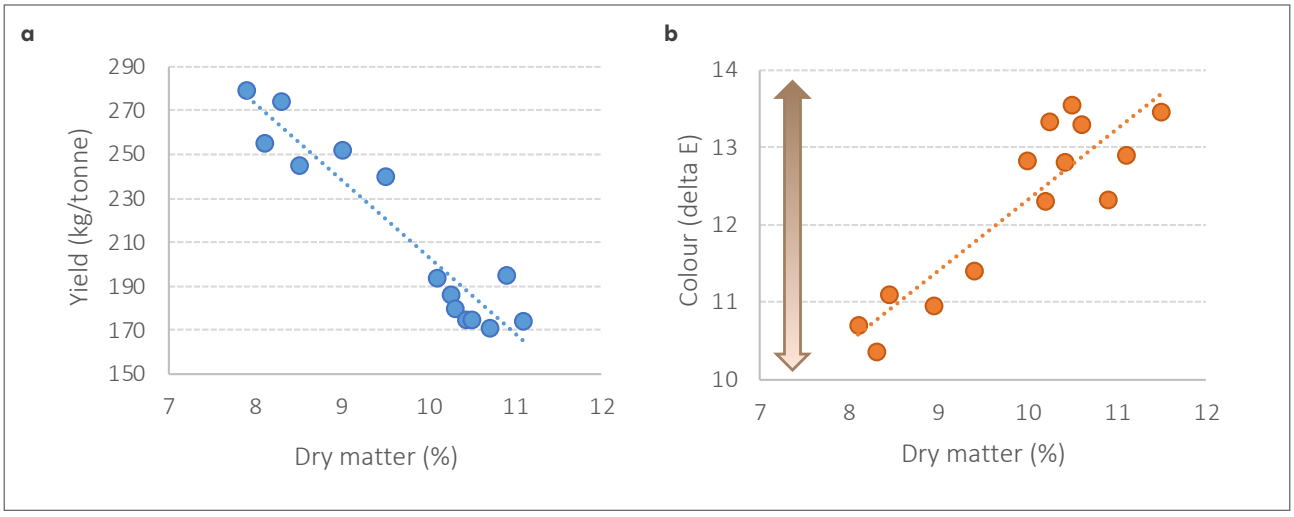


Figure 4. Relationships between mushroom dry matter and yield (a); mushroom dry matter and colour (□E) (b). Derived from Barry et al., 2016.

old carpet, rockwool and a multitude of others. While blends containing 40 to 75% peat sometimes provided good quality and yield, further reductions in peat often reduced quality. The reasons for this, and the potential for alternative casing materials, is reviewed on Page 7 of this magazine.

Irrigation

Mushrooms are 90 to 95% water, so the quality of water used, as well as how and when it is applied, will inevitably affect quality and storage life. Too little moisture produces low yields of soft, scaly, easily bruised mushrooms. Too much water increases risk from bacterial blotch, while water pooling on mushroom caps can leave discoloured watermarks.

Drip irrigation systems avoid wetting the caps, adding flexibility to irrigation schedules. In some circumstances, they can increase the proportion of 'A' grade mushrooms, especially in later flushes[6] (Figure 5).

However, implementation is not easy. Cost, technical issues, and difficulties with cleaning and re-use limit commercial adoption. Trials at the MLMRU have been testing use of drip irrigation to add nitrogen, a topic explored previously in MushroomLink (Issue 6).

Much of the water in mushrooms comes from the casing, rather than the underlying compost. Getting the right moisture in casing is a balancing act between high dry matter (associated with long storage life) and yield.

Water content falls dramatically during flushing. If a heavy first flush results in dry casing for the second flush, these mushrooms will be discoloured and susceptible to premature opening[7]. Yield and quality are best when water content is kept stable, with casing never allowed to dry out. For example, O'Danay et al (2016) showed that increasing the water content in casing from 46-48% to 58-60% improved mushroom quality[6].

It is relatively well known that adding 0.3% calcium chloride to irrigation water increases calcium content in mushrooms. It can also improve whiteness, enhance storage life, and reduce bruising sensitivity, all without reducing yield. The benefits are most pronounced in later flushes. However, the legality of this practice is unclear. Moreover, calcium salts can build up in lines and block nozzles, creating significant maintenance issues.

An alternative may be to add calcium salts to the casing. This increases osmotic potential, resulting in heavier, denser mushrooms[8]. High dry matter is associated with increased storage life, as sugar reserves (mannitol) move from the stipe to the cap during storage. However, as previously noted, improvements in dry matter are often at the expense of yield, and this method is yet to be tested under commercial conditions.

Managing disease

While *Pseudomonas tolaasii* (bacterial blotch) can occasionally devastate mushroom crops during production, problems more commonly appear during postharvest storage. Symptoms are due to the toxin tolaasin, which breaks down cell membranes, catalysing the formation of the brown pigment melanin.

Prolonged wetness is key to disease development. Poorly nourished crops and later flushes are also more

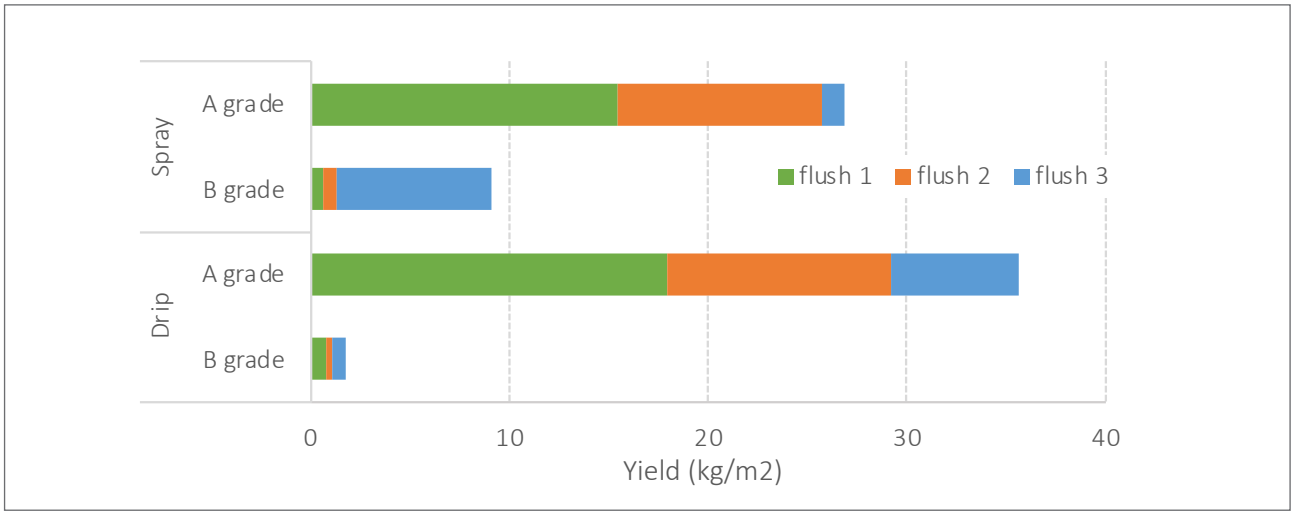


Figure 5. Yield and quality grade of mushrooms grown with normal or drip irrigation. Derived from Danay et al., 2016

susceptible to disease, as bacterial populations build during cropping.

The once common practice of adding chlorine to irrigation water to help control blotch is now believed to have little value. Geels et al (1991) reported superior results from irrigating with 50ppm stabilised chlorine dioxide (ClO_2). The sanitiser reacts specifically with reduced sulphur compounds in spores, bacteria and viruses, so is therefore less affected by organic matter – including the mushrooms and their casing material[9].

While stabilised ClO_2 is registered for use as a sanitiser on mushroom farms, the permit is for treating water (5ppm) and disinfecting walls, floors, and equipment (100ppm). As ClO_2 is not registered for control of blotch it cannot legally be used for this purpose in Australia.

BEST PRACTICE DURING HARVESTING

Bruising

Bruising is clearly a key issue during harvest. Even light squeezes, vibration, or compression on overpinned beds can trigger browning reactions. Bruising occurs when cell membranes are disrupted. This allows cell contents to mix and form melanin (Figure 6), the same brown compound triggered in reaction to tolaasin.

Such browning reactions are not instantaneous but develop over time. This means damage may not be obvious for 24 hours or more, by which time mushrooms have reached the distribution centre or retail.

Mushrooms bruise easily due to a layer of relatively fragile, low-density cells located in between the cap surface and the higher density core[10]. Susceptibility to bruising increases with time from harvest, so impacts during transport and retail can have major impacts on quality.

Mushrooms with open caps are also often more susceptible to bruising than immature mushrooms with closed caps, although differences due to size and maturity are not always consistent[11].

The search for bruising resistance has focussed on strains with reduced levels of polyphenol oxidase enzymes and/or phenolic compounds. Weijn et al[11] identified two specific compounds that were 15x to 20x higher in bruising-sensitive strains compared to tolerant strains.

Unfortunately, there is some evidence that the genes involved in browning reactions also affect mycelial growth. This suggests that molecular techniques which delete these genes, thereby reducing browning, may potentially have negative effects on yield.

The relatively new gene editing technique CRISPR would seem to have promise in testing the effects of turning off genes associated with browning. While an exciting technology, achieving success with CRISPR is far more complicated for fungi (many nucleii per cell) than for plants (one nucleus per cell). See Issue 4 of MushroomLink for a fuller explanation of mushroom breeding techniques.

Breeding a whiter mushroom is highly complex, with both traditional and non-traditional breeding techniques ongoing.

New harvest technology

Earlier issues of this magazine have described the new technologies that aim to either fully automate harvesting or simply make more efficient use of existing harvest labour. Tilting shelves, moving drawers, bed scanners and laser pointers are all designed to save cost on that most expensive part of mushroom production – picking and packing.

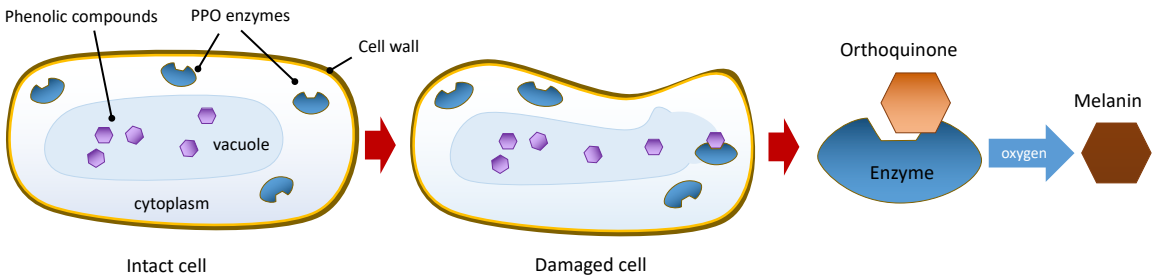


Figure 6. Mushrooms bruise because of disruption of the internal membranes in cells. This allows phenolic compounds normally held in the cell vacuole to mix with polyphenol oxidase (PPO) enzymes in the cytoplasm. The enzymes catalyse the formation of orthoquinones, which further oxidise over time, forming the brown compound melanin.

From the viewpoint of postharvest quality, any technology that makes it easier for pickers to reach the mushrooms and/or minimises handling is also likely to reduce bruising.

Conversely, some of the robotic pickers under development may reduce quality, as the suction cups or fingers used to grip mushrooms lack the sensitivity of human hands.

Figure 7. Harvest aids that make it easier for workers to see and pick mushrooms, such as the moving drawer system seen here, may also reduce bruising during harvest.

Trimming

Harvesting separates fragile mushrooms from their source of water and nutrients. However, their stems contain valuable sugar reserves. These can move into the cap postharvest, allowing the mushroom to continue to open and spores to mature.

It is likely that this is why cutting the stipe to 5mm, instead of leaving it 30-35mm long, can reduce browning and cap opening during storage[12]. While cutting stipes short impacts yield (up to 10%), it reduces the risk of veil breakage as well as damage inside the packed punnet.

Packaging

Packaging protects mushrooms from physical damage while minimising moisture loss and preventing movement. Packaging must provide enough ventilation for effective pre-cooling and removal of heat generated by respiration.

One of the challenges of the current packing system is getting enough air movement around punnets to keep them cool. This can be particularly problematic during transport, as there is limited air circulation inside trucks.

Figure 8. The bulk packed mushrooms at left have more physical damage than those at right. However, the condensation visible inside the punnets at right is also less than ideal. (Photos taken in the UK)

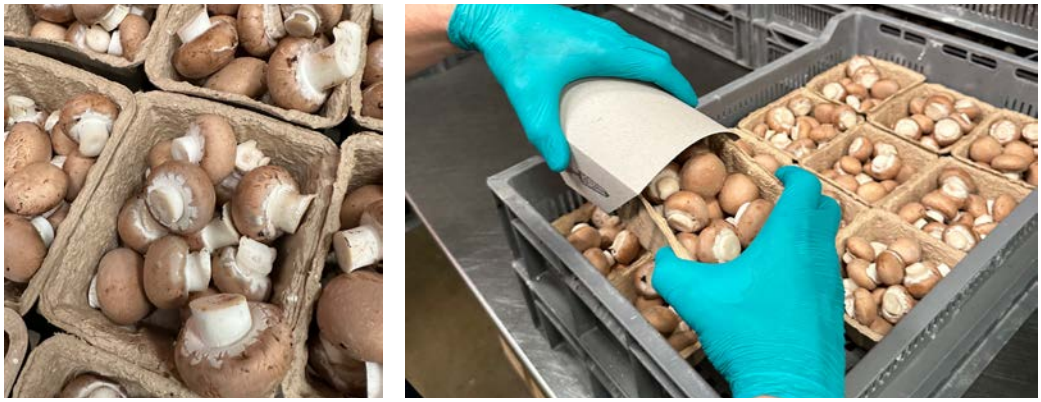


Figure 9. These compressed cardboard punnets with paper sleeve provide good physical protection and tick environmental boxes. However, this material can readily absorb 15% of its own weight in moisture, so is likely to increase weight loss from the mushrooms.

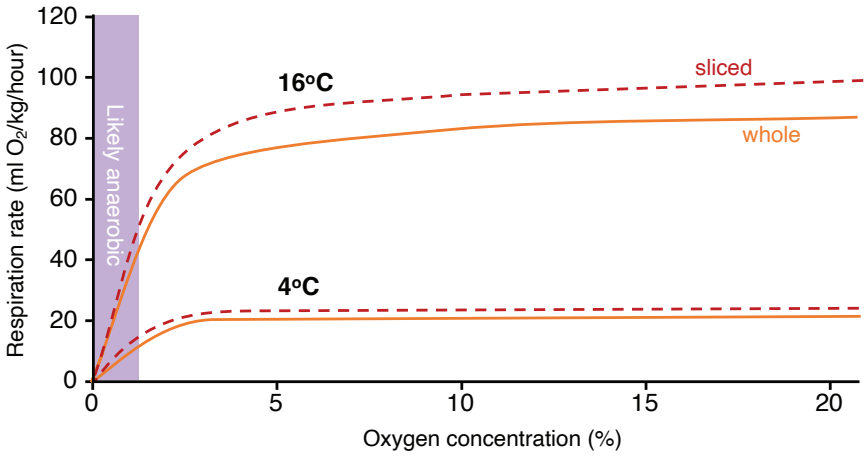


Figure 10. The effect of oxygen concentration on respiration rates of whole and sliced mushrooms. Derived from Cliffe-Byrnes and O'Beirne, 2007

Conversely, too much ventilation can allow excess weight loss.

While loose packed cartons provide excellent protection from compression, tightly overwrapped punnets are excellent at reducing bruising due to movement. For example, the sealed punnets shown in Figure 8 have greater internal air space than the tightly overwrapped punnets used in Australia. This makes them more susceptible to development of condensation inside the package and potential bruising from movement.

Hort Innovation funded project MU22008 recently reviewed options for sustainable mushroom packaging. They concluded that PVC wraps were still the best option for the Australian industry, but could be combined with punnets made from recycled PET or corrugated/fluted cardboard. Key findings are presented in Issue 5 of MushroomLink (read more here).

Modified atmosphere packaging

There is a strong, inverse relationship between respiration rate and storage life. Modified atmosphere packaging aims to reduce respiration rate by creating low O_2 and/or high CO_2 atmospheres, with the assumption this will increase storage life.

However, unlike many other fresh products, mushroom respiration is relatively unaffected by changes in O_2 and CO_2 in the surrounding atmosphere, even when sliced (Figure 10)[13]. Moreover, high CO_2 levels increase yellowing/browning and can trigger stipe elongation[14].

Despite this, researchers have continued to search for modified atmosphere packaging solutions for mushrooms. Many recent (since 2020) publications have recommended atmospheres containing up to 30% CO_2 and anything from 0 to 80% O_2, despite the difficulty of implementing such atmospheres and the likelihood they

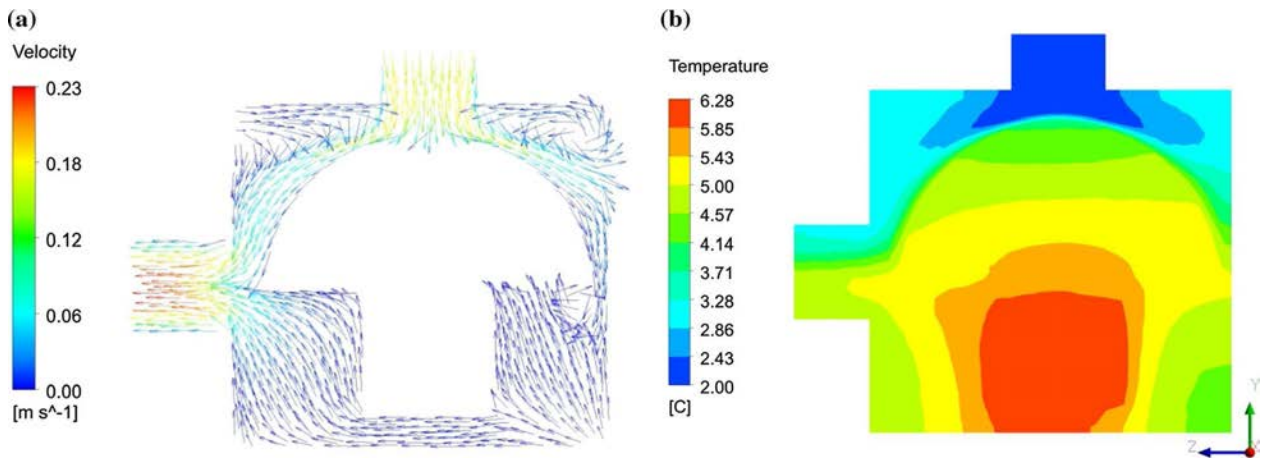


Figure 11. Air velocity contours and temperature zones inside a mushroom after one hour of cooling. From Salamat et al., 2020a

will negatively affect eating quality. None are known to have found commercial application.

COOLING AND STORAGE TEMPERATURE

Cooling method

Cooling mushrooms as quickly as possible after harvest is essential to maximise postharvest quality. Cooling slows metabolic processes and minimises weight loss, reducing cap opening and browning.

Vacuum cooling is not only fast and energy efficient, but may also reduce enzymic browning by disrupting PPO enzymes[15]. For example, Tao et al.[16] reported that vacuum cooled mushrooms were half as discoloured as those that were room cooled following four days at 4°C.

Forced air systems can reduce temperature up to 18x faster than room cooling. The faster mushrooms cool, the less moisture they lose. Salamat et al.[17] found that forced air cooling of mushrooms to close to 2°C before overwrapping punnets resulted in whiter, firmer mushrooms after 10 days storage compared to mushrooms pre-cooled to 10°C before wrapping. This is because mushrooms pre-cooled to 2°C or 10°C took 1.5 and 24 hours respectively to reach the target temperature following overwrapping.

It is clear that large differences in cooling rate occur when air does not flow evenly across mushrooms, as occurs once mushrooms are packed. Effectively, the surface area for heat exchange is reduced from that of the mushroom to that of the packed punnet.

The effect of airflow over a single mushroom was modelled by Salamat et al.[17], demonstrating that differences occur even on this small scale (Figure 11).

Storage temperature

While mushroom storage life is theoretically maximised at close to 0°C, the risk of freezing means they are usually held no lower than 2°C. Moreover, if acceptable storage life is considered to be 10 to 14 days, then this is readily achieved at 5°C and below. Temperature has the most effect between 2°C and 10°C, storage life doubling between these values (Figure 12).

Minimising temperature fluctuations during storage and transport reduces the risk of condensation forming on the mushrooms or their packaging. To ensure uniform temperature control:

- Reduce the gap between high and low room setpoints
- Minimise door opening
- Use an air curtain to reduce warm air ingress
- Ensure cold rooms are well insulated and seals are intact
- Load directly from cold rooms into thoroughly pre-cooled trucks

High temperatures increase respiration and, as previously noted, respiration rate is strongly inversely related to storage life. This is partly due to continued development, especially at over 12°C[18], but also to depletion of stored energy reserves. Slicing (or bruising) further increases respiration rate, however, this effect is less than for other products[19].

In 1999, a national mushroom cool chain management project[20] found that most mushrooms were room cooled, and that RH inside cool rooms ranged from 65 to 85%. The study also identified that retail loads were frequently consolidated at 10 to 12°C, and that retail

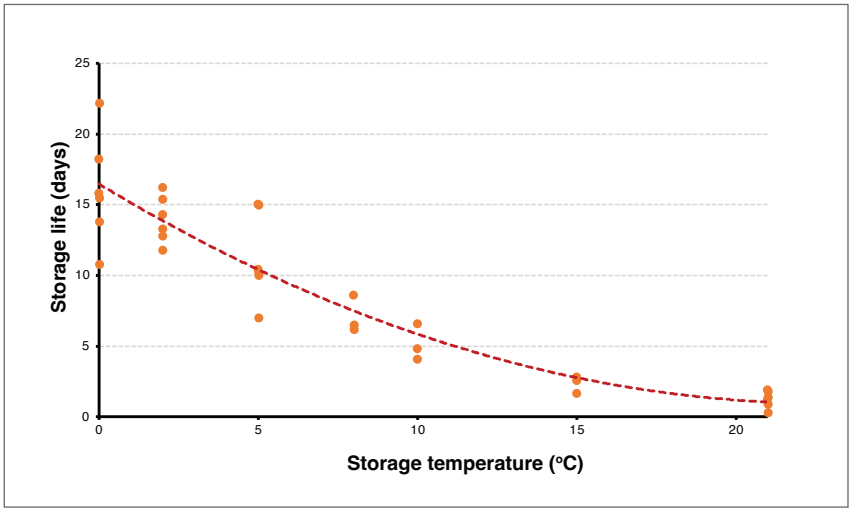


Figure 12. Effect of temperature on mushroom storage life. Authors own data

displays were often both warm and dry (RH of 35 to 55%), accelerating deterioration in stores.

Cool chain management has significantly improved since that time. Strict retailer specifications require that mushrooms are delivered below 5°C.

However, conditions during distribution and retail are less well defined. Although usually displayed in the refrigerated section, open cooling units may not offer ideal conditions for mushrooms.

The quality of mushrooms on the retail shelf is the culmination of all that has gone before. Optimum temperature management up to the retail store can help mushrooms withstand the rigours of a less than ideal display environment. As less of their limited energy reserves have been consumed, such mushrooms may well have 'longer legs'. However, this can only go so far in maintaining quality.

Improving the final steps in the supply chain may well have the greatest impact on the quality consumers see. The next steps of this project will include:

- Monitoring temperatures in supply chains to identify where breaks in the cold chain are most likely to occur and why
- Examining the quality of mushrooms at retail and linking this to what has happened prior
- Recommending strategies to optimise handling from the time mushrooms are picked to when they reach the retail shelf and consolidating information in best practice materials

Beautiful mushrooms make for beautiful sales, and those benefit everyone in the mushroom supply chain. Look out for more on this project in future editions of this magazine.

MU22011
Mushroom supply chain best practice management

Hort Innovation MUSHROOM FUND

This project has been funded by Hort Innovation using the mushroom research and development levy and funds from the Australian Government. For more information on the fund and strategic levy investment visit horticulture.com.au

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COLD MUSHROOMS ARE **QUALITY MUSHROOMS**

Postharvest temperature management.

By Dr Jenny Ekman

My old professor at university used to say that the three most important things in postharvest management were Temperature, Temperature and..... Temperature.

Temperature is certainly the key factor determining the storage life of fresh mushrooms. It affects weight loss, colour change, firmness, stipe elongation, cap opening, bacterial growth and overall freshness. While there are many things growers can do to improve quality at harvest (see MushroomLink Summer p11, *Best practice in mushroom supply chains* for more on this), it is the temperatures that mushrooms experience afterwards that are key to determining the quality consumers experience.

WHAT IS TEMPERATURE, ACTUALLY?

Temperature is a measure of the kinetic energy carried by molecules within an object or material. Any collision between a molecule with high kinetic energy, and one with lower kinetic energy, transfers energy from one to the other. To us, this translates as the warmth or coolness of an object or material, whether mushrooms, their packaging, or the air around them.

Unlike mass or volume, temperature (i.e. the kinetic energy of molecules) cannot be measured directly. Rather, we gauge temperature by observing its effects on other materials, such as the expansion of metals, or reflection of infrared radiation.

Einstein said, "*Energy cannot be created or destroyed, it can only be changed from one form into another*".

Heat is one such type of energy.

Respiration by harvested mushrooms converts the energy stored in sugars and carbohydrates into forms that can be used by cells. Some of that energy is also converted into heat. The faster mushrooms are respiring – due to their temperature, development stage or damage – the more heat energy is produced.

For example, using mean respiration rates of mushrooms, it can be calculated that a kg of mushrooms at 19°C produces nearly 21 kJ heat/kg/day. However, respiratory heat drops to 3.5 kJ/kg/day once the mushrooms are cooled to around 5°C (Figure 1). Every degree of cooling decreases respiration, and therefore the heat produced, just a little more.

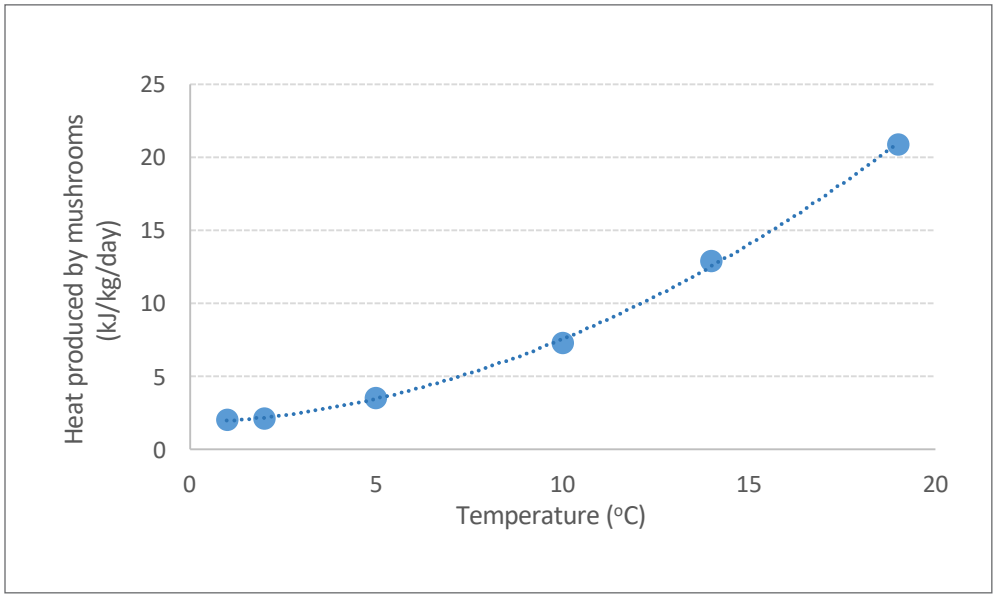

Figure 1. Effect of air temperature on respiratory heat produced by mushrooms. Respiration rates are average values from authors own data. Note this calculation is based on 6 moles CO_2 generating 2,667kJ heat (USDA, 1986), which is not verified for mushrooms.

PRINCIPLES OF COOLING

Cooling is what happens when heat energy is transferred from mushrooms into other media, whether water, air, packaging, or other mushrooms.

As a general rule, the speed at which energy is transferred depends on:

- the medium
- the object's surface area
- the object's thermal conductivity and
- the temperature differential between the object and the cooling medium.

The medium

By the 'medium', we are mainly referring to the air or water that surrounds the mushrooms. However, packaging can also form part of the medium, conducting heat to, or from, the mushrooms.

Air is a poor conductor of heat. Water is a better conductor of heat, transferring energy 24 times as efficiently. If you need proof of this, just think how cold you are likely to get ocean swimming in winter compared to going for a brisk walk. Even though both air and water may be 15°C, that swim is going to be a lot shorter!

Hydro-cooling (immersion in cold water) is clearly not an option for mushrooms. However, just as water can transfer heat away during cooling, it can also allow warming.

A key example is cold room insulation. Like a puffer jacket, cold room insulation works because of the air trapped in layers of foam inside the panelling. This prevents transfer of heat from the outside of the room to the inside.

Older rooms often have poor door and floor seals, or damage where forklifts have punctured the panel skin. If this allows moisture to penetrate the internal foam, the insulation will be ineffective. Likewise, wet, non-insulated concrete floors can allow heat to penetrate the cold room. Poor insulation means increased energy consumption, poor temperature control and lower relative humidity overall.

Surface area

Individual mushrooms have a large surface area relative to their volume. This means they can cool very quickly indeed. However, once mushrooms are packed into a punnet or carton, the effective surface area is reduced to that of the packed product.

If the punnets are placed inside crates on a pallet and the whole load is wrapped with cling film, the effective surface area is only that of the outside of the loaded pallet. The surface area is now low compared to volume, making it hard to remove heat from the mushrooms inside.

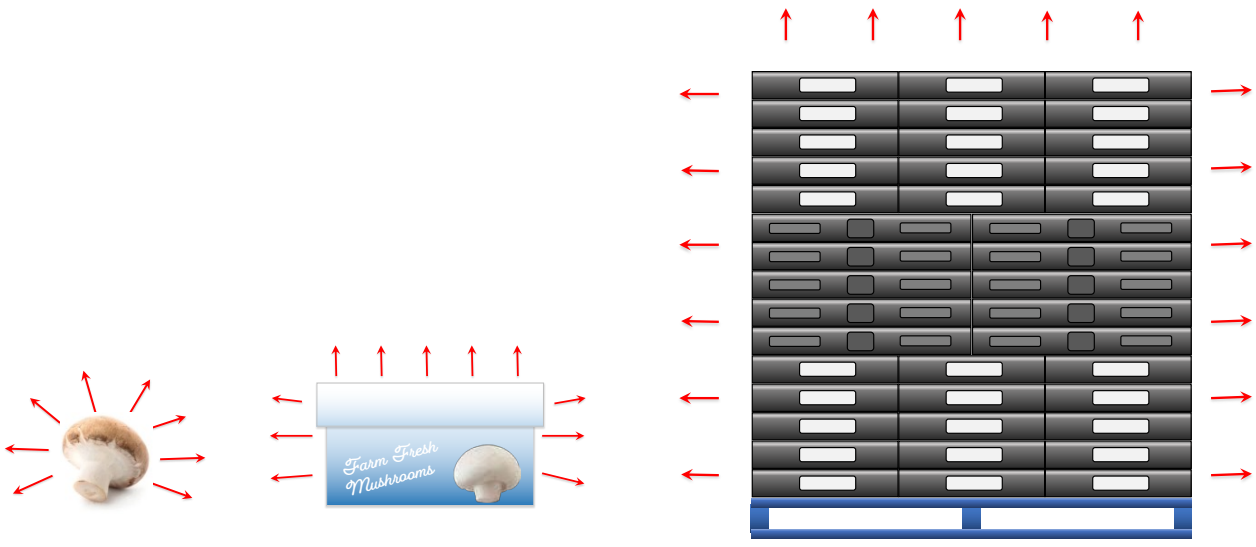

Figure 2. Surface area is a key factor in the speed of cooling. Whereas a single mushroom has a very high surface area compared to its volume, mushrooms inside a carton have only a medium surface area to volume ratio, while stacking onto a pallet reduces surface area to volume even further.

Thermal conductivity

Thermal conductivity is a measure of how easily products lose heat. For example, cabbages are hard to cool because the layers of air trapped in between the leaves prevent heat from moving from the core to the surrounding air.

In contrast, mushrooms have a relatively loose internal structure and lack a true skin. Their thermal conductivity is therefore high, making them easier to cool (Figure 3).

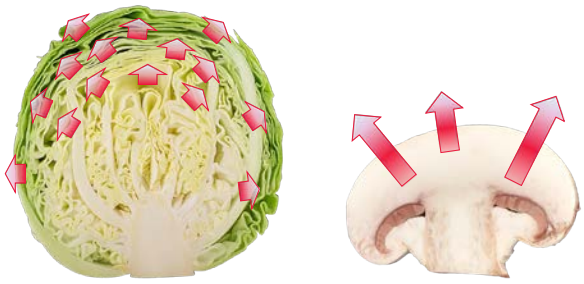

Figure 3. The layers of trapped air between cabbage leaves make it difficult for heat energy to escape. In contrast, the porous structure and lack of a true skin of mushrooms means their thermal conductivity is high, and heat can more easily be removed.

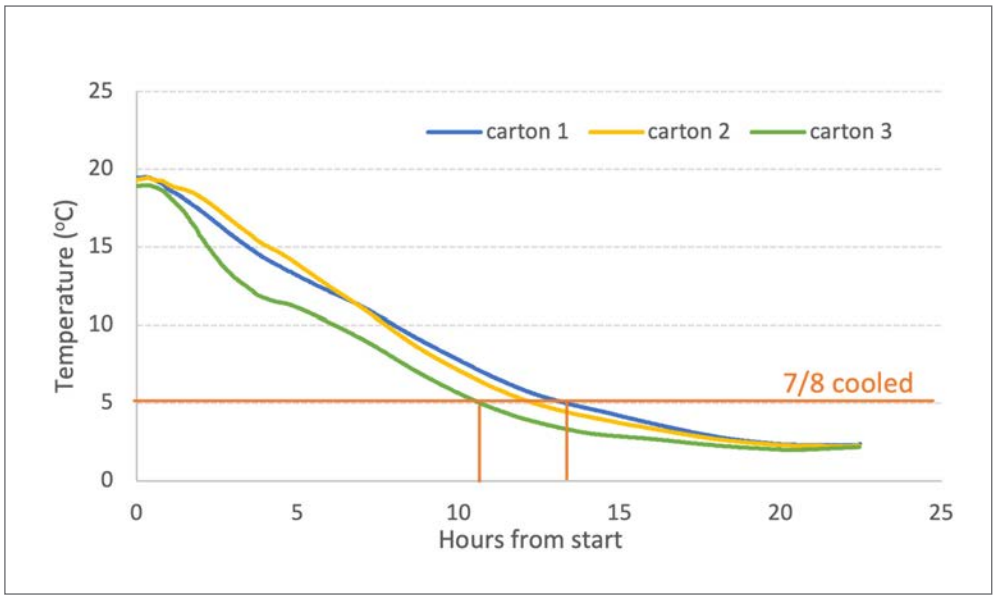

Figure 4. Pulp temperatures inside three cartons of loose mushrooms placed inside a cold room. Temperature fell from 19°C at harvest to a target of 3°C; mushrooms were 7/8 cooled once they reached 5°C, which took 11 to 13 hours.

Temperature differential

Products cool fastest when there is a big difference between them and the cooling medium. As mushrooms approach the temperature of, for example, the cold room air, the cooling rate will slow.

Because the last few degrees take the longest, it is difficult to compare rates of cooling between different systems. It is easier to compare the time taken to '3/4 cooled' or '7/8 cooled'. That is, when 3/4 or 7/8 of the temperature differential between the product and the air has been eliminated.

For example, if the mushrooms are 18°C at harvest, and the temperature target is 2°C, the temperature differential is 16°C.

The mushrooms will be ¾ cooled when they are 6°C and 7/8 cooled when they are 4°C:

$$18°C - (3/4 \times 16°C) = 6°C$$

$$18°C - (7/8 \times 16°C) = 4°C$$

COOLING METHODS

Room cooling

The easiest way of cooling mushrooms is to simply put them into the cold room. However, the cold room air has to remove both their latent heat and the heat generated by respiration, which is faster while mushrooms are warm. This means that cooling can be slow, even when fans are moving air around the room.

If the mushrooms are already packed into cartons or punnets, then cooling will be even slower.

Cooling ratees are important because mushrooms will continue to lose moisture while they are warmer than the cold room air, even if the air is humidified to 85%RH or more.

This is because the warm, moist air spaces inside the mushrooms are essentially 100%RH. This means the air inside the mushrooms can hold a lot more water vapour than the cold room air, even if both are saturated.

Molecules always move from areas of high to low concentrations, and water vapour is no exception. This difference in the partial pressure of water vapour between the warm inner tissues and the cold air effectively pulls moisture out of the mushrooms.

The relationship between the partial pressure of water vapour, temperature and humidity is described by the psychrometric chart. As shown in Figure 5, there is a significant vapour pressure deficit between warm mushrooms and cold room air.

Room cooling is also likely to result in condensation. As warm air cools, it is able to hold less water vapour. The point at which moisture condenses out of the air is the dewpoint. Temperature gradients result in condensation on mushrooms, the inside of packages, and even in different parts of the cold room.

Forced air cooling

Forced air systems pull cold room air through packed product. In effect, this reduces the surface area from the outside of the carton or pallet to that of the mushrooms inside. Forced air cooling rates can be 10 times faster than simply placing the packed mushrooms in the room.

Moreover, as air always moves from cold areas to warmer ones, there is no risk of condensation. Despite the increased volumes of air moving past the product, faster cooling means that weight loss is reduced.

It is important to note that even high amounts of air movement within the room cannot achieve the same effect as forced air cooling. Air is lazy and will take the path of least resistance. Forced air systems **pull** the air

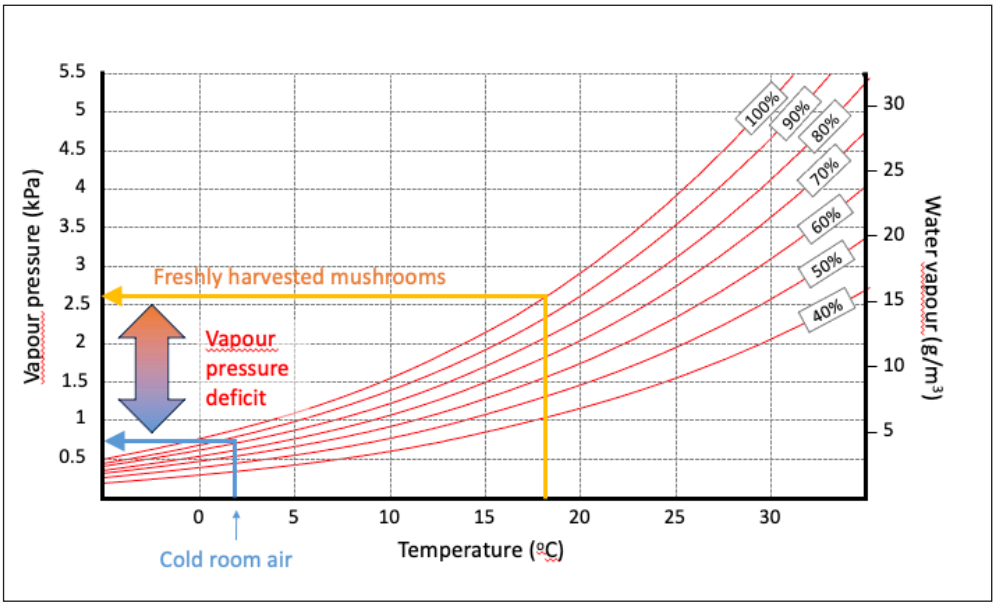

Figure 5. The relationship between temperature, humidity and water vapour pressure is described by the psychrometric chart. In this example, the vapour pressure deficit between mushrooms (18°C + 100%RH) and the room air (3°C + 85% RH) is approximately 1.8 kPa.

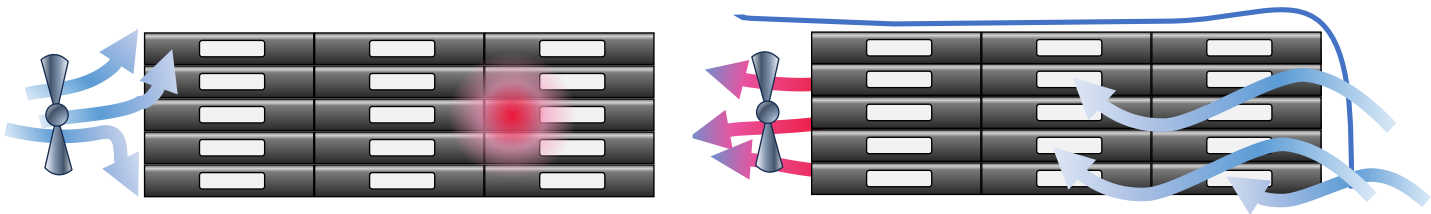

Figure 6. Although blowing air around the cold room can help remove heat from the outside of packed product, warm areas can persist within the consignment (left). Forced air systems pull air through the packed product, cooling product evenly and efficiently while avoiding condensation (right).

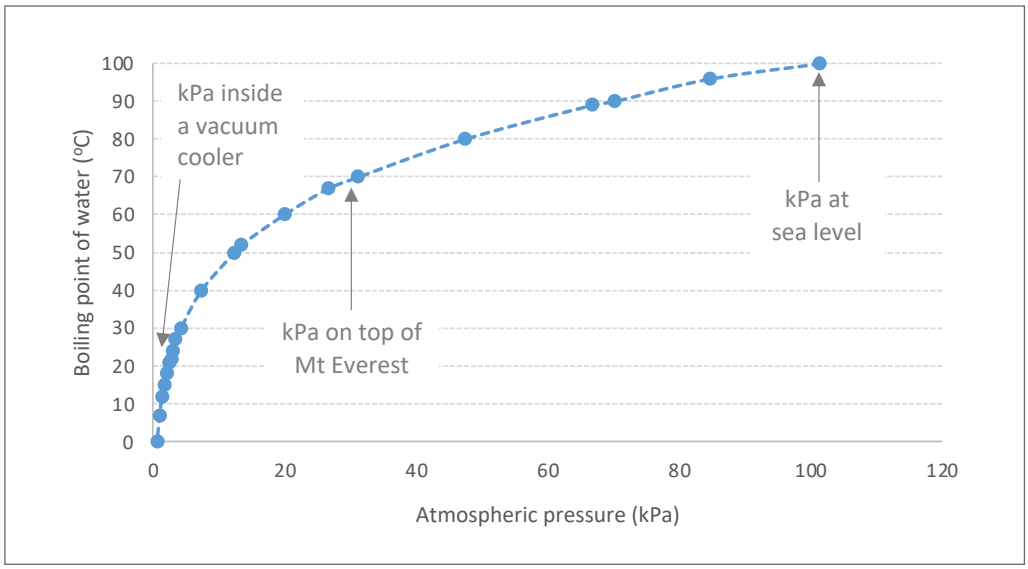

Figure 7. Effect of atmospheric pressure on boiling point of water. Data from myengineeringtools.com.

through the cartons. Fans will simply **blow** it around the outside (Figure 6).

Forced air cooling is widely used for other fresh products. Although rarely used for mushrooms, it does provide a low cost cooling strategy for some growers.

Vacuum cooling

The fastest and most energy efficient way to cool mushrooms is vacuum cooling. Vacuum coolers work by evaporating water from fresh produce. For this reason they work best with products that lose water easily, like leafy greens, herbs – and mushrooms.

At normal atmospheric pressure (around 101.3 kPa) water boils at approximately 100°C. This phase change (liquid into gas) for water absorbs energy. Changing 1ml of liquid water into vapour absorbs 2.26kJ of energy.

This is why water or sweat drying from your face feels cooling in hot dry weather.

As water changes from liquid to gas it not only absorbs energy but also increases volume 1,671 times.

At high pressure the transformation from liquid to gas is more difficult, so more energy needs to be put in to make phase change occur. In effect, water's boiling point increases. Conversely, reducing the pressure means that water changes more easily into vapour.

On top of Mt Everest, reduced atmospheric pressure means that water boils at around 70°C. At 10kPa (1/10th normal atmospheric pressure), water boils at 45°C, while at 1kPa water boils at only 6.7°C (Figure 7).

Commercial vacuum coolers can exert a pressure of close to -100.7kPa, dropping water's boiling point to just

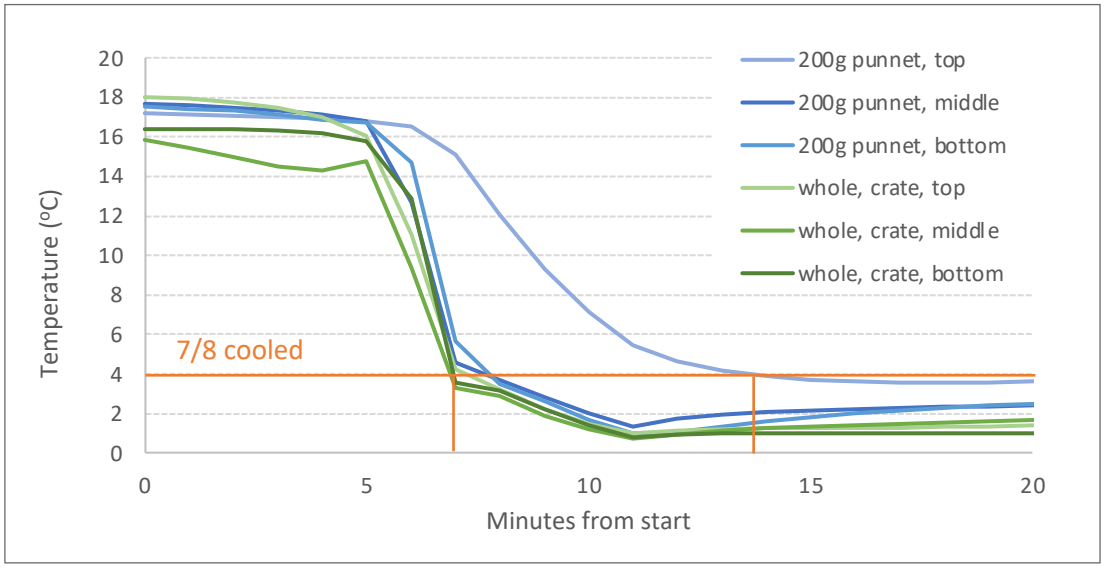

Figure 8. Pulp temperatures during vacuum cooling of packed punnets and loose crates of mushrooms in the top, middle and bottom of pallets. Temperature fell from 17°C at harvest to a target of 2°C; mushrooms were 7/8 cooled once they were 4°C; most reached this in 7 to 8 minutes.

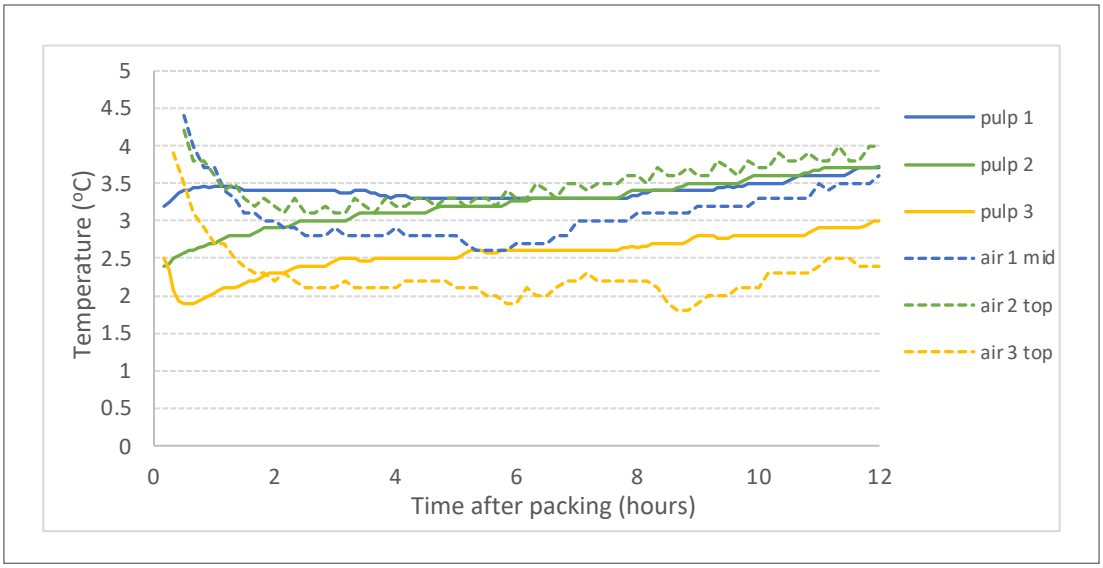

Figure 9. Pulp and air temperatures inside cartons containing sliced mushrooms on three pallets in a single storage room. Cartons were located centrally in the stack (pallet 1) or two from the top (pallets 2 and 3). The cold room was running at approximately 2.2°C.

above zero. It is important to not go any lower as this will freeze the mushrooms.

As cooling is by evaporation, mushrooms inevitably lose some moisture during vacuum cooling; approximately 1% for every 6°C change. However, they can easily lose more weight during room cooling, as the process is much slower.

Unlike other cooling methods, vacuum coolers are unaffected by packaging (as long as water vapour can escape), with cooling fairly uniform through the load.

Vacuum coolers can operate based on a timed cycle or using a probe inserted into the product. The cycle stops once the probe reaches the target temperature. Using a probe prevents 'overcooling', avoiding excess weight loss and energy consumption.

However, if a probe is used, it is essential it is inserted into the largest size mushroom being cooled, with the tip accurately located in the mushroom core.

In this example shown in Figure 8, mushrooms in 200g punnets cooled at the same rate as those in open crates – with a single exception. While 5 of 6 probes reached 7/8 cooled in less than 8 minutes, one took nearly 14 minutes.

The most likely reason for this is that the probe was not fully in contact with the mushroom flesh. Probes measure temperature right at their tip, so if this does not have good contact with the flesh, it will measure air temperature instead. In a vacuum cooler, air temperature falls more slowly than product temperature, so this is not a good measure of cooling.

It is notable that 7/8 cooling was achieved in a few minutes using a vacuum cooler, compared to around 12 hours with room cooling. This difference is likely to have significant impact on quality and shelf life.

ENERGY EFFICIENCY

Cold rooms are good for storing mushrooms, but inefficient at cooling them.

Typically, 5 to 15% of the total load on the cold room is due to transmission of heat through the roof, walls, and floor. If the walls are exposed to direct sunlight this will be much higher. Another 10 to 20% of energy load can be due to internal factors such as people, machinery, lights, fans, and equipment. Depending on how often the door is opened, there may be up to 10% additional load due to warm air infiltration.

This means that only around 55 to 75% of the total energy used by the cold room is actually cooling the mushrooms. If this is not enough to remove the heat energy produced by respiration, the room will be unable to maintain its setpoint, let alone provide cooling.

Using a forced air system dramatically reduces cooling time. Cooling products faster increases the energy efficiency of cooling from 10 to 30% (room cooling) to an estimated 70 to 75%.

However, forced air is still less efficient than vacuum cooling, which is 80 to 85% energy efficient. This is because nearly all of the energy consumed extracts heat from the mushrooms, rather than cooling the air and materials around them.

KEEPING MUSHROOMS COLD

Cooling mushrooms can be thought of as adding value with electricity. Allowing the mushrooms to warm back up cancels that value.

However, this can be harder than it seems, especially once mushrooms are punnetised, packed, and palletised. Their rapid respiration rate can easily increase temperature inside the unventilated punnet.

If heat cannot readily transfer to the surrounding air, then the mushrooms will start to warm up. Higher temperatures mean faster respiration, creating a heat 'snowball'.

In the example shown in Figure 9, pulp temperatures of sliced mushrooms packed into cardboard cartons

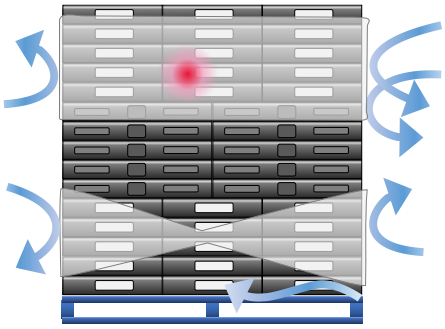

Figure 9. There is little airflow through pallets of packed stock, especially if they have been plastic wrapped to stabilise the load. Without airflow, heat energy produced by the mushrooms cannot be removed, potentially allowing hot spots to develop.

were warmer than the surrounding air in two of three monitored pallets. Both air and pulp temperatures trended upwards during storage, even though the room remained at 2 to 2.5°C and there was good airflow around the pallets. This demonstrates the difficulty of removing heat from packed mushrooms, especially when inside wrapped pallets.

MANAGE THE RISK OF WARMING

Techniques to help reduce risk include:

- Handle mushrooms gently, especially sliced product, as damage increases respiration rate
- Cool mushrooms thoroughly, preferably using vacuum cooling
- Don't wrap pallets until despatch, so as to allow air movement through the crates / cartons
- Maintain air flow around pallets
- keep them well spaced inside the cold room
- leave a gap of at least 20cm between pallets and the walls
- Add a fan to circulate air around the room
- Check the room insulation, making sure it is sealed against moisture
- Minimise door opening and consider adding air curtains or airlocks to reduce ingress of warm external air
- Ensure the room cooling capacity is sufficient to remove the heat generated by respiration at peak loading

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Hort Innovation MUSHROOM FUND

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Key points

- Temperature is a measure of the kinetic energy carried by molecules.
- Temperature is the primary factor affecting mushroom storage life and quality, influencing weight, colour, firmness, and bacterial growth.
- Mushroom respiration generates heat, with higher temperatures increasing respiration rates and, therefore, heat.
- Cooling rate depends on the cooling medium, product surface area, thermal conductivity, and temperature differential.
- Room cooling, forced air, and vacuum cooling are common cooling methods, with vacuum cooling being the fastest and most energy efficient.
- Room cooling is slow and likely to result in condensation, reducing mushroom quality and storage life.
- Once mushrooms are cold, preventing re-warming is crucial for maintaining quality.
- Strategies to limit re-warming include thorough pre-cooling, maintaining airflow through and around pallets, reducing ingress of warm air and ensuring the cold room is operating efficiently.

FACTSHEET

MEASURING TEMPERATURE

MushroomLink

Dr Jenny Ekman

Measuring temperature is not as straightforward as you might think.

Temperature cannot be measured directly. Temperature measurements record the effect of heat energy on a thermometer or probe.

It is essential to ensure that the probe is correctly calibrated, so that the measurement is accurate.

Managing temperature is critical to maintain postharvest quality. It is also essential to meet retailer specifications, which often require that mushrooms are delivered below 5°C. Given a usual storage temperature of 2-3°C, followed by transport and potentially some 'self heating' inside the punnets, pulp temperatures at delivery can easily approach that 5°C limit.

A correct measurement method with a reliable probe is vital.

KEY POINTS

- Mushrooms must be delivered to retailers' DCs below 5°C
- Self-heating during transport can bring mushrooms close to this limit
- Given this tight range, it is very important that temperature probes are working properly
- When calibrating:
  - Liquids provide the best medium for calibration.
  - A slurry of melting ice provides a reliable and accurate measurement of 0°C
- When measuring:
  - As the probe may transfer some heat, insert into the mushroom or punnet and allow the reading to stabilise
  - Remove and re-insert, ensuring the tip of the probe has good contact with the mushroom flesh
  - Wait at least 10 to 15 seconds before recording temperature

STEP 1 - PROBE CALIBRATION

The best way to calibrate a probe is in liquid, using a melted ice slurry.

Calibration in air is **not recommended** as air is a poor conductor of heat. If a reference thermometer is used to calibrate in air, significant gradients can exist between it and the probe being assessed, no matter how close together they may be.

In contrast, water is a good conductor of heat, being 24x more efficient than air. Gentle stirring further eliminates any potential temperature gradients within the medium.

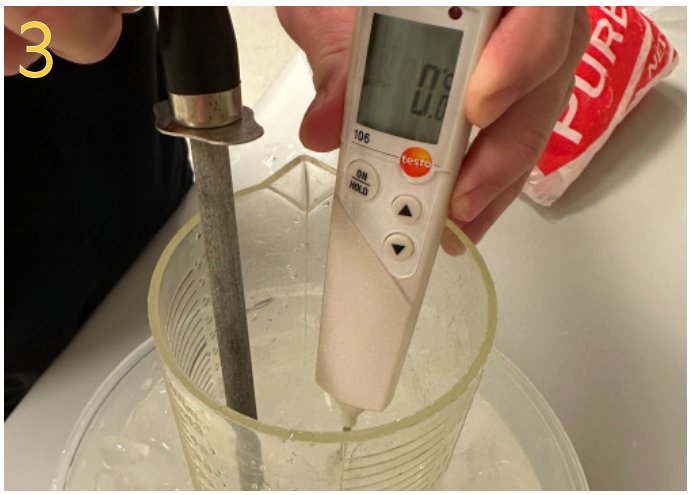
Probes should be calibrated at temperatures close to those expected in the product; calibrating a probe at room temperature will not necessarily translate to an accurate measurement at 3°C.

The best medium to calibrate probes is a slurry of melting ice. This provides a reliable and accurate measurement of 0°C, so is close to the target temperature of the mushrooms.

- Obtain a large thermos or construct a double insulated vessel for the calibration
- Crush some ice and place in the thermos or in the central part of the double vessel (fill the outside of the vessel with ice to insulate the inner part)
- Add just enough water just to cover the ice, stir, and allow to equilibrate for at least 5 to 10 minutes
- While continuously stirring the ice slurry, place the probe into the ice and wait for the reading to stabilise
- If the probe does not read zero, record the variation (+/-) and calibration date on a sticker and attach it to the probe

Place ice in a ziplock bag and crush with a hammer

Add crushed ice to thermos or double insulated vessel and just cover with water



Stir melting slurry and allow to equilibrate. Keep stirring while the probe stabilises, record variation from 0°C

STEP 2 – MEASURING TEMPERATURE IN PUNNETS

Note that some probes come with a default 'hold' mechanism. Once the temperature is stable for five seconds, the probe will keep that temperature on the display. However, five seconds may not be long enough for true temperature stabilisation.

It is recommended that either the hold feature is turned off, or that it is increased to a longer period, say 10 to 15 seconds.

Temperature probes often work by measuring the different expansion coefficients of metals in response to temperature. This measurement occurs right at the tip. It is important that the tips of probes are treated carefully, and not forced into or through hard objects.

The tip of the probe needs to be placed in the core of the mushroom measured. However, the probe itself may also transfer some heat. To ensure this does not impact the measurement:

- Insert the probe into the core of a mushroom and allow it to stabilise
- Remove the probe and re-insert into a different mushroom, choosing one at the centre of the punnet
- Record the temperature once temperature is stable for at least 10 to 15 seconds

In the case of sliced mushrooms, it is virtually impossible to measure pulp temperature. The best method is therefore to press down lightly on the punnet, ensuring good contact between the probe tip and the flesh. Make sure the probe tip is right in the centre, not touching the base or walls of the punnet, as this is where the actual temperature measurement is taken.

To make sure the probe is the same temperature as the mushrooms, always take one measurement, allow the probe to stabilise, then take a second measurement of a different mushroom or location in the punnet. Ensure the probe tip is in the core of the mushroom or centre of the punnet.

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Australian Mushroom Supply Chain

BEST PRACTICE GUIDE

Hort Innovation MUSHROOM FUND

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CONTENTS

1. INTRODUCTION

Consistent mushroom quality at retail is essential to keep consumers satisfied – and buying more mushrooms. Maintaining quality through the supply chain depends on many factors, including effective preharvest management, well managed harvesting and packing operations, postharvest treatments and temperature control.

Drawing on the latest international research, as well as data collected in 2024 from Australian mushroom supply chains, this guide aims to summarise best practice for mushroom supply chains, from grower to transport to retailer. It includes guidelines on how the key factors affecting mushroom quality can be managed in order to supply consistent, high-quality mushrooms to customers and the end-consumer.

This guide is suitable for all supply chain participants, from grower to retail. "If we can manage the supply chain properly, we reduce rejections at distribution centres, improve retail quality, minimise waste, and ensure food safety" – **Dr Jenny Ekman,** Project Leader, MU22011.

2. PRE-HARVEST

Postharvest operations can only deliver high quality mushrooms if they are grown well from the start. Growing procedures affect both initial quality and that remaining at the end of the supply chain. Although each farm is different, there are common pre-harvest factors that directly affect postharvest quality.

BEST PRACTICE

- ✓ **To reduce bruising and browning:**
  - Choose a low browning variety
  - Optimise irrigation, humidity and nutrition during production
  - Keep the crop well-nourished and control disease
- ✓ **Balance airflow around the growing room to:**
  - provide even control of temperature and relative humidity (>85%)
  - manage CO_2 levels through the cropping cycle
  - avoid scaling due to higher air movement
- ✓ **Avoid overpinning beds**
- ✓ **Manage irrigation to:**
  - Maintain water content in casing and compost during flushing
  - Minimise time that mushroom caps remain wet after irrigation

2.1. Growing room environment

Temperature, humidity, and airflow in growing rooms have a huge impact on mushroom quality. However, balancing ventilation requirements with maintaining stable temperatures can present some challenges.

For example, high CO_2 levels can result in stipe elongation, stretched veils, and smaller caps. Managing CO_2 accurately and uniformly within the room is difficult without adequate airflow. However, rapid airflow, particularly if humidity is below 85%, can result in mushrooms that are 'scaly' and sensitive to bruising.

Quality is greatly reduced if beds are over-pinned. Growers can influence pinning by manipulating temperature, air speed, humidity, CO_2, bed moisture, casing and mycelium structure. This is clearly a complex topic. Whichever way it is managed, keeping mushrooms well-spaced on the beds is an essential first step to picking good quality mushrooms.

There is often a balance between quality and yield. For example, mushrooms with high dry matter may be firmer and whiter, increasing shelf life. However, factors that increase dry matter, such as increased salt concentrations in casing and high levels of calcium tend to reduce yield (Figure 3).

Figure 1. Monaghans Mushrooms in the UK uses perforated plastic wrap to reduce airflow over the lower bed, as well as a soft air delivery system to distribute air evenly through its 70m long growing rooms.

Figure 2. Slight scaling due to increased airflow on the outer edge of the bed; inner mushrooms are not affected.

2.2. Irrigation

Mushrooms are 90 to 95% water, so the quality of water used and when it is applied, inevitably affects quality and storage life.

- Too little moisture produces low yields of soft, scaly, easily bruised mushrooms.
- Too much water increases risk from bacterial blotch, while water pooling on mushroom caps can leave discoloured watermarks.

It has been estimated that 20 to 50% of the water in mushrooms comes from the casing, with the remainder from the compost. It is therefore important to keep the casing layer moist throughout the production cycle. This can be challenging, as flushing pulls large volumes of water out of the substrate.

If a heavy first flush results in dry casing and/or compost for the second flush, these mushrooms will be discoloured and susceptible to premature opening. Yield and quality are best when water content is kept stable (approximately 60% by volume), with casing never allowed to dry out.

2.3. Managing disease

A range of diseases affect mushroom quality and yield, including Trichoderma (*Trichoderma aggressivum*), dry bubble (*Lecanicillium fungicola*) and cobweb (*Cladobotryum mycophilum*). While sometimes devastating, affected mushrooms are unlikely to be harvested and packed.

In contrast, while bacterial blotch (*Pseudomonas tolaasii*) can occasionally devastate mushroom crops during production, problems more commonly appear during postharvest storage. Symptoms are due to the toxin tolaasin, which breaks down cell membranes, catalysing the formation of the brown pigment melanin.

Prolonged wetness and high humidity are key to disease development. Poorly nourished crops and later flushes are also more susceptible to disease, as bacterial populations build during cropping.

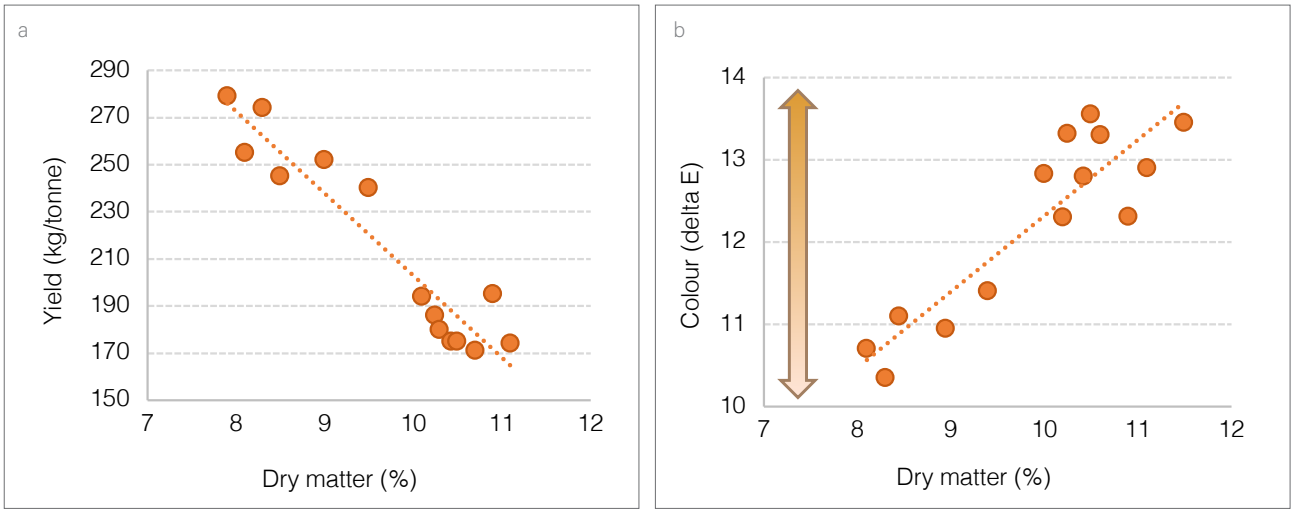


Figure 3. Relationships between mushroom dry matter and yield (a); mushroom dry matter and colour (ΔE) (b). Derived from Barry et al., 2016.

3. HARVEST AND PACKING

Harvest is where the effort that has gone into producing compost, managing the environment and growing the mushrooms finally pays off. Harvest is also often the most expensive part of production. So, it is important that harvest doesn't damage the mushrooms and that packing materials are appropriate and protective.

BEST PRACTICE

- ✓ **To reduce bruising and browning**
  - Handle gently
  - Harvest before caps open
  - Cool as soon as possible after harvest – at least within 2 hours
- ✓ **Trim stems cleanly using a sharp blade**
- ✓ **If slicing or processing:**
  - Pre-cool mushrooms first
  - Check that blades are sharp and drops are short to minimise damage
  - Clean and sanitise equipment regularly
- ✓ **Packaging should physically protect the product and minimise moisture loss while also allowing air circulation for cooling and avoiding wetness**
- ✓ **Library trays can provide a valuable record of quality if issues occur within the supply chain**

3.1. Harvest and bruising

Bruising is clearly a key issue during harvest. Even light squeezes, vibration, or compression on overpinned beds can trigger browning reactions. Bruising occurs when cell membranes are disrupted. This allows cell contents to mix and form melanin, the same compound triggered by bacterial blotch bacteria (Figure 4).

Mushrooms bruise easily because of a layer of relatively fragile, low-density cells located in between the cap surface and the higher density core. Browning reactions are not instantaneous but develop over time. This means that damage may not be obvious for 24 hours, by which time mushrooms have reached the distribution centre or retail (Figure 6).

Factors that increase the likelihood of bruising include:

- Warm storage temperatures – bruise development is reduced at lower temperatures
- Maturity – mushrooms with open caps are often more susceptible to bruising than those with closed caps
- Time from harvest – susceptibility increases as mushrooms age during transport and retail
- Flush – third flush mushrooms are often more easily bruised than those from earlier flushes
- Variety – some varieties are bruise-resistant, possibly due to lower levels of polyphenol oxidases

Low humidity, disease and senescence also all increase mushroom browning (Figure 5).

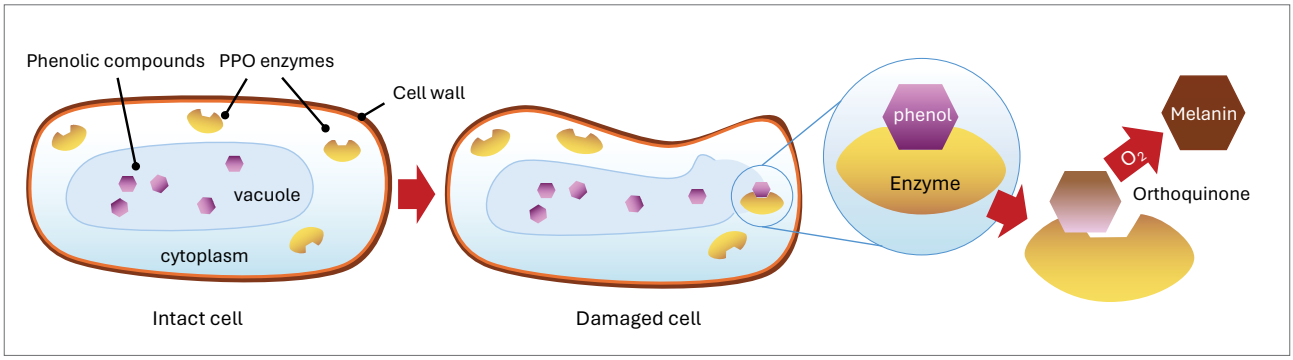


Figure 4. Mushrooms bruise because of disruption of the internal membranes in cells. This allows phenolic compounds normally held in the cell vacuole to mix with polyphenol oxidase (PPO) enzymes in the cytoplasm. The enzymes catalyse the formation of orthoquinones, which further oxidise over time, forming the brown compound melanin.

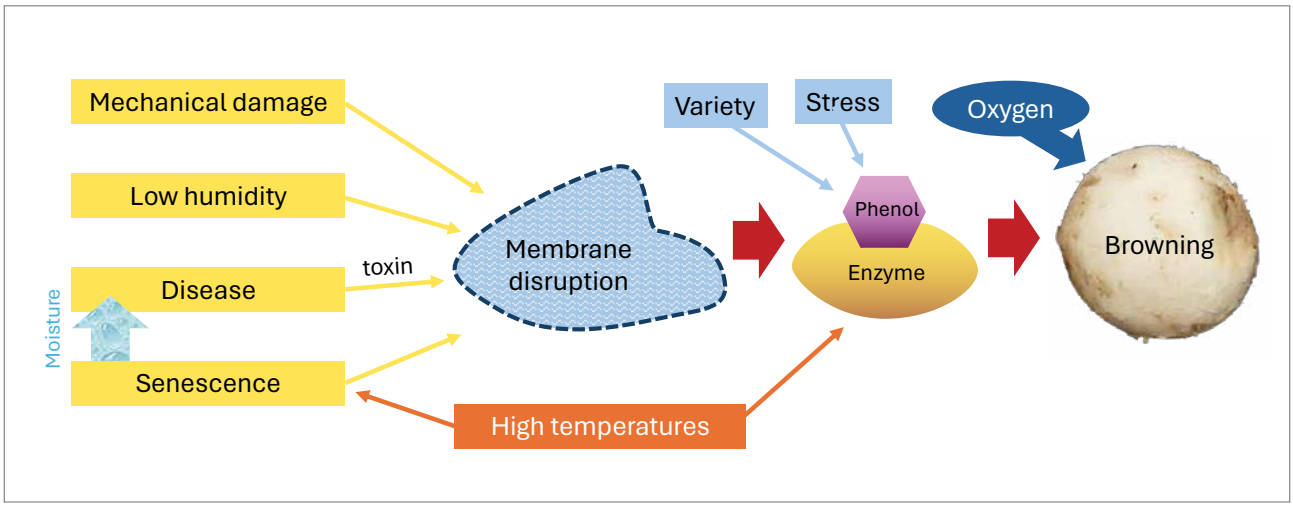
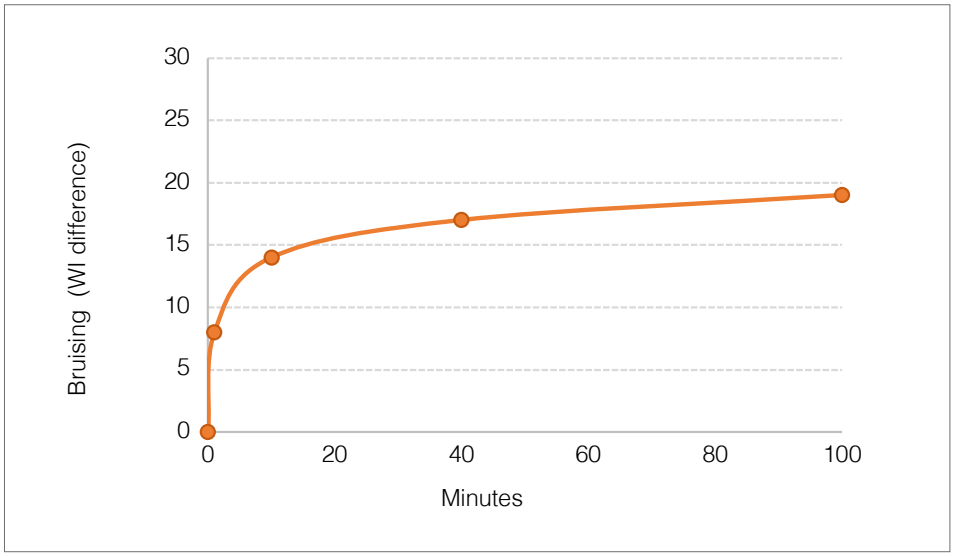


Figure 5. A range of factors can cause browning in addition to bruising and other physical damage. High temperatures, stress during production and variety can increase the intensity of browning reactions.



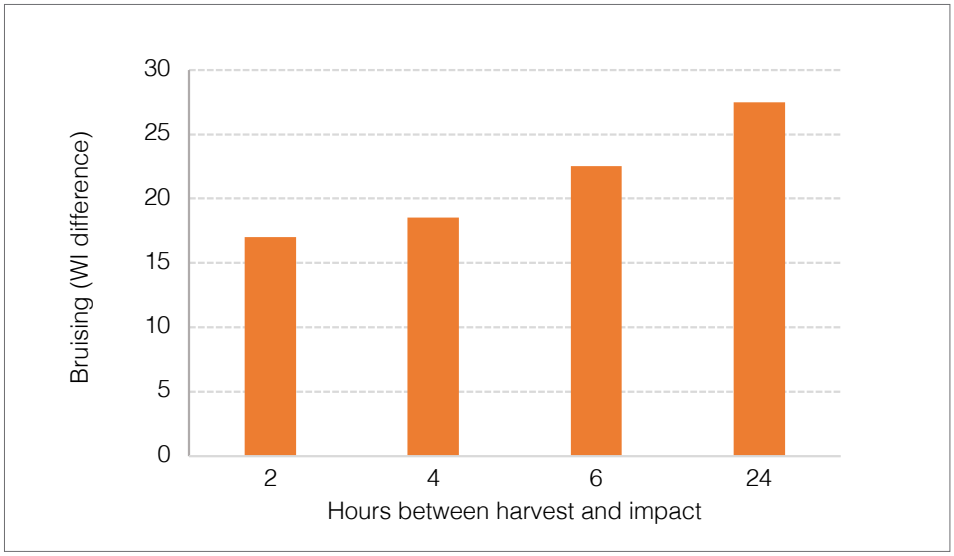


Figure 6. Bruises continue to darken after the impact has occurred (top) and are more intense as the interval between harvest and when damage occurs increases (bottom). Bruising expressed as change from white (WI difference), trials conducted at 20°C. Derived from Weijn et al., 2012

Figure 7. Harvest aids that make it easier for workers to see and pick mushrooms, such as the moving drawer system (left) or tilting shelves (right), may help to reduce bruising during harvest.

Tilting shelves, moving drawers, bed scanners and laser pointers are all designed to save cost on that most expensive part of mushroom production – picking and packing. From the viewpoint of postharvest quality, any technology that makes it easier for pickers to reach the mushrooms and/or minimises handling is also likely to reduce damage (Figure 7).

Conversely, one of the challenges with using robotic pickers is avoiding damage. It is difficult to match the sensitivity of human hands with suction cups and robotic fingers.

3.2. Trimming

Like the mushroom cap, mushroom stems contain reserves of sugars. These can move into the cap postharvest, allowing the mushroom to continue to open and spores to mature. Leaving stems long (30-35mm) can increase cap opening and browning during storage.

Stems should be trimmed straight using a sharp knife. Blunt cuts and tears increase stem browning, often seen as an indicator of freshness.

3.3. Processing

- Mushrooms are frequently sold pre-sliced, or sometimes otherwise processed. To reduce browning and maximise quality and shelf life:
  - Pre-cool mushrooms thoroughly before slicing
  - Conduct slicing in a cool area (as close as possible to 5°C) to reduce re-warming
  - Return sliced product to the coolroom promptly
  - Ensure cutting blades are kept sharp
  - Limit drops on the packing line to reduce further damage

Slicing, as with other forms of damage, stimulates respiration. It is important to remove heat generated by respiration from sliced product, keeping it below 5°C at all times. Good temperature management for processed product is not only important for quality, but also for food safety.

Equipment used to slice or process mushrooms must be regularly cleaned and sanitised.

3.4. Packaging

Packaging does more than just contain a certain weight and volume of mushrooms. It can protect mushrooms from physical damage, minimise moisture loss and prevent movement that would otherwise result in bruising. Packaging must provide enough ventilation for effective pre-cooling and removal of heat generated by respiration without increasing moisture loss.

Figure 8. Cardboard punnets are biodegradable, but likely to absorb moisture from the mushrooms, contributing to softening and weight loss.

Uncoated cardboard punnets can readily absorb 15% of their weight in moisture, so are likely to increase weight loss from the mushrooms.

Plastic punnets provide an effective physical barrier to damage and moisture loss. The downside is that puddles can form if temperature fluctuations cause condensation. Ridges and moulding in the punnet base are used to reduce the chance of free water contacting the mushrooms.

Although the stretchable films used to overwrap punnets are plastic, some water vapour can move through them. This means they provide a good barrier to moisture loss while minimising the risk of condensation. Tight overwrapping also stops mushrooms moving in punnets.

3.5. Library Trays (reference trays)

Library trays are a great way to check postharvest quality. Retaining a few punnets from each packout provides a valuable record if issues occur in the supply chain.

Record grow room, harvest date, and pack date. Library trays should be cool stored at 4 to 5°C (normal refrigeration temperatures) until the best before or use by date, then assessed as needed for quality assurance.

4. COOLING

Temperature is the key postharvest factor determining the storage life of fresh mushrooms. It affects weight loss, colour change, firmness, stipe elongation, cap opening, bacterial growth and overall freshness. While there are many things growers can do to improve quality at harvest, it is the temperatures that mushrooms experience afterwards that are key to determining the quality consumers experience.

BEST PRACTICE

- ✓ **Temperature is the key postharvest factor affecting quality and shelf life of mushrooms**
- ✓ **To minimise browning and moisture loss, cool mushrooms to between 2 and 4°C as soon as possible after harvest:**
  - Room cooling is slow and inefficient, increasing weight loss
  - Forced air systems are relatively cheap and significantly improve cooling efficiency
  - Vacuum cooling systems cool mushrooms extremely quickly, avoid temperature gradients through the load, can be used on packed product and are highly energy efficient

4.1. Cooling method

Cooling mushrooms as quickly as possible after harvest (within approximately 2 hours) is essential to maximise postharvest quality. Cooling slows metabolic processes and minimises weight loss, reducing cap opening and browning.

Mushrooms have a large surface area relative to their volume, and no true skin, so are easier to cool than many other horticultural products (Figure 9). However, maintaining good air flow is essential to remove heat produced by respiration (Figure 10).

Mushrooms should always be fully pre-cooled to between 2 and 4°C before storage or transport. Trucks generally lack the cooling capacity and air movement to cool mushrooms. Loading warm mushrooms into a truck will almost certainly impact quality at retail and shelf life for consumers.

Mushrooms will lose moisture while they remain warmer than the cold room air, even if the relative humidity in the room is high. This is because the warm, saturated air inside the mushrooms can physically hold more water vapour (ml/m^3) than cold room air (Figure 11, over).

Figure 9. Mushrooms cool much more easily than other products because they have a large surface area relative to their volume, lack a protective skin, and (unlike a cabbage!) do not retain pockets of trapped air within their structure.

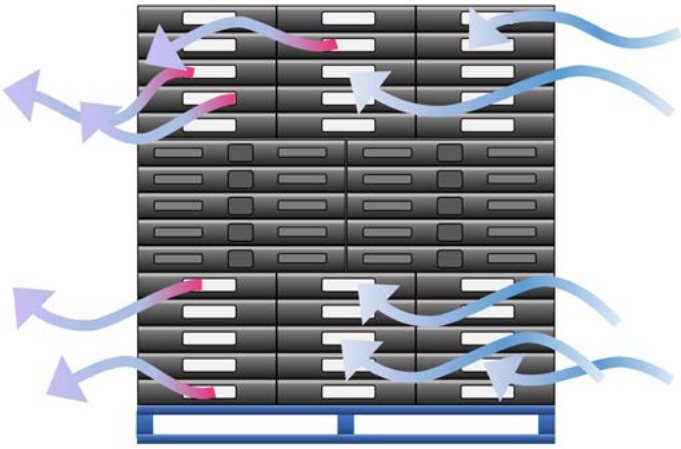


Figure 10. Cooling involves moving heat energy out from the mushrooms and into the surrounding air. Good air circulation, such as that provided by well vented cartons, helps this to occur.

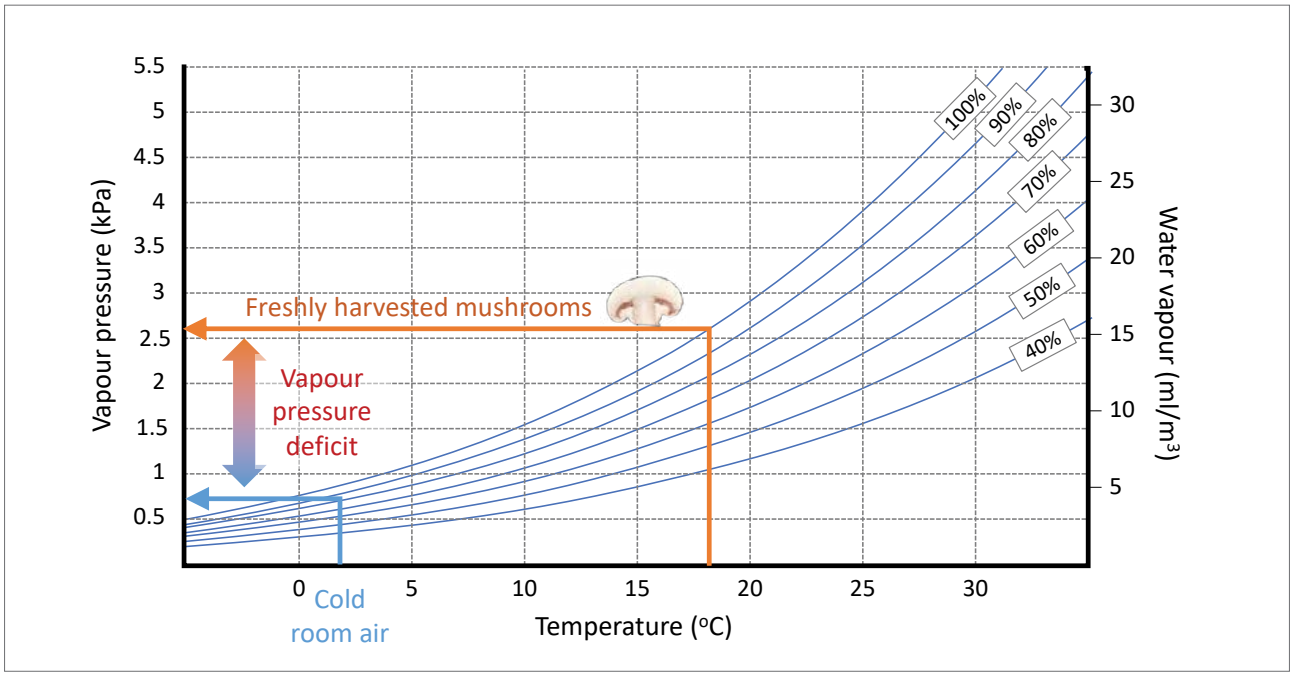


Figure 11. The relationship between relative humidity (RH), temperature and the partial pressure of water vapour is described by the psychrometric chart. The tissues inside mushrooms will always be close to 100% RH. If they are warmer than the cold room air, the difference in vapour pressure between the inside and outside of the mushrooms will cause them to lose moisture.

The volume of water vapour molecules held in the air is described as the partial pressure of water vapour. As molecules always move from high to low concentrations, water vapour will move from the warm air spaces inside the mushrooms into the lower partial pressure of the surrounding air.

The best cooling method for mushrooms is therefore the fastest one available.

4.1.1. Room cooling

Room cooling is when mushrooms are simply placed into a cold room. Room cooling is easy, but slow (Figure 12).

Heat energy inside warm mushrooms needs to be removed by the cold room air. The speed at which mushrooms cool is therefore a function of the amount of air movement around them.

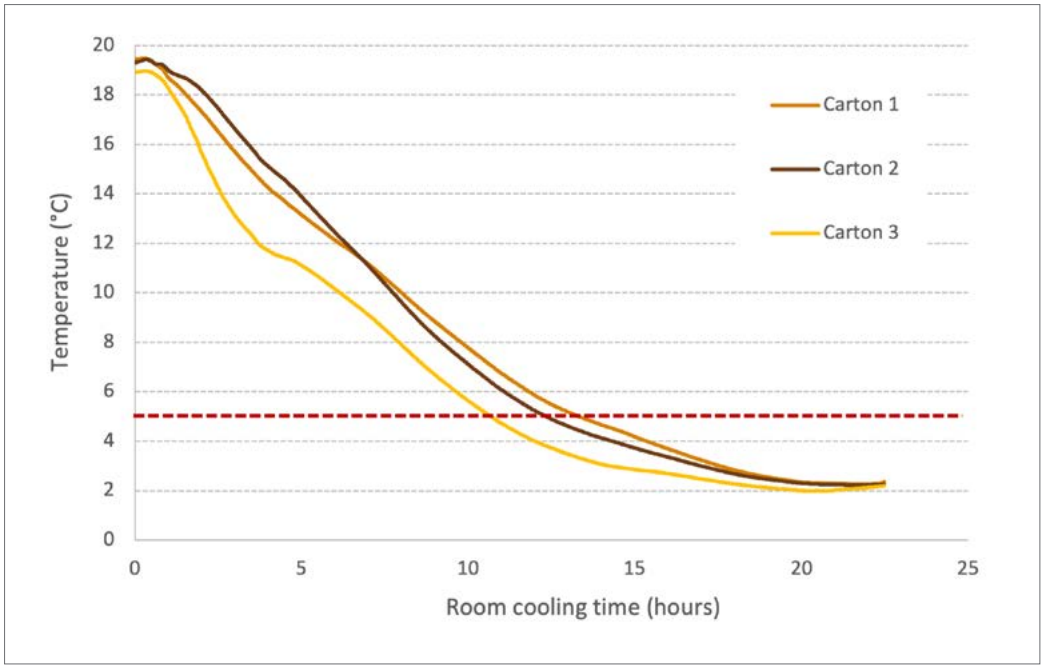


Figure 12. Temperatures of mushrooms inside cardboard cartons, placed individually inside a cold room set at 2 °C. It took 10 to 14 hours to cool the mushrooms below 5 °C. Cooling times would certainly be longer for mushrooms inside cartons packed onto a pallet.

In the example shown in Figure 12, it took 10 to 13 hours for mushrooms packed into cardboard cartons and placed in a room set at 2°C to cool to 5°C. Cooling rates would have been even slower had the cartons been at the centre of a full pallet.

Room cooling is also likely to result in condensation. As warm, humid air cools, it is able to hold less water vapour. The point at which moisture condenses out of the air is the dewpoint. Temperature gradients result in condensation on mushrooms, the inside of packages, and even in different parts of the cold room.

4.1.2. Forced air cooling

Forced air cooling can be conducted where limited cooling capacity is available. Forced air systems actively move the cold room air across the product, removing heat. By pulling air past packed product, they effectively increase the heat-conducting surface area from the outside of pallets to the products inside. This can increase the rate of cooling more than 10-fold.

As forced air systems move air from cold to warmer parts of the load, condensation does not occur. Actively moving the air also minimises temperature variability within the load.

A simple forced air system can be set up with a fan, a 'plenum' and a tarpaulin (Figure 13). The key is to pull air evenly past the mushrooms.

Using a forced air system is relatively cheap and can dramatically reduce cooling time compared to room cooling. As a result, it has been estimated that forced air systems increase the energy efficiency of cooling from approximately 30% (room cooling) to between 70 and 75%.

4.1.3. Vacuum cooling

The best, fastest and most energy efficient way to cool mushrooms is vacuum cooling (Figure 14). Vacuum coolers cool product uniformly through the entire load, resulting in consistent quality and shelf life. They are also unaffected by packaging, so long as water vapour can escape.

Vacuum coolers work by reducing air pressure inside the chamber. At low air pressure, water inside the mushrooms turns from liquid into gas. This 'phase change' absorbs energy from the surroundings, cooling the mushrooms.

Mushrooms inevitably lose some moisture during vacuum cooling; approximately 1% for every 6°C change. However, this is likely to be less than during room cooling, as the latter process is much slower.

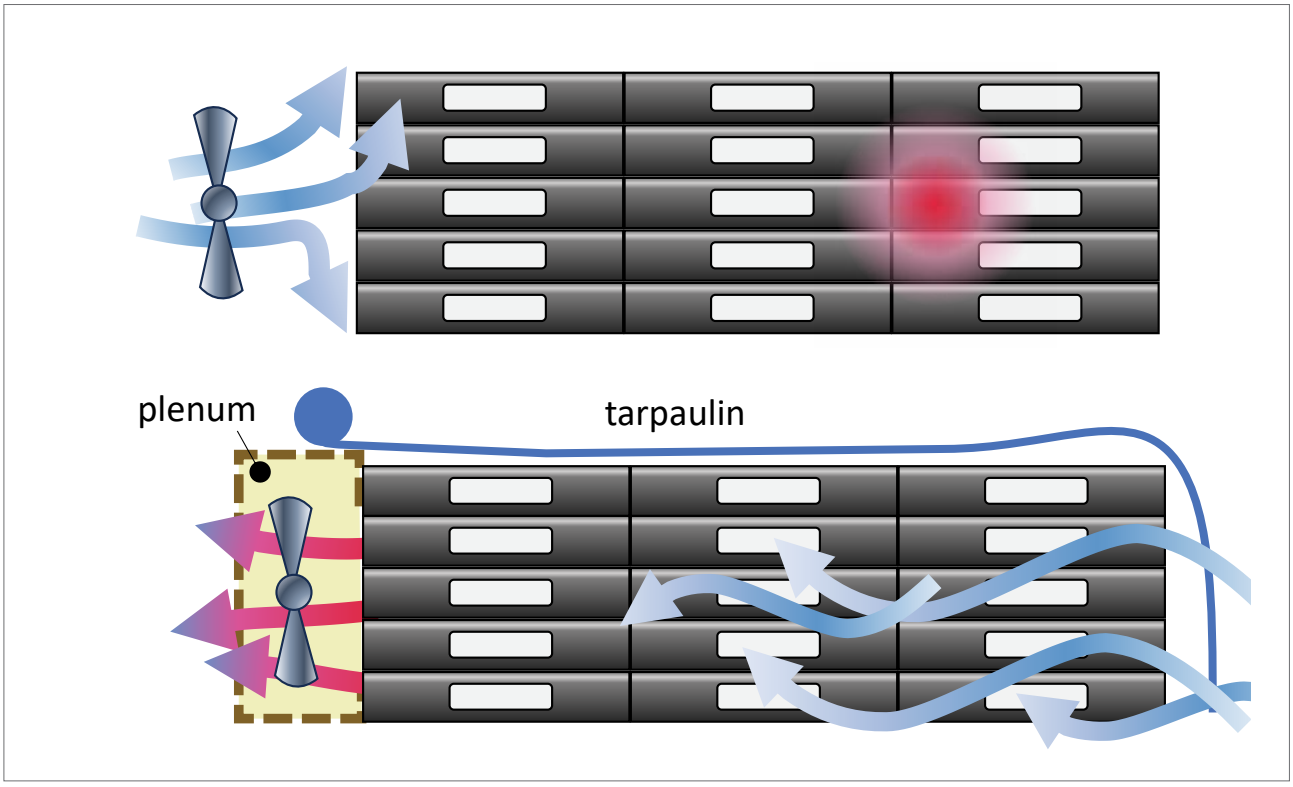


Figure 13. A simple forced air system with fan, plenum and tarpaulin (top), actively guides air through crates of packed mushrooms. This provides far more effective cooling than blowing air around a pallet (bottom).

Vacuum coolers can operate based on a timed cycle or using a probe inserted into the product. The cycle stops once the probe reaches the target temperature. Using a probe prevents 'overcooling', avoiding excess weight loss and energy consumption.

However, if a probe is used, it is essential it is inserted into the largest size mushroom in the load. It is also important to locate the tip accurately in the mushroom core. Mushrooms cool faster than the air inside a vacuum cooler; if the probe measures the air the cycle will run longer than needed. Probes measure temperature at the tip, not along their length.

Vacuum coolers need to seal well in order to operate efficiently. Figure 14 compares vacuum coolers at three different farms. The newer unit at Farm C drew down more quickly than the small chamber at Farm A and an older unit at Farm B. However, all three coolers reduced mushroom temperature below 5°C within 10 minutes of operation. This is extremely fast, especially when compared to 13 hours for room cooling to the same temperature.

Vacuum coolers are an expensive capital outlay. However, in the long term costs are reduced as vacuum cooling is 80 to 85% energy efficient. This is because nearly all of the energy consumed extracts heat from the mushrooms, rather than cooling the air and materials around them.

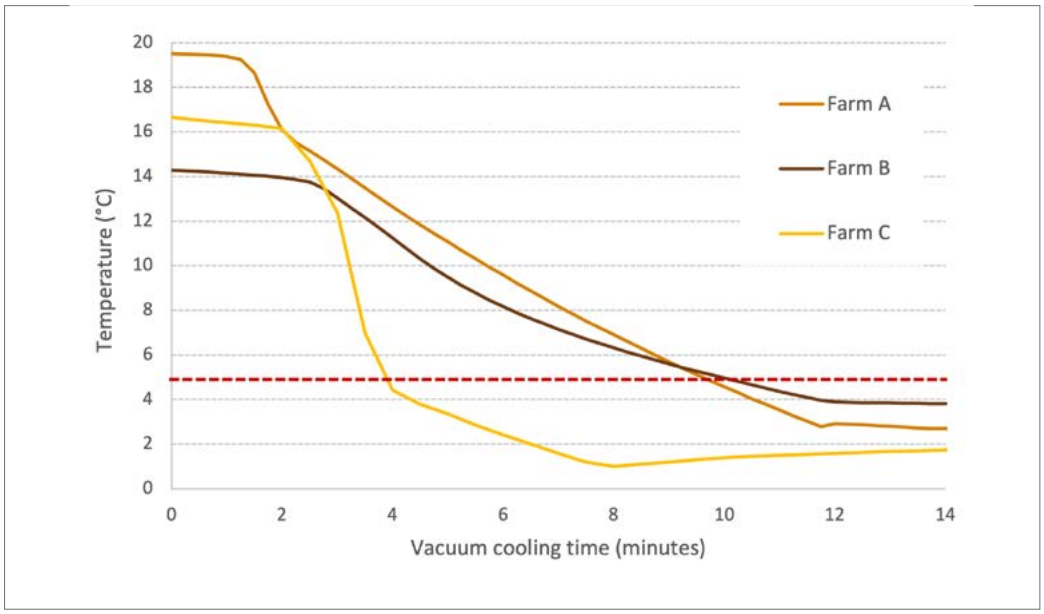


Figure 14. Pulp temperatures during vacuum cooling of packed punnets and loose cartons of mushrooms, average values from three farms with different equipment. All coolers took less than 10 minutes to cool mushrooms below 5°C

Figure 15. Two types of vacuum cooler used for mushrooms

5. STORAGE

Cooling mushrooms can be thought of as adding value with electricity. Allowing the mushrooms to warm back up after cooling cancels that value.

BEST PRACTICE

- ✓ **Cool mushrooms thoroughly before storage and transport, preferably using vacuum cooling**
- ✓ **Delay wrapping pallets until close to despatch so as to allow air movement through the crates / cartons**
- ✓ **Maintain air flow around pallets**
  - keep them well spaced inside the cold room
  - leave a gap of at least 20cm between pallets and the walls
- ✓ **Add a fan to circulate air around the room**
- ✓ **Check the room insulation, making sure it is sealed against moisture**
- ✓ **Minimise door opening and consider adding air curtaining or airlocks to reduce ingress of warm external air**
  - Ensure the room cooling capacity is sufficient to remove the heat generated by respiration at peak loading

5.1. Cold room efficiency

Cold rooms are good for storing mushrooms, but inefficient at cooling them.

Typically, 5 to 15% of the total load on the cold room is due to transmission of heat through the roof, walls, and floor. If the walls are exposed to direct sunlight this will be much higher. Another 10 to 20% of energy load can be due to internal factors such as people, machinery, lights, fans, and equipment. Depending on how often the door is opened, there may be up to 10% additional load due to warm air infiltration.

This means that only around 55 to 75% of the total energy used by the cold room is actually cooling mushrooms. If this is not enough capacity to remove the heat energy produced by respiration, the room will be unable to maintain its setpoint.

For example, using mean respiration rates of mushrooms, it can be calculated that a kg of mushrooms at 19°C produces nearly 21 kJ heat/kg/day. However, respiratory heat drops to 3.5 kJ/kg/day once the mushrooms are cooled to around 5°C (Figure 17). Every degree of cooling decreases respiration, and therefore heat energy, a little more.

To operate well, cold air must circulate well throughout the room. Leaving gaps between pallets and around the walls, adding extra fans, and avoiding blocking air delivery and return areas is essential (Figure 18).

Ccold rooms must also be well insulated, minimising entry of warm air. Foam panelling works because the air bubbles held inside are a poor conductor of heat. If panelling has been damaged by forklifts, it is no longer sealed against moisture. Water is an efficient conductor of heat, so wet panelling is ineffective.

Figure 16. Cold room air delivery systems can keep mushrooms cold, but are inefficient at cooling them

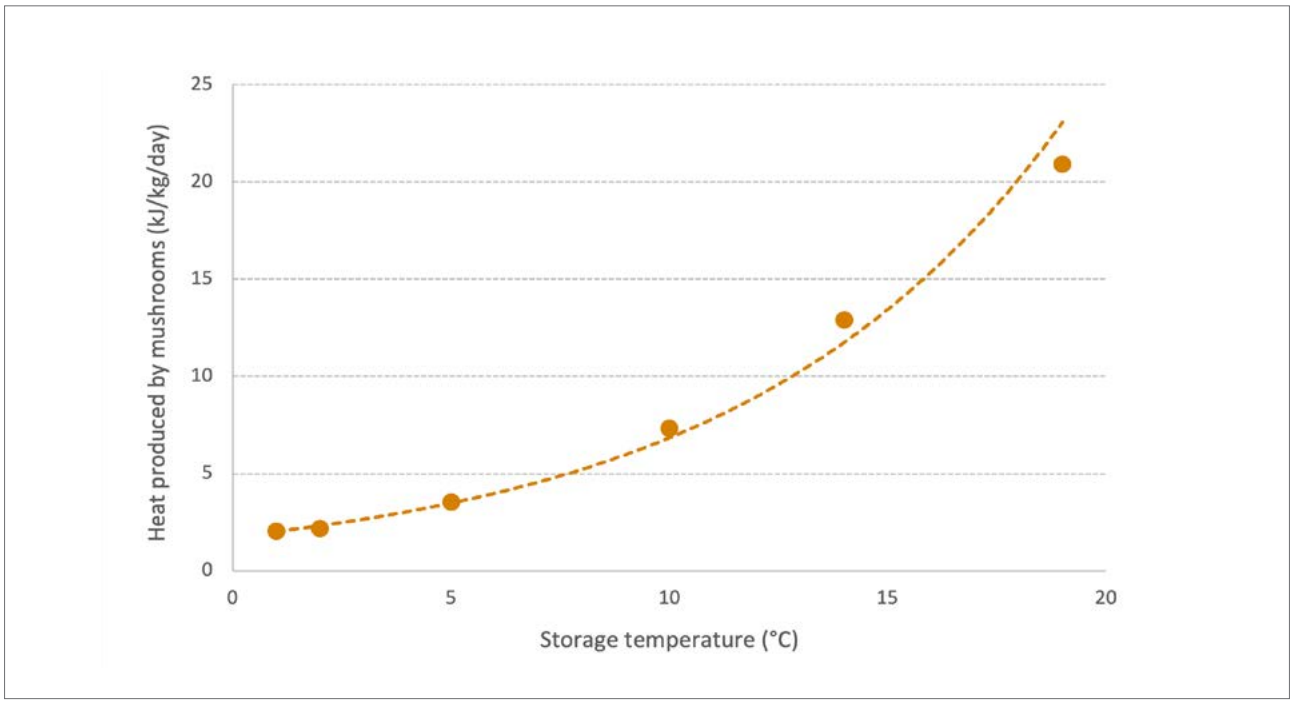


Figure 17. Effect of air temperature on respiratory heat produced by mushrooms. Respiration rates are average values from author's own data. Note this calculation is based on 6 moles CO_2 generating 2,667kJ heat (USDA, 1986), which is not verified for mushrooms.

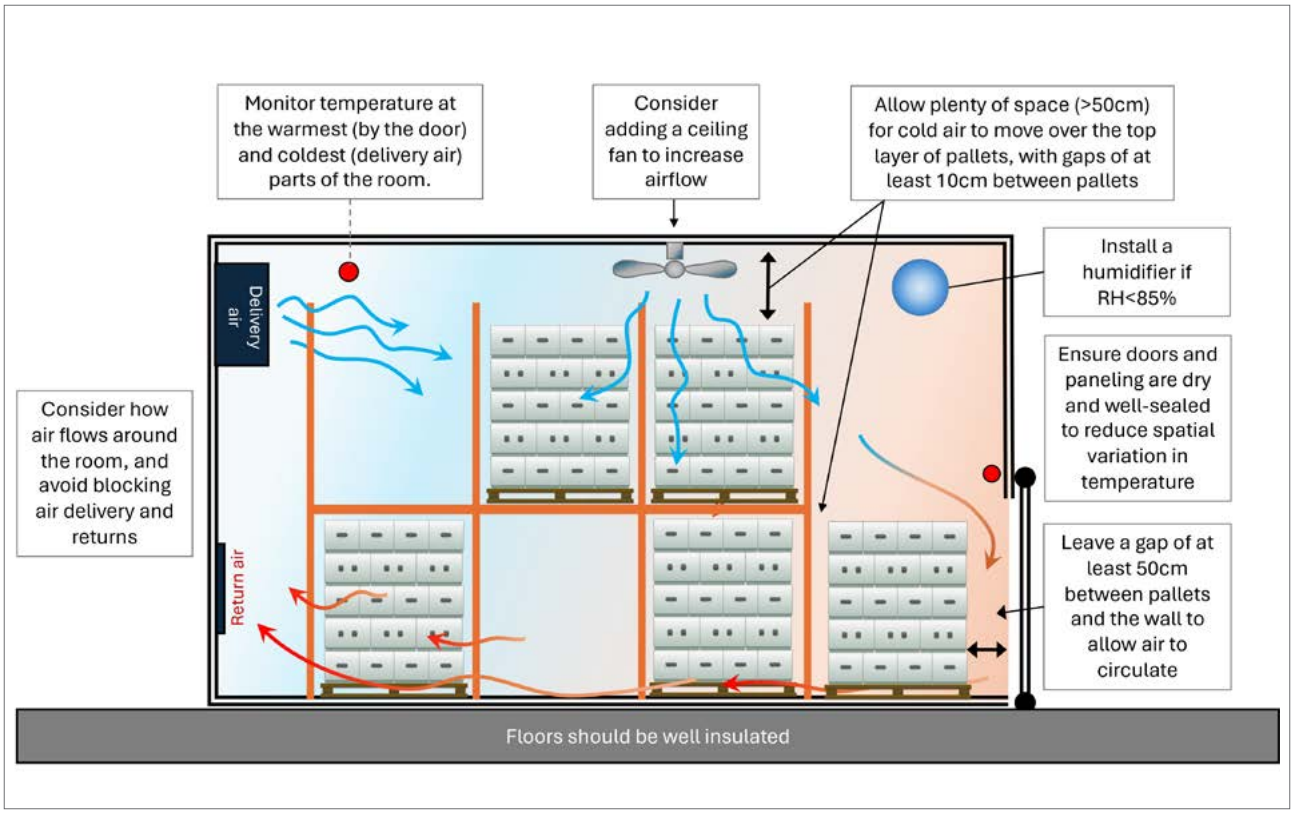


Figure 18. An ideal cold room should have good air circulation around and between pallets, effective insulation on walls and floor and a well-sealed door. Adding a ceiling fan can increase airflow, while plumbing in a humidifier can help keep RH high.

5.2. Storage temperature

While mushroom storage life is theoretically maximised at close to 0°C, the risk of freezing means they are generally held no lower than 2°C. Moreover, if acceptable storage life is considered to be 10 days after picking, then this is readily achieved at 5°C.

Between 20 and 5°C, mushroom storage life approximately doubles for every 5°C temperature decrease (Figure 19).

Minimising temperature fluctuations during storage and transport reduces the risk of condensation forming on the mushrooms or their packaging.

To ensure uniform temperature control:

- Reduce the gap between high and low room setpoints
- Minimise door opening
- Use an air curtain to reduce warm air ingress
- Pack and slice cold mushrooms in a coolroom (Figure 20)
- Ensure cold rooms are well insulated, with dry doors and panelling and intact seals
- Add fans to increase air movement around the room

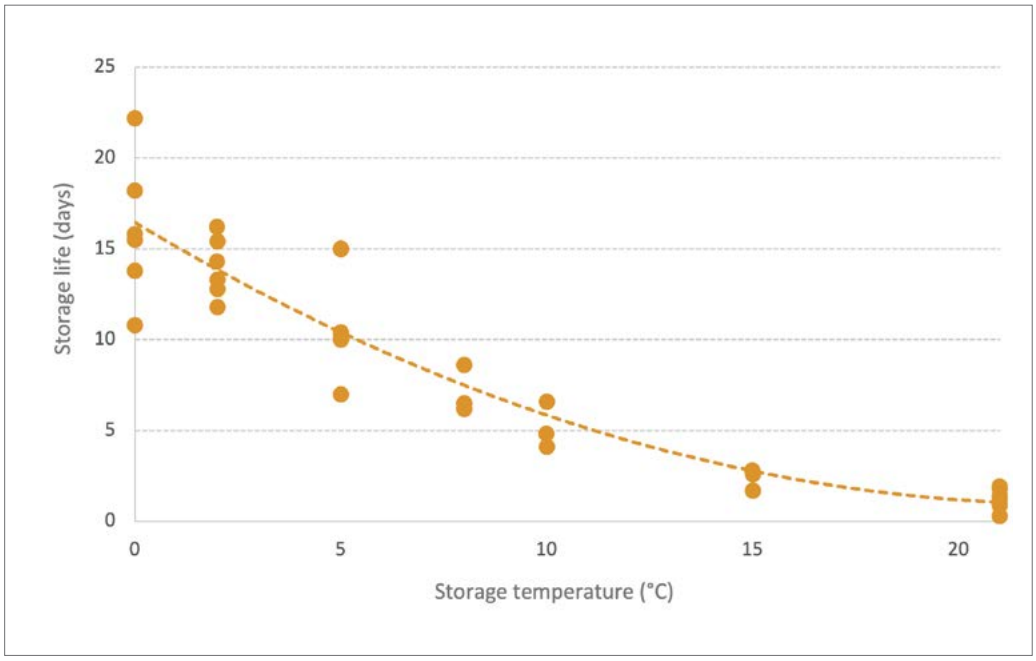


Figure 19. Effect of temperature on mushroom storage life. Author's own data.

Figure 20. To reduce re-warming of punnetised mushrooms, this farm cools the packing area to approximately 5°C and minimises the time pallets of stock are out of the cold room.

5.3. Managing the storage room

Removing heat from respiration can be harder than it seems, especially once mushrooms are put into punnets, packed, and palletised. It is difficult to transfer heat from inside punnets to the surrounding air. Higher temperatures mean faster respiration, potentially creating a heat "snowball.'

In the example shown in Figure 21, pulp temperatures of sliced mushrooms packed into cardboard cartons can be warmer than the surrounding air. In this study, both air and pulp temperatures trended upwards during storage, even though the room remained at 2 to 2.5°C.

Keeping good airflow around the pallets, being mindful of warm areas within the room, and not wrapping until necessary (Figure 22, 23) can help reduce heat build-up in stored mushrooms. If necessary, mesh type pallet wraps, rather than a solid sheet can potentially allow for more airflow through the pallet.

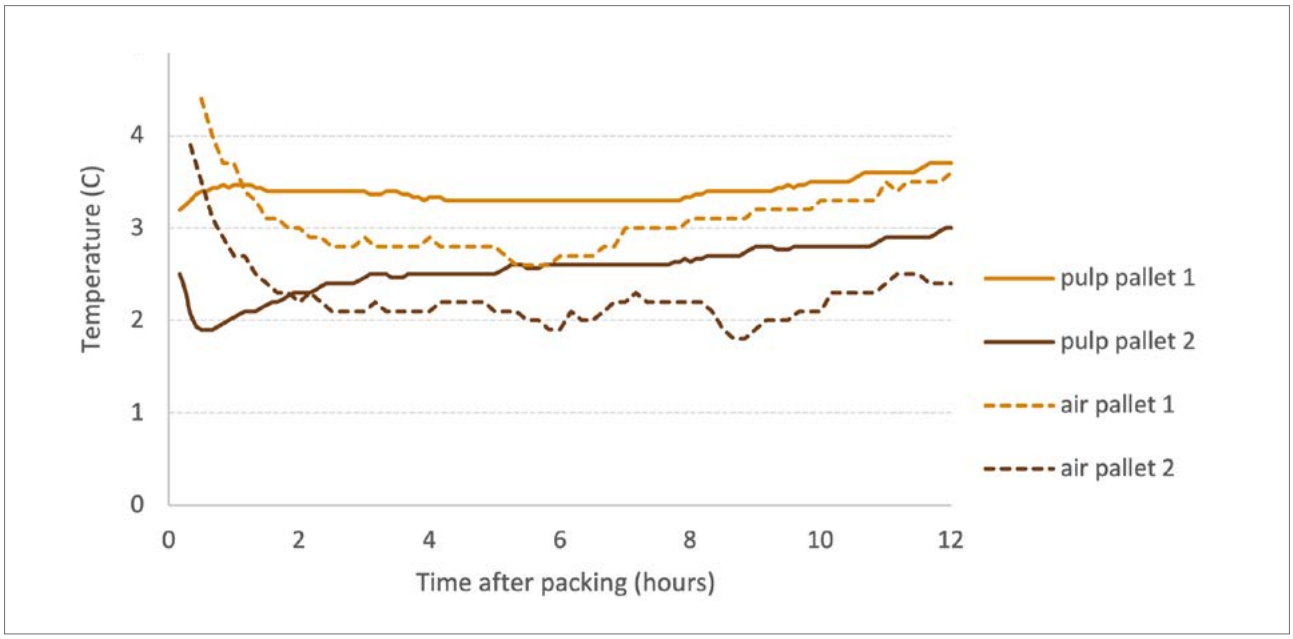


Figure 21. Pulp and air temperatures inside cartons containing sliced mushrooms on two different pallets in a cold room running at approximately 2.2°C. In both cases, the pulp temperatures are 0.5 to 1°C higher than the air, likely due to heat generated by respiration.

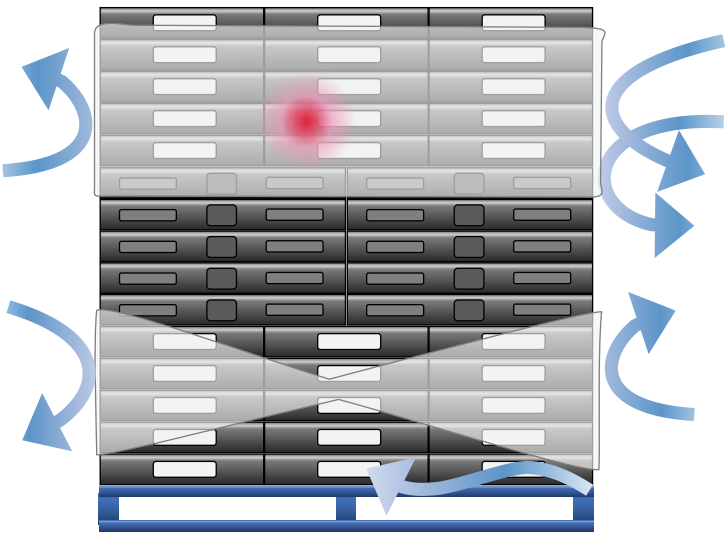


Figure 22. There is little airflow through pallets of packed stock, especially if they have been plastic wrapped to stabilise the load. Without airflow, heat energy produced by the mushrooms cannot be removed, potentially allowing hot spots to develop.

Figure 23. The fans inside cold air delivery units are relatively small. Adding a large ceiling fan, such as shown above, or vertical fans in line with those in the delivery unit, can greatly improve air movement.

6. TRANSPORT

Mushrooms are frequently transported at least twice; once to the market or supermarket DC, then again to the retail store. Farms have full or part control over transport to DC or market, where mushrooms may be the only product loaded. However, mushrooms become part of mixed loads when transported to retail stores.

BEST PRACTICE

- ✓ **Cool packed mushrooms below 5°C before transport; truck refrigeration systems are not designed to cool product and air circulation is limited**
- ✓ **Pre-cool trucks before loading**
- ✓ **Avoid exposure to ambient temperatures when loading/ unloading by using airlock systems whenever available**
- ✓ **If loading a full truck, ensure that bars and spacers used to stabilise the load do not block airflow**
- ✓ **Set truck thermostats at 2 to 4°C with the sensor placed in the delivery air (not return air)**
- ✓ **Monitor mushroom temperature during transport**
  - Temperature loggers are the best way to verify that transport temperatures are within the desired range
  - Data loggers that connect to mobile telecommunication services, providing warnings in real time, are increasingly affordable and widely available
  - Ease of data retrieval and meaningful analysis should be a key consideration when choosing a datalogger system

6.1. Loading at the farm

Mushrooms should be between 2 and 5°C before loading. Warm mushrooms should not be loaded into trucks.

Having invested in thoroughly cooling mushrooms, it is important they do not warm up during loading. If possible, load mushrooms directly from the cool room into a pre-cooled truck trailer using an air lock system.

Loading pallets is a compromise between ensuring the load is stable and allowing good air circulation around the pallets. If loading a full truck trailer:

- **Place the first pallet against the front** of the trailer to prevent delivery air short-cutting back into the cooling system (Figure 25).
- **Use foam spacers** to stabilise pallets while still allowing air gaps down the sides and centre between pallets.
- **Position stabilising bars** between rows of pallets. If using stabilising sheets ensure they do not block airflow through the load (Figure 24).
- **Ensure the trailer is fully loaded** for long distance transport, as a large space at the back will disrupt airflow.
- **Avoid using Tautliner** trucks as they have poor airflow and insulation.

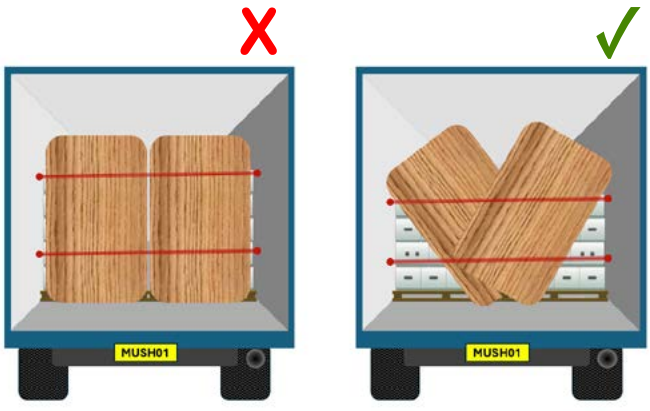


Figure 24. If using stabilisation sheets, avoid blocking airflow through the truck load (as at left), angling them as shown on the right.

6.2. Temperature management on trucks

Truck cooling systems are generally designed to maintain product temperatures, not reduce them. However, this is not always the case.

A series of supply chain studies have found that while some trucks offer excellent temperature control, packed mushrooms can become warmer, colder or experience major temperature fluctuations during transport.

Issues with temperature management are most likely to occur when trucks are carrying mixed loads to stores. Cold mushrooms may be placed alongside warmer or colder products. As a relatively fragile item, they may be placed on top of pallets, potentially putting them directly into the cold delivery air (Figure 26).

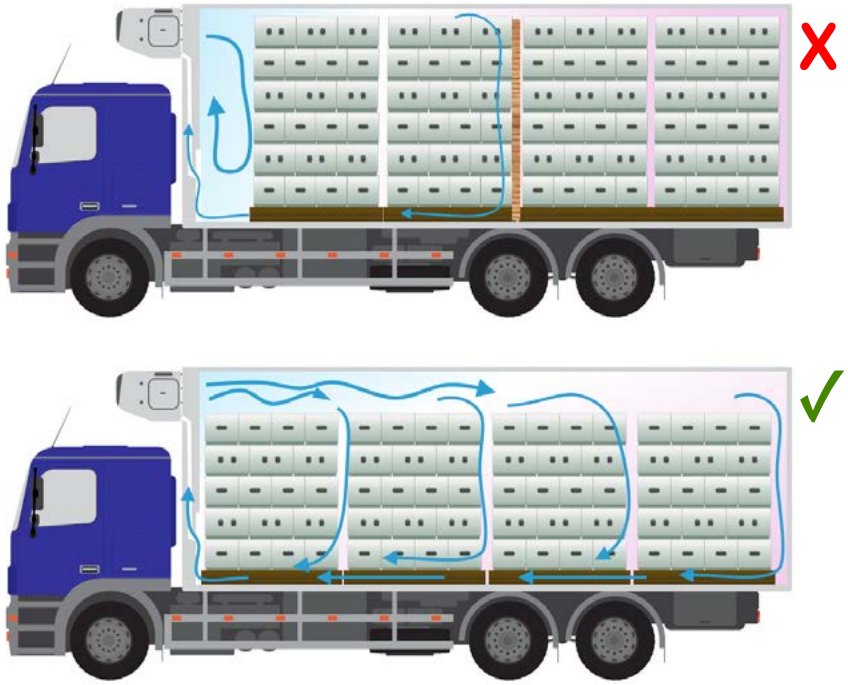


Figure 25. Load trucks so as to ensure air circulates around all pallets. Do not allow cold air to short circuit back into the air return or block air flow with stabilising panels

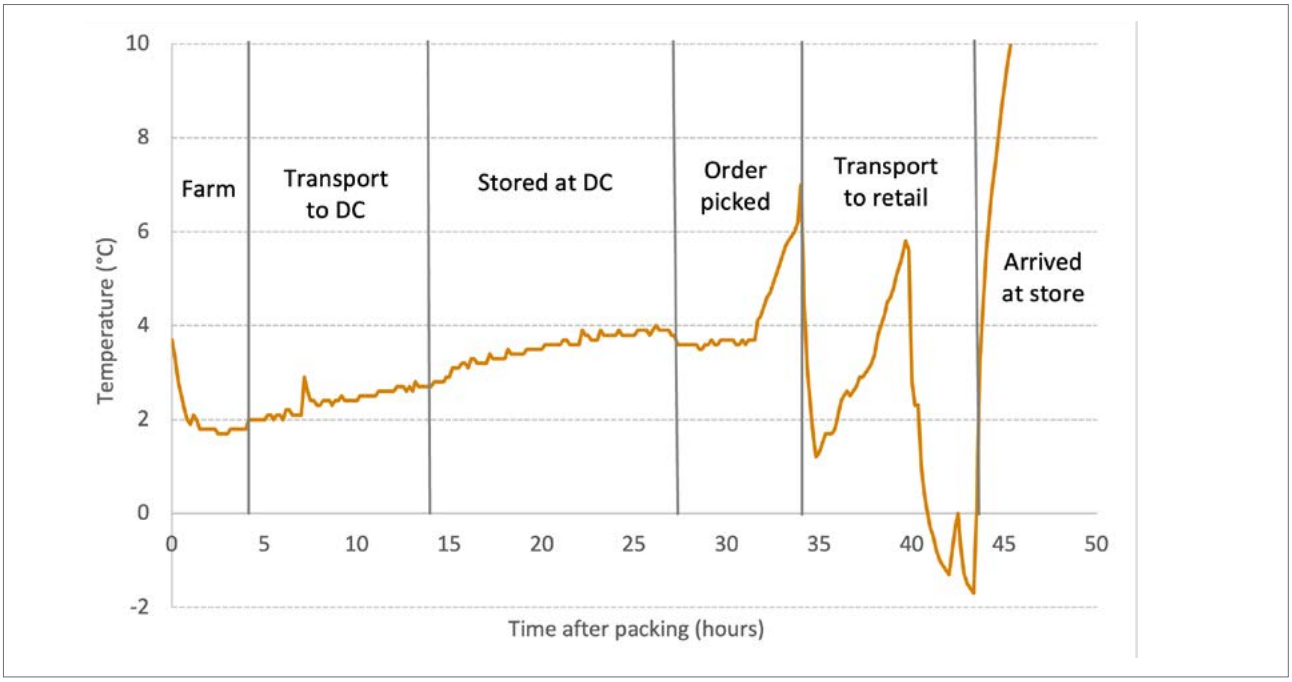


Figure 26. Air temperature inside a crate of mushroom punnets during storage and transport. Temperature was well managed at the farm and DC, but showed major swings during transport, even dropping below zero. Such temperatures are likely to result in condensation, and could even cause freezing injury.

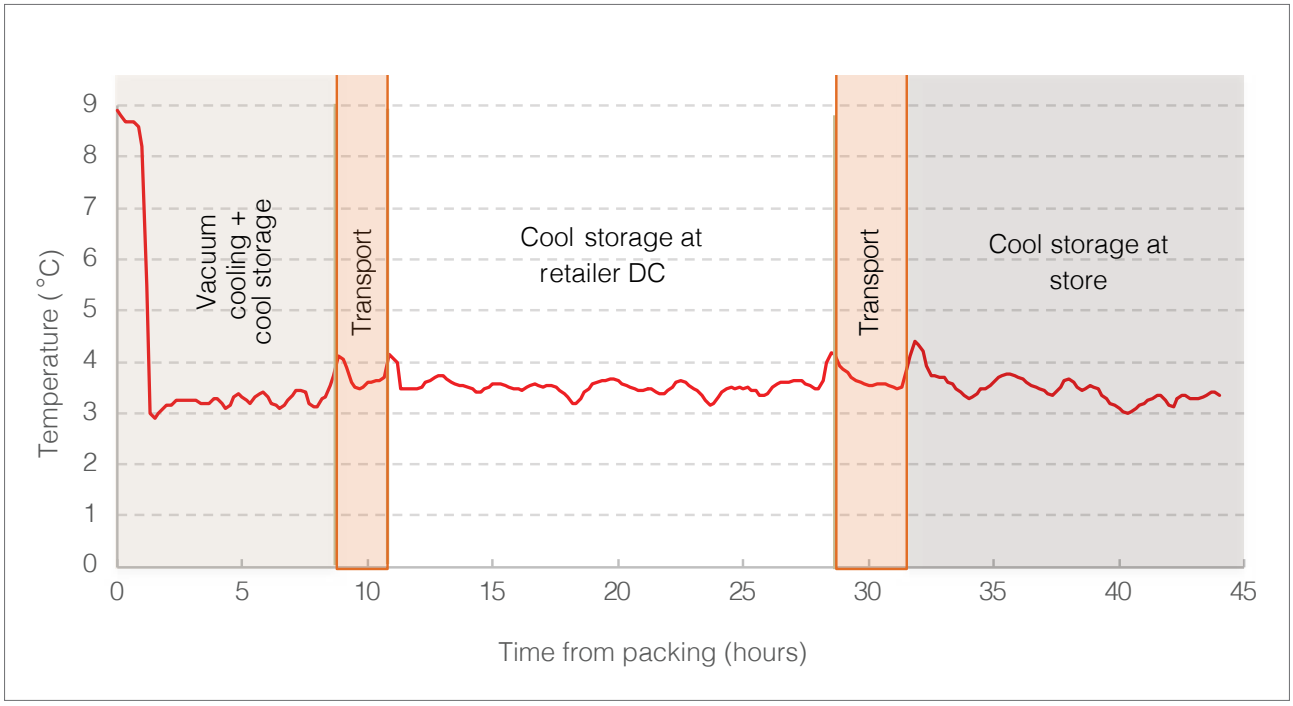


Figure 27. An optimal supply chain temperature profile from harvest to retail store. Mushrooms are cooled rapidly via vacuum cooling and maintained below 5°C with minimal temperature spikes

More often mushrooms warm slightly during transport. However, the degree of warming that occurs is likely to be strongly related to position on the truck. Ideally, warming should be kept within 1°C, with temperature stable during transport (Figure 27).

To achieve this, truck cooling systems should be set at 2 to 4°C, with the sensor placed in the delivery air (not the return air as this can result in temperatures dropping too low).

There should be sufficient air exchange that high levels of CO_2 and ethylene do not build up during transport. While unproven, there is some evidence that exposure to ethylene (for example, from ripening fruit) may reduce mushroom quality and storage life.

6.3. Monitoring temperature during transport

The only way to know if truck temperature management systems are operating correctly is to record and check the data.

A large range of data loggers are available (Figure 28):

- Single use loggers are cheap and easy to use, but need to be retrieved and downloaded
  - Single use air temperature loggers are easily available and cheap
  - Single use RH loggers are also available
- Loggers equipped with probes measure the mushrooms rather than the air around.
- Probe loggers **must** be removed before transfer to retail, along with the package they were in
  - Both single use and multi use probe loggers are available
  - Some multi-use probe loggers are equipped with Bluetooth, so can be monitored via wifi or from a short distance without removing them from the load
- Single use loggers with mobile telecommunication are increasingly affordable and upload data in real time using wifi or the mobile phone network.
  - These loggers generally measure multi parameters, including temperature, RH, location, light and impacts, making it easier to interpret the results within supply chains
  - As data can be accessed through the cloud, these loggers do not need to be retrieved
  - If a cool chain breach occurs an alarm can be sent in real time, allowing corrective actions to occur
- Multi-use, mobile telecommunication logger services are also available.
  - These are cheaper (if re-used) than single use loggers while offering the same range of measured parameters
  - Multi-use loggers are more environmentally

sustainable than disposable models

- Some manufacturers operate a retrieval system as part of the service

For all supply chain members, monitoring temperature is an easy and cheap form of insurance. This is especially the case with systems that operate remotely using mobile telecommunications or GPS. These loggers do not just explain why something went wrong after the event, but provide a warning in real time through cloud-based systems.

The key issue with such devices is that the signal can be blocked by truck or cold room insulation. Locating a logger or base station (connected to satellite units) at the top of the load and/or by the door can help improve signal and, therefore, timeliness of position and data outputs.

Ease of data retrieval and analysis should be a key consideration when choosing a logger service. If it is difficult to access or understand the data then chances are it will not be used. Systems that upload to the cloud, make it easy to see where a consignment is, track what has happened and provide meaningful data summaries, can potentially provide better value for money than cheap options that fail on these counts.

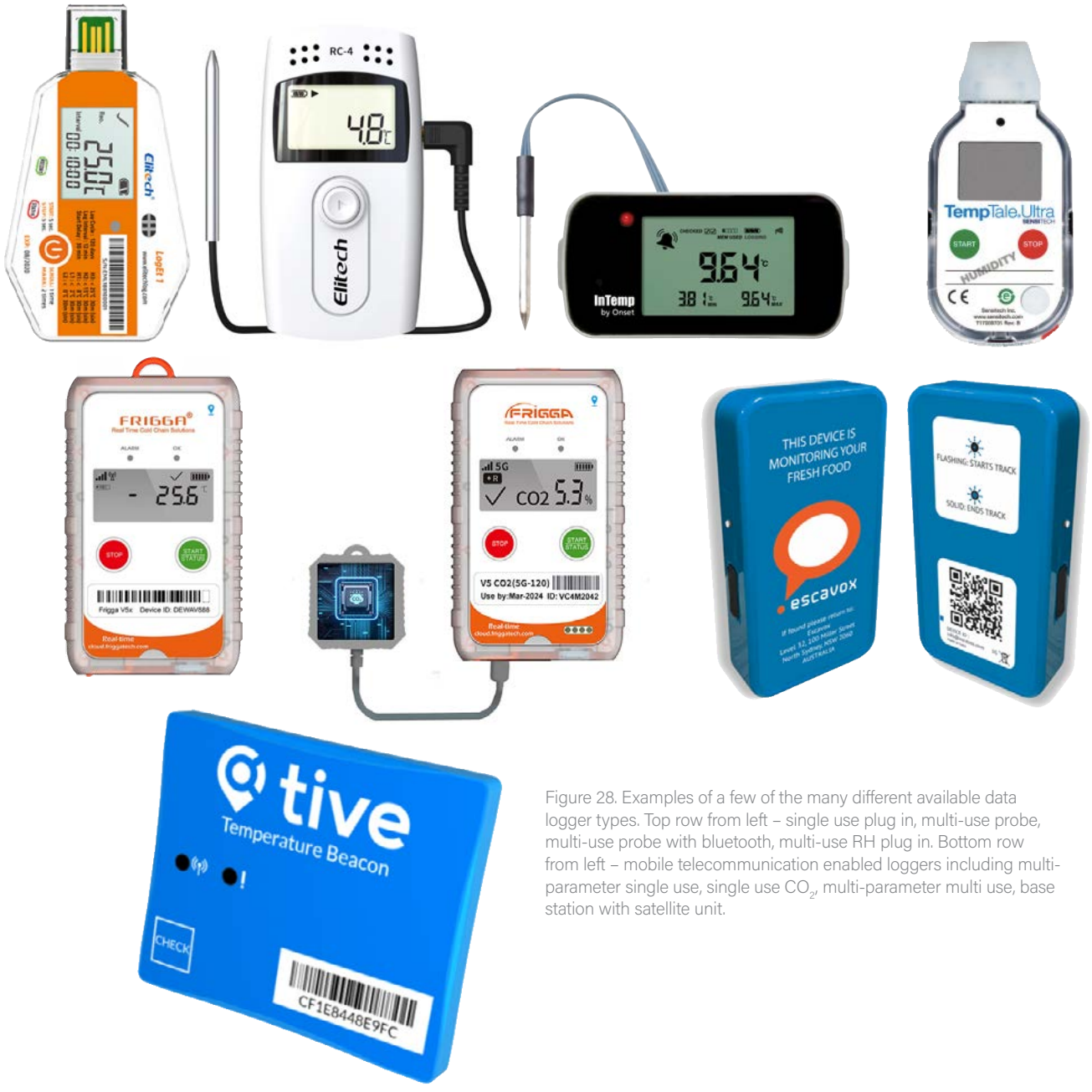


Figure 28. Examples of a few of the many different available data logger types. Top row from left – single use plug in, multi-use probe, multi-use probe with bluetooth, multi-use RH plug in. Bottom row from left – mobile telecommunication enabled loggers including multi-parameter single use, single use CO_2, multi-parameter multi use, base station with satellite unit.

7. DISTRIBUTION CENTRE

On arrival at the DC, mushrooms are typically assessed by measuring temperature, visually assessing quality and checking details such as pack weight, labelling and best before dates.

Temperature should always be measured immediately on receival using a correctly calibrated probe thermometer. Quality is more subjective, but mutual agreement on methodology and clear photographs defining acceptability can help reduce disputes.

BEST PRACTICE

- ✓ **Check temperature immediately on delivery**
- ✓ **Calibrate probes regularly, either through the supplier or using melting ice**
- ✓ **Always use a probe thermometer to measure pulp temperature**
  - Ensure the probe tip is in good contact with the mushroom pulp
  - Do not use the first reading in case it is affected by the probe temperature
  - Allow the display to fully stabilise before recording temperature
- ✓ **Use objective methods as much as possible when assessing quality**
  - Photographs of what is considered a minor or major defect can help reduce subjectivity
  - Specifications need to be clear on what is considered a 'unit' – a punnet or an individual mushroom
- ✓ **Although retailer DC's are set below 5oC there is often little air movement, which limits their capacity to remove heat generated by respiration**
- ✓ **To minimise impacts of storage at the DC:**
  - Ensure there is efficient stock rotation – practice first in, first out
  - Check that there is plenty of air movement around pallets
  - Avoid placing mushrooms next to warm or strongly respiring products

7.1. Measuring temperature

Temperature is clearly critical for maintaining good quality of mushrooms through the supply chain. Avoiding temperature increases also helps to ensure food safety, particularly for processed product.

Many retailers require delivery at 5°C or less. Mushrooms may be rejected if temperatures are outside retailer tolerances. Accurate measurement of temperature is therefore clearly essential. Where temperature is a critical concern:

- **Calibrate probes regularly** – at least annually
  - Calibration can be confirmed by the supplier
  - Calibration against melting ice can be done in house using the method described in Chapter 9 of this guide (Figure 29)
  - It is **not recommended** to calibrate probes by comparing them with a reference probe in air, or by placing inside a temperature block; air is a poor conductor of heat, so significant gradients can occur even at short distances
- **Always use a probe thermometer** to measure pulp temperature, not an infrared device
  - It is the temperature of the mushrooms which is important, not that of the surrounding air or packaging

- **Consider the accuracy and resolution of the thermometer**
  - Use a temperature probe with a resolution of 0.1°C and accuracy of at least ±0.5°C
  - Include limits of accuracy when determining if temperatures meet specifications (a reading of 5.3°C is NOT out of specification (5°C) if the probe is only accurate to ±0.5°C)

Some probes come with a default 'hold' mechanism. Once the temperature is stable for, for example, 5 seconds, the probe will keep that temperature on the display. However, five seconds may not be long enough for true temperature stabilisation.

Figure 29. Probes should be calibrated regularly, either by the manufacturer or using melting ice; see section 9 for instructions.

It is recommended that either the hold feature is turned off, or that it is increased to a longer period, for example 15 seconds.

Temperature probes generally work by measuring the different expansion coefficients of metals in response to temperature. This measurement occurs right at the tip. It is important that the tips of probes are treated carefully, and not forced into or through hard objects.

When recording temperature of an incoming consignment:

- Record temperature **immediately** at the time of delivery
  - Temperatures recorded after mushrooms have been placed on the dock for more than a few minutes may be affected by the surrounding air
- Measure temperature in at least three different locations within the pallet / consignment
  - Choose samples loaded towards the centre of the pallet rather than the outside edges
  - Do not choose samples which have been directly under the delivery air or placed near the door, as these may be outliers
- **Do not use the first reading**, as this may be affected by the probe temperature
  - Insert the probe into the core of a mushroom and allow it to stabilise
  - Remove the probe and re-insert into a different mushroom, choosing one at the centre of the punnet or carton
- Ensure the probe tip is in good contact with the mushroom pulp (Figure 30)

Figure 30. Ensure the temperature probe tip is right in the core when measuring whole mushrooms. If measuring sliced mushrooms, insert the probe into the centre of the punnet and press down lightly to ensure good contact with the mushroom pulp.

- At the core of whole mushrooms
- In the centre of the punnet or pack of sliced mushrooms
- Press down on the punnet when measuring sliced mushrooms to ensure the probe tip is not measuring air

- Record the temperature once the value is stable for at least 10 to 15 seconds

7.2. Assessing quality

Many of the attributes consumers value in mushrooms – including colour, firmness, maturity and freedom from damage are not easily assessed using objective methods, especially in a busy distribution centre.

To reduce subjectivity, some retailer specifications include photographs defining what is, or is not, acceptable. They may also include limits such as "bruising affecting >1cm^2 per mushroom" or "feathering without discolouration affecting 20 – 40% surface area" (Figure 31).

In practice these assessments can be difficult to implement. For example, accurately estimating percentage surface area on a round object such as a mushroom is problematic, but a 1cm^2 blemish looks very different on a large portobello to a small button. A bruise that one person considers superficial, may well be another's major damage.

Major defects are commonly limited to 2% of the consignment and minor defects to 10%. It is important to clearly define whether a 'unit' is a punnet or an individual mushroom. For example, if one punnet of ten inspected punnets contains two mushrooms with defects, does this mean;

a. One in 10, so 10% of the total punnets inspected, have failed

b. You need to **count** the defective/non defective mushrooms in 10 punnets to calculate percentage fail

c. You need to **weigh** the defective / non-defective mushrooms in 10 punnets to calculate percentage fail

Clarifying these types of issues, and including as many clear images as possible, can help to reduce disputes over what or is not acceptable.

There is potential to add objective measures of firmness and colour. Inexpensive, hand-held colour meters are available that can measure mushroom colour, including whiteness. Firmness of whole mushrooms can be measured using non-destructive fruit firmness meters. However, taking such measurements requires both time and skill. Unless significant, ongoing disputes over quality are occurring, such methods are unlikely to be commercially useful.

7.3. Mushroom storage

Consignments of mushrooms are commonly stored for anything from a few hours to two days before despatch to stores. During this time it is important they are stored below 5°C. Wherever possible mushrooms should be dispatched to stores within 24hrs of arrival at the DC.

Storage areas in most retailer DCs are set between 2 and 4°C. However, significant variation can occur. For example, in one DC set at 2°C it was 2.7°C in the storage area but 4.5°C near the docks. Temperatures can increase to 6°C in higher traffic areas.

Figure 31. Estimating percentage surface area affected by a blemish is difficult on round objects. While the above is a guide for flat mushrooms, a strongly domed mushroom will be quite different.

While these temperatures are within an acceptable range, air must be colder than the product in order to remove heat.

Retail DCs are often extremely large. Cold air delivery units are situated high on the walls above the storage areas. There is likely to be minimal air circulation in the centre of such a vast space, other than that generated by movement of forklifts and workers. Without air movement, heat from respiration is likely to increase temperatures inside wrapped pallets, sealed cartons and overwrapped punnets of mushrooms.

Supply chain studies confirm that temperatures of mushrooms stored at DCs are often warmer than the room setpoint. In the example shown in Figure 32, the room was set to 3.5°C but air temperatures within the pallets generally ranged between 4 and 5°C.

The exception was pallet 3. A large decrease in temperature occurred in the hours before despatch, likely associated with picking the order. This appears a common pattern, with either an increase or decrease in temperature often associated with stock picking.

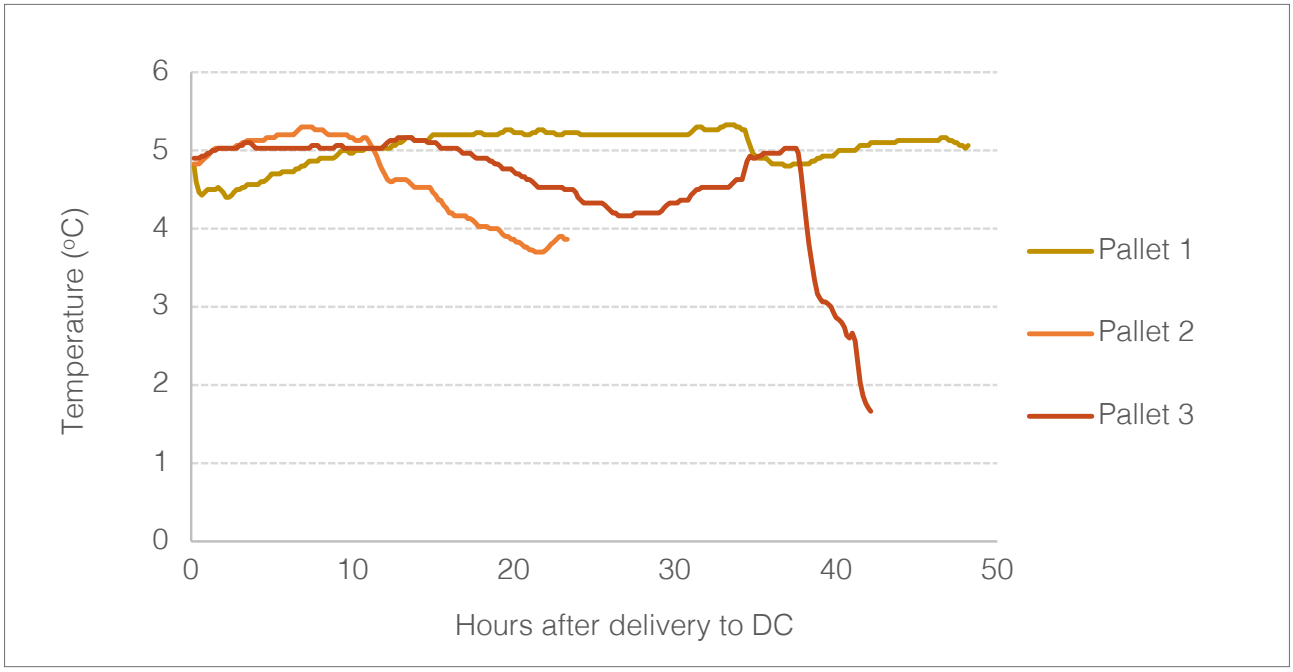


Figure 32. Air temperatures inside three pallets loaded with mushroom punnets at a retail DC, data recorded between arrival and despatch to stores.

KEY CONSIDERATIONS ARE:

- Minimise time in storage through stock ordering and rotation
- Ensure there is plenty of air movement around pallets at all times
- Avoid placing mushrooms next to warm or strongly respiring products, especially if they produce large amounts of ethylene

8. RETAIL

While the majority of mushrooms are kept at 5°C or less during delivery to the distribution centre and storage there, it is after orders are picked for stores that temperature management becomes less reliable.

The quality of mushrooms on the retail shelf is the conclusion of all that has gone before. Unfortunately, poor management at stores can undo the gains made through good practices in the rest of the chain.

BEST PRACTICE

- ✓ **Place mushrooms in the cold room at back of store immediately after delivery**
- ✓ **Check that the cold room is running correctly**
  - Cold rooms should run at around 4°C
  - Logging the temperature can show if it is significantly higher or lower, or varying by 2°C or more between refrigeration cycles
  - Ensure door seals are intact and avoid leaving the door open
- ✓ **Always display sliced or processed mushrooms in chilled units**
- ✓ **Preferably display whole mushrooms in chilled units**
- ✓ **If using an unrefrigerated display then only put out small quantities at a time**
  - Adjust stocking rates so that mushrooms are displayed for no more than two hours
  - Never leave mushrooms unrefrigerated overnight
- ✓ **Handle punnets carefully**
  - Avoid piling punnets on top of each other or squeezing into displays
- ✓ **Display older stock at the front and keep racks full**
- ✓ **Remove poor quality mushrooms from displays**

8.1. Receival and storage

Mushrooms can warm up extremely rapidly if left at ambient temperatures after delivery. Like other refrigerated fruit and vegetables, they need to be placed in the cold room immediately.

However, this is not the end of the story. Temperature monitoring indicates that cold rooms at the back of retail stores vary widely in their efficiency. Cold rooms are normally recommended to be set at around 4°C. However, they commonly run higher, lower or with significant variation between refrigeration cycles (Figure 28). This can indicate a problem with sensor calibration, insulation or leakage.

Although the time that mushrooms spend in storage at stores is likely to be short, condensation due to temperature fluctuations can impact quality both in store and after purchase by consumers.

If insulation is not in good condition, the cold room compressor needs to run much harder, producing rapid temperature fluctuations. Check that the door seals are in good condition, the cold room panels are intact and keep the door closed when not actually moving product in or out.

Figure 33. Air temperatures around a carton of loose mushrooms. In this supply chain, temperatures were managed very well at the DC and during transport, however the cold room at the back of the retail store is performing poorly.

8.2. Shelf display and handling

Mushrooms are generally displayed in chilled display units. These are not without their issues, as temperatures are highly variable. A supply chain study found that although the average display temperature was 4.7°C with 80 to 85%RH, temperatures inside the units ranged from 2.6 to 8°C (Figure 33).

The mushrooms are frequently warmer than the display, averaging 5.7°C. However, temperatures of product sampled as part of the study ranged from 2.5 to 10.1°C. Some of the highest temperatures (9 to 10°C) were recorded on sliced product; unless turnover is fast, display under such conditions is likely to substantially reduce quality and storage life.

In theory, the best way to display mushrooms is inside a cabinet with a glass door – similarly to milk. However this greatly reduces the visibility of mushrooms, making them harder for consumers to find. The resulting improvement in shelf life therefore needs to be balanced against a potential drop in sales.

Mushrooms are also occasionally displayed unrefrigerated, at ambient temperatures (Figure 35). This is most likely if they are on special or featured in, for example, the in-house magazine. Unrefrigerated displays put mushrooms right where consumers can see them, and can definitely drive impulse sales.

It is essential that only a limited amount of stock is placed on an unrefrigerated display at any one time. This will help to keep turnaround fast and minimise effects on storage life and quality (Figure 35).

Figure 34. Examples of unrefrigerated displays. Punnets should not be piled on top of each other, and sliced mushrooms must never be displayed unrefrigerated. Note the visible browning and deterioration of the caps and stems, already visible on the display.

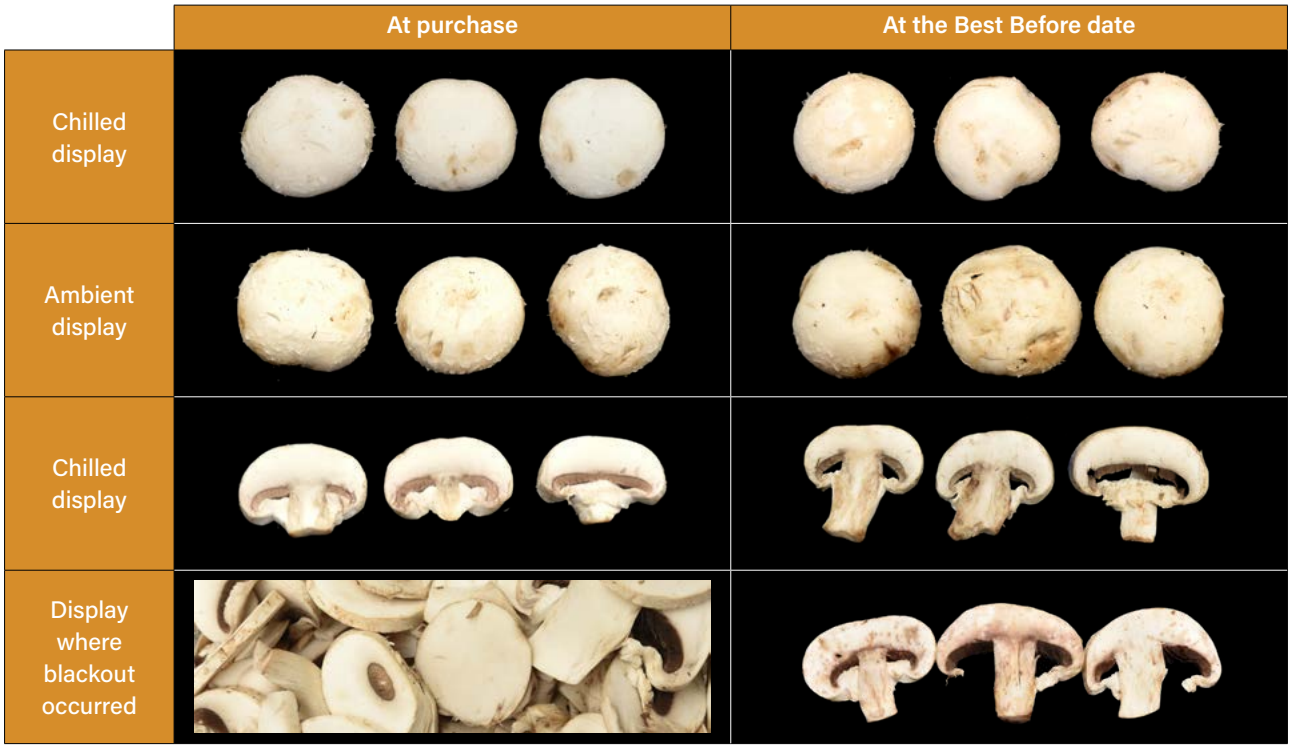


Figure 35. Condition of whole and sliced mushrooms from the same batches purchased from a chilled display, an ambient temperature display, and a chilled display which had suffered a blackout for several hours the evening before purchase. Photographs taken immediately after purchase then at the Best Before date following storage at 5°C. All mushrooms purchased from continuously chilled displays were still acceptable at the Best Before date, those from other displays were not.

Some general rules are:

- Whole mushrooms should not be left unrefrigerated for more than two hours
- Whole mushrooms must never be left unrefrigerated overnight.
- Sliced or processed mushrooms must NEVER be displayed unrefrigerated.
  - *High temperatures not only have major effects on quality, but also create unacceptable food safety risks.*

Good stock rotation will ensure that displayed mushrooms look their best. Older punnets need to be kept at the front of displays to ensure they sell first, but removed if they are visually unappealing.

Loose mushrooms in cartons are more difficult to manage. Fresh mushrooms should **never** be simply poured into the old cartons to top up the display. However, placing old mushrooms from the bottom of a nearly empty box onto the top of the replacement box can also create issues. Consumers are more inclined to rummage through the box if old mushrooms are placed on top of fresh ones. Such rummaging inevitably increases scuffing and bruising.

In some cases, it may be better to simply dispose of a few older mushrooms than to increase the risk of damage to a larger volume of fresh, white product.

Punnets also need to be handled carefully. Never be tempted to squeeze extra punnets onto displays, or stack them multiple layers high. Mushrooms at retail are highly susceptible to bruising, especially if they were picked several days earlier. The resulting compression damage will not be visible immediately, but emerge over the next 24 hours or more.

Finally, keep the displays filled, and remove any poor quality mushrooms. Attractive displays sell more mushrooms!

9. CALIBRATING PROBE THERMOMETERS

The best way to calibrate a probe is in liquid, using a melted ice slurry.

Calibration in air is **not recommended**; air is a poor conductor of heat. Significant gradients can exist between the probe being calibrated and the reference thermometer, no matter how close together they are. Water conducts heat 24x more efficiently than air and stirring makes it possible to eliminate potential gradients.

Probes should be calibrated at temperatures close to those expected in the product; calibrating a probe at room temperature will not necessarily translate to an accurate measurement at 3°C.

A slurry of melting ice provides a reliable and accurate measurement of 0°C, so is close to the target temperature of the mushrooms.

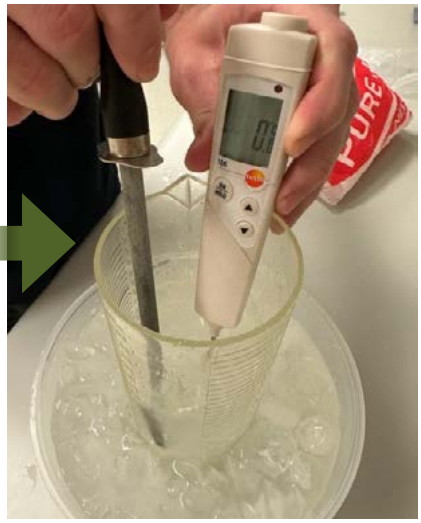
- Obtain a large thermos or construct a double insulated vessel for the calibration (for example, one container inside a larger one)
- If using a double vessel, fill the outside with ice to insulate the inner part
- Finely crush some ice and place in the thermos or in the central part of the double vessel
- Add just enough water just to cover the ice, stir, and allow to equilibrate for at least 5 minutes
- While continuously stirring the ice slurry, place the probe into the ice and wait for the reading to stabilise
- If the probe does **not** read zero, record the variation (+/-) and sticker it onto the probe.
  - Consider replacing probes which read more than 1°C above or below 0°C
- Add or subtract the variation from zero to all future temperature measurements

1

Place ice in a ziplock bag and crush with a hammer

2

Add crushed ice to thermos or double insulated vessel and just cover with water



3

Stir melting slurry and allow to equilibrate. Keep stirring while the probe stabilises, record variation from 0°C

10. LINKS AND REFERENCES

Hort Innovation MUSHROOM FUND

Postharvest management of mushrooms

a Review

Contents

1 Introduction

The Australian mushroom industry invests more than $3 million in marketing annually. However, no marketing campaign will be successful if quality is not what the consumer expects. Moreover, consistently presenting high quality mushrooms to consumers at retail is a proven way to increase purchases.

This is particularly important at the current time; mushroom consumption has fallen slightly to around 2.6kg/person/year, compared to 2.9kg/person/year in 2017, while production has increased slightly and exports fallen. The result has been downward pressure on prices at the same time as costs for energy, raw materials and labour have increased dramatically.

Mushrooms have a short postharvest storage life. Unlike other products, they lack an external skin to protect them from water loss, damage, and microbial attack. Their delicate structure is easily damaged, leading to browning. With a high respiration rate, few stored carbohydrates and over 90% water content, they soon shrivel and deteriorate.

The quality of mushrooms at harvest is determined by growing practices. Postharvest management can only minimise quality loss from this point on. Harvest practices, postharvest treatments, cooling, storage and packaging all seek to maintain quality through the supply chain.

A search for "Topic = *Agaricus* + quality" in the peer reviewed literature using the CAB abstract search engine reveals a surge in annual publications on this topic. While many may only tangentially relate to postharvest management of mushrooms, this does indicate a growing interest in this topic.

Much of this has been driven by Chinese researchers. Indeed, the most published author on this topic is Wang Xiangyou from the Shandong University of Technology, with 31 peer reviewed publications. This eclipses the previous records set by R.B. Beelman (27) and K.S. Burton (20).

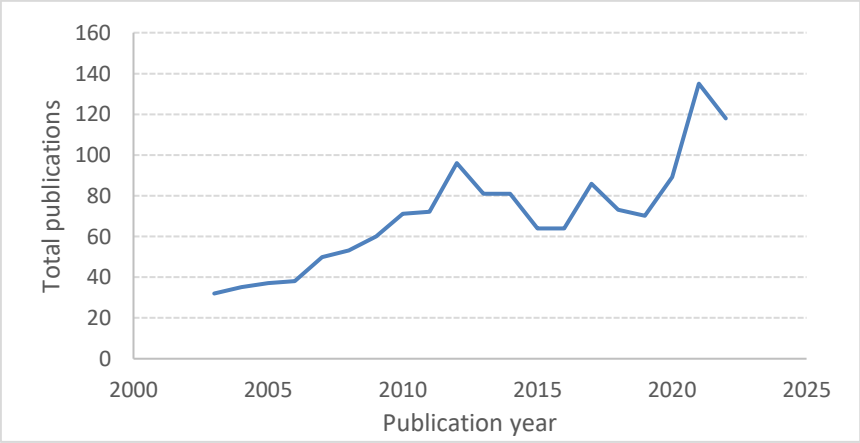


Figure 1. Number of peer reviewed publications retrieved using a search for "Topic = Agaricus + quality" using CAB abstracts.

The purpose of this review is to summarise research on pre and postharvest management of mushrooms. Together with new research specific to Australian supply chains, this information will form the basis of best practice recommendations for the Australian industry.

2 Preharvest effects on postharvest quality

The quality of mushrooms at harvest cannot be improved, only maintained. Preharvest practices are therefore critical to producing high quality mushrooms.

Postharvest quality is affected by pre-harvest practices. Preharvest infections and poor nutrition can result in faster than normal postharvest deterioration. Conversely, some pre-harvest practices can extend postharvest shelf life [1].

2.1 Growing environment

Key finding

Temperature, humidity and airflow within growing rooms affect mushroom quality as well as yield. 'Airing' the room allows off-gassing of volatiles that would otherwise prevent mushroom formation and reduces CO_2; high CO_2 can increase stipe elongation and reduces cap size.

2.1.1 Temperature and humidity

High temperatures stimulate respiration and increase the rate of senescence, as well as activating tyrosinase and potentially increasing growth of bacteria on the mushroom surface[2].

Mushrooms grow and form fruiting bodies at particular temperature ranges [3].

Smooth primordia can form under constant temperature conditions, however drops in temperature are required to trigger some of these primordia to develop into fruiting bodies (Eastwood et al., 2013).

Agaricus bisporus grown at lower temperatures (11-13°C) had increased firmness and calcium levels compared to mushrooms grown at 17-19°C. However, the low temperature range also reduced yield [4].

Low relative humidity degrades texture and structure and may increase enzyme activity [5], with the result mushrooms can become scaly. Low RH (85%) also increases susceptibility to bruising compared to higher RH (92%) particularly for early flushes [6].

High moisture can also be an issue. Mushroom caps can contain tiny dimples, which allow water to pool. Even if bacterial blotch is not present, these can result in 'watermarks' on the cap surfaces.

2.1.2 Airflow and CO_2

The formation of mushrooms is triggered by "airing", reducing CO_2 levels within the growing room to below 1,000ppm.

- Airing allows release of the eight-carbon volatile 1-octen-3-ol from the substrate.
- 1-octen-3-ol has been shown to suppress formation of the primordia which later develop into fruiting bodies (Baars et al., 2020).

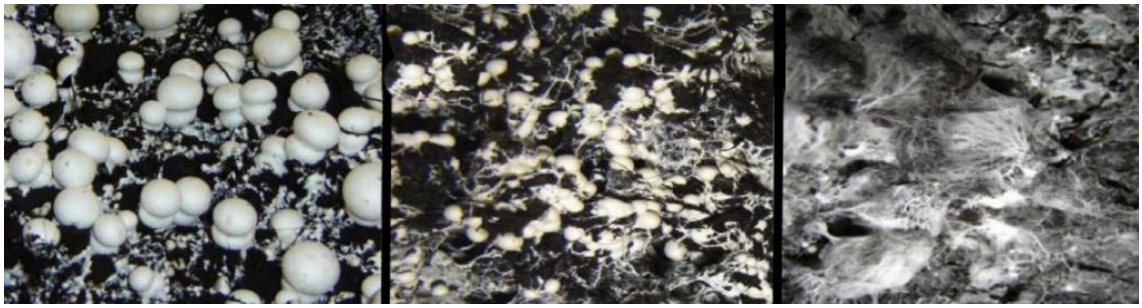


Figure 2. Mushrooms formed under normal growing conditions (left); failure for primordia to develop into mushrooms at a constant 25oC (centre) and failure for primordia to develop in an unventilated room (right). From Eastwood et al (2013)

- While it is important to dry mushrooms quickly after irrigation, if the air velocity is too high mushroom caps are likely to develop dry scales and browning [7].
    - Rapid airflow physically damages the mushroom tissue, stimulating formation of melanin [8].
    - Managing CO_2 accurately and uniformly within the room is difficult without adequate airflow. Air-trainers, such as netting diffusers and cones linked to airlines, can be used to soften or increase speed, guiding ventilation to where it is needed.
    - Airflow needs to be balanced against the metabolic heat produced by the crop. So, for example, rates of air exchange may need to be higher approaching flush 1 than during flush 3.
- High CO_2 levels can result in stipe elongation, stretched veils, and a smaller cap [9]

2.2 Casing and compost

Key finding

Casing type and amount of lime added can have mixed effects on mushroom quality. Whereas high rates of lime had adverse effects on quality in one study, another found reduced sensitivity to bruising.

Peat-based casings generally produce the best quality mushrooms. However, some of the newer alternatives can also provide satisfactory results, especially when used as partial blends with peat.

2.2.1 The role of lime in casing

- Sugar beet lime (SBL) is a waste product commonly added to casing in Ireland, the UK and North America. Trials tested the effect on yield and quality of different grades of SBL, added to peat at rates of 50 to 125 kg/m^3 [10]. Optimum yield and quality was obtained by adding 75 kg/m^3 of <0.25mm particle size SBL to casing.
- Conversely, Burton[6] found that increasing the SBL content of casing from 9% to 30% – a rate likely significantly higher than the maximum volume added in the study above – reduced susceptibility to bruising in first flush mushrooms without affecting total yield.

2.2.2 Casing material and method

- Although Burton [6] reported that shallow casing (25mm) produced mushrooms less susceptible to bruising than deep casing (50mm), this difference occurred only in the second flush and is a result from a single trial.
- Pardo et al[11] tested a number of different casing materials, including mixtures of soil, black peat, brown sphagnum peat and limestone quarry gravel. Mushroom quality was best when using black peat, however the difference was small.
- Similar results were reported by Barry et al[12], who found that casing with 70% peat or 100% peat produced whiter mushrooms than casing materials made from blends of spent mushroom substrate and vermiculite.
- Spent mushroom compost (SMC) has been widely investigated as a partial replacement for peat in casing. An investigation of a range of blends of SMC with peat by Pardo-Gimenez et al[13] found that blending with up to 60% SMC did not affect quality. However, increasing the SMC to 80 or 100% significantly reduced whiteness.
- Sphagnum peat plus SBL was compared to a local casing made of mineral soil plus coconut fibre [14]. There was no significant difference in colour, dry matter or biological efficiency between the two.
- Addition of 25% coal tailings to either brown or black peat did not affect cleanliness (or yield) of the mushrooms produced[13].
- In South Africa, the only local source of peat is reed-sedge 'topogenous' peat. While yields are satisfactory, this material often dirties the mushrooms, so is not a preferred casing[15].

2.3 Irrigation

Key finding

Mushrooms are 90 to 95% water, so the quality of water used, and when and how it is applied, will strongly influence mushroom quality and storage life. While too little irrigation can result in mushrooms being scaly and dry, too much encourages growth of bacterial blotch.

Mushrooms need to dry off relatively quickly following irrigation. Drip irrigation avoids wetting the caps, adding flexibility to irrigation schedules. However cost, technical issues, and difficulties with cleaning and re-use, have limited commercial adoption.

Water used in sporophore formation is mainly drawn from the casing. Wet casing (especially over dry compost) reduces quality and can increase bacterial disease. Conversely, dry casing can result in soft mushrooms that are susceptible to bruising.

Additives to irrigation water include sanitisers and calcium products. Stabilised chlorine dioxide has been demonstrated to help manage bacterial blotch and improve colour. Addition of 0.3% calcium chloride to irrigation water increases calcium content in the mushrooms and improves storage life and resistance to bruising. Some studies have proposed adding both $CaCl_3$ and chlorine dioxide. However, neither product is currently registered for this purpose, and there are concerns that adding salts to irrigation water increases nozzle blockage.

Research need

Examine whether calcium added to casing can increase calcium uptake in the fruiting bodies. Investigate use of moisture probes to optimise irrigation and test use of drip irrigation to quantify quality benefits (if any).

2.3.1 Irrigation method

- Drip irrigation systems offer an alternative irrigation system for mushrooms. The drip lines are laid between the Phase 3 compost and casing, at shelf filling. While the systems have a number of advantages (as detailed below), issues with management of moisture through the beds, as well as cleaning and re-use of the lines, has so far limited commercial uptake.
    - No bacterial blotch occurred with drip irrigation, while 6% of mushrooms grown with spray irrigation were diseased (Danay & Levanon, 2013).
    - Drip irrigation reduces potential dissemination of fungal spores e.g. *Verticillium*, etc.
    - Danay et al[17] found that drip irrigation slightly increased yield, but that the main effects were on mushroom quality, particularly for third flush (Figure 3). The authors note also note decreased incidence of bacterial blotch on drip irrigated mushrooms, although no figures are presented.

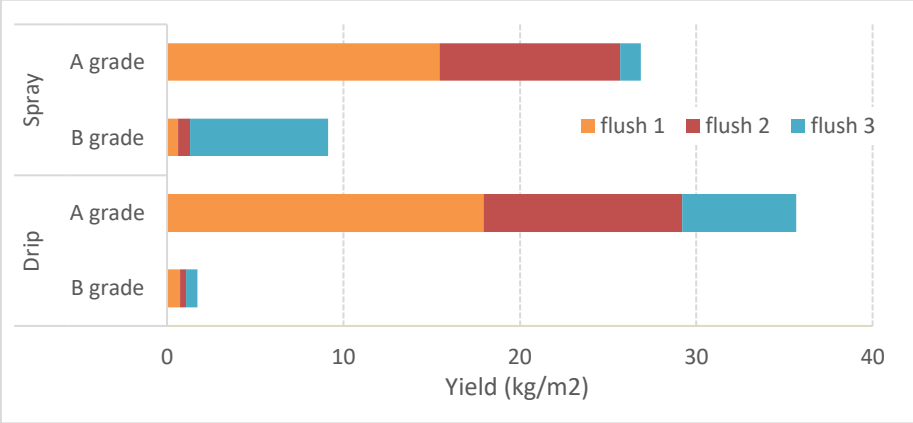


Figure 3. Yield and quality grade of mushrooms grown with normal or drip irrigation. Derived from Danay et al., 2016.

2.3.2 Casing moisture

- High moisture levels in the casing maximise yield, but dry matter is likely to be reduced. While high dry matter has been associated with both reduced and increased whiteness, it is likely to contribute to increased storage life due to improved levels of carbohydrates.
    - Wet casing overlaying dry compost reduces evaporation from the mushrooms. This can result in browning mushrooms that weep liquid, or water-soaked “windows”[7].
    - Excessive moisture increases the development of bacterial blotch and other diseases. [18].
- Dry casing can increase susceptibility to browning and bruising[6], and is difficult to re-wet.

- Dry casing can result in water stress; mushrooms may feel soft and damp and have increased susceptibility to browning and bruising[7].
- If casing dries out it can become somewhat hydrophobic, a problem made worse by increased mycelial overlay on the surface[12].
- Peat that has been partially dried never recovers the same water holding potential as material that has remained continually wet [19].

- During flushing, the availability of water in the casing material falls dramatically. Short periods of relative dryness have little effect. However, longer term average moisture content has large effects on yield and dry matter. Yield and quality are both optimised when water is applied evenly during production and cropping, instead of allowing casing material to dry out[20];
  - Maintaining casing at 58-60% volumetric water content resulted in significantly whiter mushrooms than when casing was kept at 46-48% v/v, with casing at 52-54% v/v providing an intermediate result[12].
  - If a heavy first flush results in dry casing for the second flush, these mushrooms will be discoloured and susceptible to premature opening[7].
- Optimising moisture levels in the casing material is essential to maximise yield. However, a balance is required, as high yield may come at the expense of low dry matter and, potentially, other quality attributes (Figure 4).

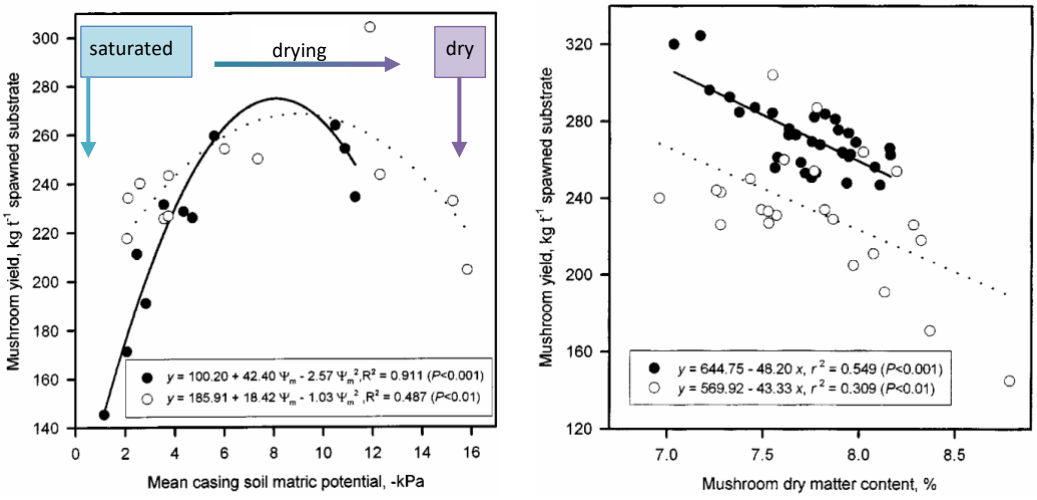


Figure 4. Effect of moisture content of casing on yield of mushrooms (left) and relationship between yield and dry matter (right). Data from two separate experiments (● and ○), reported in Noble et al., 1998.

- Burton[6] found that first flush mushrooms grown with wet casing (-4kPa) were less susceptible to bruising than those grown in drier casing (-8 to -12kPa). However, the opposite occurred in the third flush, mushrooms grown in dry casing proving the least susceptible to bruising.
- Although Noble et al (2000) found that matric potential was more important for mushroom development than osmotic potential, van Loon et al[21] demonstrated that adding mineral salts to casing (thereby increasing the osmotic potential) significantly increased mushroom density and dry matter.

2.3.3 Dry matter

- While levels of dry matter (DM) are strongly influenced by casing attributes and moisture content, the relationship between DM and quality varies:

- Higher levels of DM can be associated with ***increased*** whiteness at harvest, particularly in association with high flesh calcium levels[22].
- High DM can also be associated with ***reduced*** whiteness[12], or increased yellowness[11] at harvest, both yield and whiteness being maximized at lower DM (Figure 5).

- High dry matter is frequently associated with decreased yield, as shown in Figure 4 and Figure 5.
- Dry matter often declines with each flush [23].

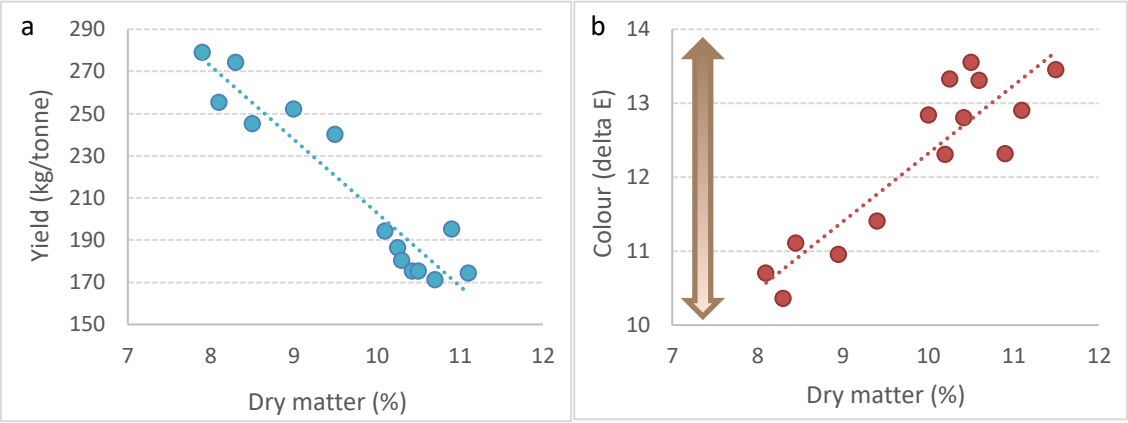


Figure 5. Relationships between mushroom dry matter and yield (a); mushroom dry matter and colour (ΔE) (b); Derived from Barry et al., 2016.

Even if mushrooms are less white initially, high DM can improve storage life (Figure 6) [21], likely due to increased energy reserves.

- Mannitol (the main storage sugar in mushrooms) moves from the stipe into the cap during postharvest storage[14].

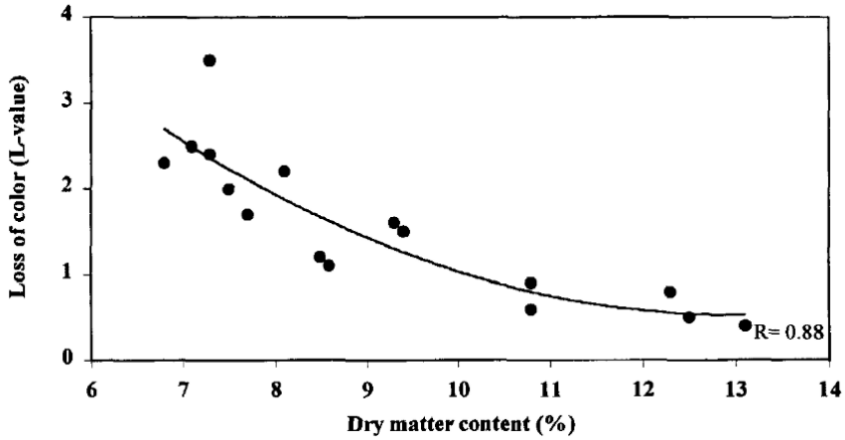


Figure 6. Change in L values (whiteness) after 7 days storage at 8°C as a function of dry matter. From van Loon et al, 2000.

2.3.4 Irrigation with sanitisers

- Early efforts to control bacterial blotch involved addition of sanitisers to irrigation water. While chlorine products generally had limited effectiveness, stabilised chlorine dioxide (ClO_2) provided excellent control [24].

- Irrigation with 50ppm ClO_2 was far more effective in controlling blotch than up to 250ppm chlorine in sodium hypochlorite.
- Stabilised ClO_2 specifically reacts with reduced sulphur compounds, interfering with transport of nutrients across cell walls. This means it is less reactive with organic material than hypochlorite. It is active at pH levels between 4 and 10 and far more effective than chlorine against spores, bacteria and viruses.
- Stabilised ClO_2 is registered and used as a sanitiser during mushroom production in many different countries.
- In Australia, stabilised chlorine dioxide is registered for use as a sanitiser in mushroom growing facilities:
  - To treat water at 5ppm
  - For disinfecting walls, floors, equipment etc. at 100ppm

- The effects of adding stabilized chlorine dioxide to irrigation water was further improved by combining 50ppm stabilised ClO_2 ('Oxine') with 0.75% calcium chloride. The greatest benefits were observed for the third flush mushrooms, differences that increased during postharvest storage[8].
- More recently, a range of sanitisers have been evaluated as postharvest treatments. These could be tested for similar effects pre-harvest.
  - Hydrogen peroxide is used as an irrigation treatment by some Northern American growers.
  - Electrolysed water (EW) is increasingly used as a low dose chlorine sanitiser; free chlorine and other ions are generated by passing an electrical current through water containing low levels of salts. Mushrooms were washed for 3 minutes in EW containing 5 to 100mg/L free chlorine. EW containing 25mg/L free chlorine was the most effective at retaining quality during storage (Figure 7)[25].
  - Cold plasma, and plasma activated water (PAW), have been shown to kill bacteria on plant surfaces. Plasma treatment of water generates reactive oxygen molecules in solution as well as reducing pH and increasing conductivity.
    - Although dipping mushrooms in PAW reduced bacterial counts by 1.5 log (approx. 97%) browning in storage was not reduced, but actually increased at the longest dip time[26].
    - Initial trials at the Marsh Lawson Mushroom Research Unit suggest that pre-harvest irrigation with PAW could reduce postharvest development of brown blotch and improve quality (Tighe, pers. com.)

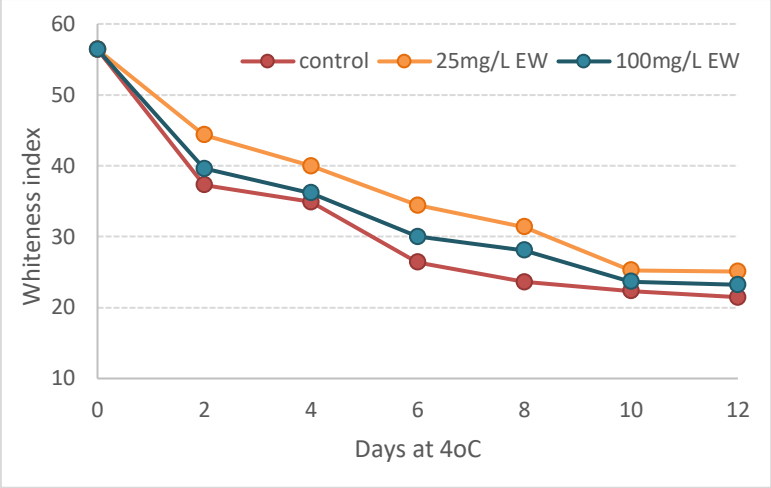


Figure 7. Changes in the whiteness index (calculated from L, a and b values) of mushrooms washed for 3 minutes in a solution containing electrolysed water, then stored at 4°C. Derived from Aday, 2016.

2.3.5 Irrigation with calcium chloride

- Mushrooms irrigated with 0.3% calcium chloride ($CaCl_2$) are whiter at harvest, develop less browning during storage and are resistant to bruising[27]. This is due to higher levels of calcium in the mushrooms. Calcium is linked to cell wall integrity, so higher levels of Ca result in stronger cell membranes[28] (Figure 8).
    - $CaCl_2$ treated mushrooms are less damaged by deliberate bruising, a difference clearly visible to the human eye[29].
    - This treatment approximately doubles calcium content of the mushrooms compared to untreated controls, e.g. Beelman and Simons[30] – 8.5 to 17.5µg/g tissue; Beelman et al[31] – 11.1 to 26.6µg/g tissue, with the effects frequently greater in the later flushes e.g. Kukura et al[32] 14 to 29µg/g tissue second flush.
    - This accumulation occurs in all tissues *except* the outer skin of the cap[33]; this suggests that calcium is not absorbed directly through the mushroom cap, but taken up through the mycelia. It further suggests that the effects of $CaCl_2$ are due to physiological changes, rather than purely superficial factors.

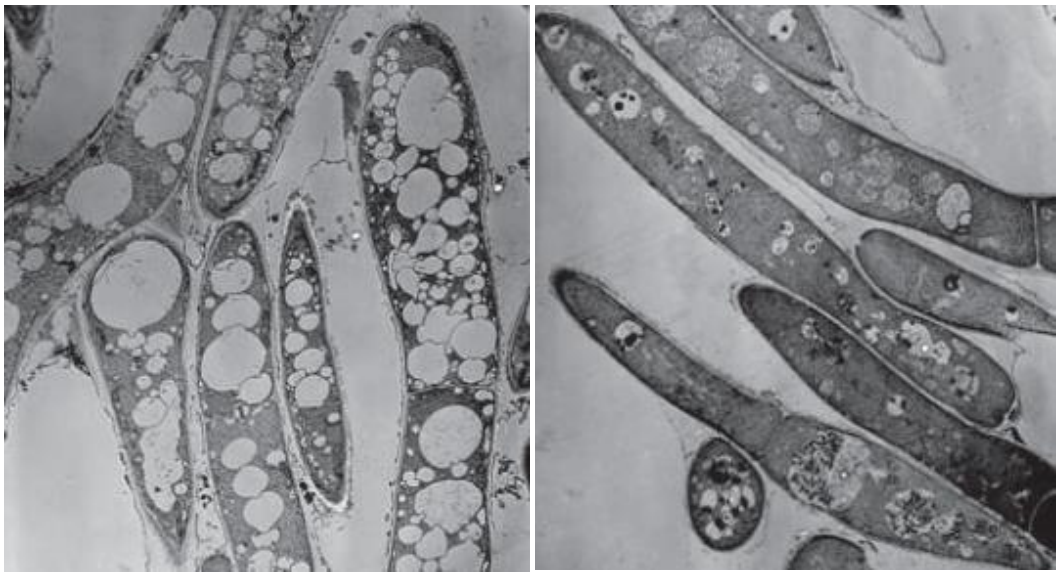


Figure 8. Electron micrographs of bruised tissue in mushrooms irrigated with water only (left) or irrigated with water containing 0.3% CaCl2 (right). The vacuoles in the CaCl2 irrigated tissue have remained intact, limiting the opportunity for enzymic reactions. From Kukura et al, 1998.

Improvements in quality, and the increases in calcium, are mainly observed in the second and third flushes (Figure 9Figure 10).

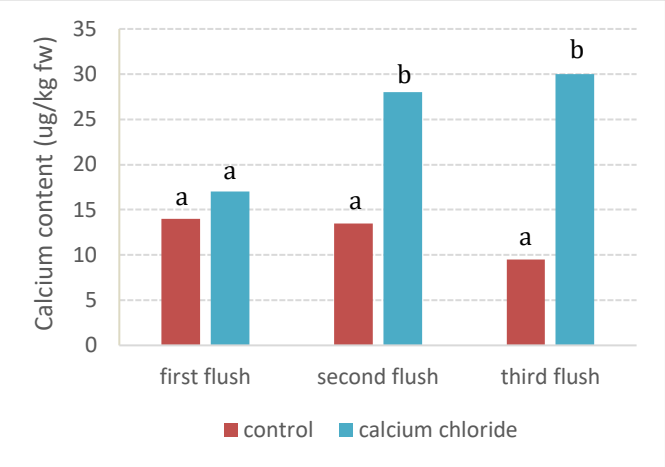


Figure 9. Calcium content of mushrooms irrigated with 0.3% CaCl2. Derived from Kukura et al., 1998.

- While $CaCl_2$ improves whiteness at harvest, greater differences emerge during storage between treated and untreated mushrooms in terms of both browning[34] and development of bruises[32] (Figure 10).

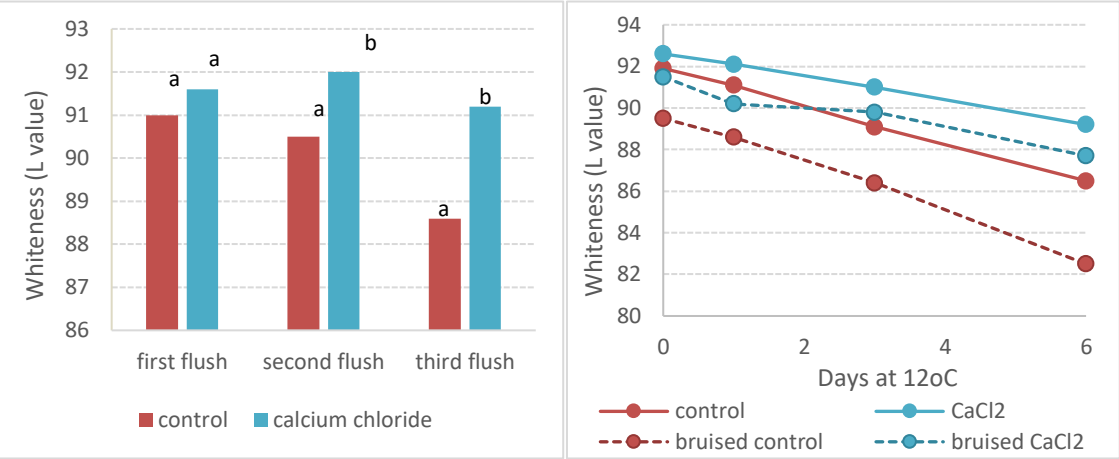


Figure 10. Effect of irrigation with 0.3% $CaCl_2$ on initial colour at harvest (left) and browning of bruised and unbruised mushrooms during storage at 12°C (right). Derived from Kukura et al., 1998.

- A trial at the Marsh Lawson Mushroom Research Unit (MLMRU) compared mushroom quality following irrigation with 0.3% $CaCl_2$, tap water or reverse osmosis filtered water. In the case of flush 3, the effects of the treatment were visible after only a few days of storage (Figure 11).

Figure 11. Third flush mushrooms irrigated with tap water (left) or 0.3% $CaCl_2$ (right) then stored for 6 days at 3°C.

- The effects of adding $CaCl_2$ to irrigation water on dry matter are variable.
    - The majority of trials report significant increases in dry matter. For example, trials by Desrumaux et al (2000) found that 0.4% $CaCl_2$ significantly increased dry matter, but that lower concentrations had less effect. Beelman et al. (2000) and Hartman et al (2000) also reported significant increases in dry matter from irrigating with 0.3% $CaCl_2$.
    - Irrigation with 0.6% calcium lactate also increased dry matter[35], as did addition of table salt (NaCl) to casing, suggesting that changes are primarily due to increased osmolarity in the casing soil and water[21].
    - However, other researchers e.g. Miklus and Beelman (1996) have found no effect on dry matter.
- The effects on yield are generally minor. Kaluzewicz et al[35] found that yield was decreased by the addition of 0.6% but not by 0.4% $CaCl_2$, with effects varying between strains. Philippoussis et al[36] found no effect on yield of 0.1% $CaCl_2$. Overall, addition of 0.3% $CaCl_2$ to water appears to have no consistent effect on yield[30].
- It is unclear whether $CaCl_2$ can be added to irrigation water without registration through the APVMA. Another significant potential problem is the blocking of irrigation nozzles and lines due to salt buildup.

2.4 Pinning

Key finding

Over-pinning on mushroom beds increases bruising both as the mushrooms grow and when they are picked. Careful management of CO_2 levels in the growing environment is essential; dropping CO_2 quickly can result in over-pinning, whereas dropping CO_2 too slowly will reduce yield. Reductions in temperature, the microbiota present of the substrate and the moisture content and granulation of casing also influence the number of pins that form.

- One of the key factors in producing white mushrooms is avoiding over-pinning on the beds.
    - Mushrooms that press against each other as they develop will be bruised even before harvest.

- Tightly clustered mushrooms are difficult to pick, so are likely to be further damaged simply by the process of harvesting from the beds (T. Adlington, pers. com.).
- Over-pinned crops are likely to be over-mature and soft, so are easily bruised[37].

- Pinning is stimulated in response to removal of accumulated eight-carbon volatiles (such as 1-octen-3-ol) which are produced by the mycelia. Pinning is also stimulated by drops in temperature (e.g. from 25°C to 18°C) and reductions in CO_2 levels (e.g. from 5,000 ppm to less than 1,000 ppm).
- According to Eastwood et al[38], CO_2 is the most important factor determining the number of fruiting bodies that develop due to the presence/absence of 1-octen-3-ol.
    - 1-octen-3-ol may be removed through airing or inclusion of activated carbon in casing.
    - 1-octen-3-ol is also metabolized by microbiota in the casing material, particularly various *Pseudomonas* species including *P. putida*. Monitoring levels of 8 carbon volatiles in casing, and addition of certain Pseudomonas isolates, could theoretically allow better control over pinning[39].
- The number of pins that develop also depend on the way casing material is applied; granulated, moderately moist material will result in more pins than clumping, wet material.

2.5 Disease and crop health

Key finding

Bacterial blotch, usually caused by *Pseudomonas tolaasii,* is the main disease that reduces mushroom quality. Symptoms are primarily due to production of the toxin **tolaasin**, which breaks down cell membranes, catalyzing formation of the brown pigment melanin. Wetness on mushroom caps is key to development of disease, with later flushes and poorly nourished crops generally more susceptible.

Antimicrobial washes can reduce bacterial blotch. Bacteriophages and antagonistic bacteria have successfully controlled blotch in trials, but the diversity of the bacteria that can cause disease is likely to make biological control challenging.

2.5.1 Bacteria

- While bacterial blotch can occasionally devastate crops pre-harvest, it most commonly becomes a major problem during postharvest storage[40]. Toxins released by the bacteria (tolaasin by *P. tolaasii*) disrupt the structure of the mushroom cell membranes, triggering the appearance of yellow or brown lesions on the mushroom cap[41].
- Bacterial blotch of mushrooms is a complex disease, characterized by light to dark brown sunken lesions on the mushroom caps.
    - It can be caused by a number of Pseudomonad bacteria including *Pseudomonas tolaasii*, *P. 'reactans'*, *P. costantinii*, *P. gingerii* [42], *P. fluorescens*[43] and several others.

- *Agaricus* mushrooms can also be affected by cavity disease, caused by *Burkholderia gladioli*. Symptoms range from mild blotching to deep, sunken cavities extending through the cap[44].
- Other bacterial diseases include *Janthinobacterium agaricidamnosum*, which causes soft rot, and *P. agarici*[45] which causes drippy gill or yellow blotch.
- *P. tolaasii* is the main cause of bacterial blotch symptoms. While it can devastate crops pre-harvest, growth and symptoms more commonly occur during postharvest storage[46].

- As previously noted, adding sanitiser to irrigation water is one way to manage bacterial blotch. Chlorination of irrigation water with sodium hypochlorite (bleach) was once widely practiced but of limited value[47]. Stabilised chlorine dioxide may be more effective [48]. A variety of other methods of protecting mushrooms from bacterial blotch have been proposed including;
  - A bioactive compound was extracted from strains of Streptomyces bacteria which was structurally related to Penicillins[47]. Given the importance of Streptomyces and current concern about antibiotic resistance, this approach would seem unlikely to gain support.
  - Twenty two essential oils were evaluated for control of *P. tolaasii*, as well as other bacterial pathogens. *P. tolaasii* was the hardest to control, with only wintergreen oil (mostly methyl salicylate) providing any in-vitro effect[49].
  - Application of antagonistic bacteria, including *Pseudomonas putida* and *P. fluorescens*. These bacteria reduced disease incidence in inoculated beds of mushrooms from approximately 90% to 12 – 25%[50].
  - Soler-Rivas et al[51] reported that an extract from *Pseudomonas reactans* reduced the symptoms of brown blotch infection by 50% in inoculated mushrooms, mainly due to inhibition of browning.
  - Bacteriophages can destroy host bacteria and multiply rapidly under suitable conditions. Nguyen et al isolated[41] 21 phages that infect *P. tolaasii*. Small scale laboratory tests indicated that a selected phage was highly effective against brown blotch.
  - A 2022 study isolated 42 bacteriophages active against 23 different strains of brown blotch; a cocktail of eight different phages sprayed onto infected mushrooms completely prevented brown blotch symptoms during 1st and 2nd flush [52].
  - One of the issues with phages is that they are often highly specific to a particular bacterial strain, and that resistance can develop rapidly [53].

2.5.2 Fungi

- The main fungal diseases of mushroom in Australia include dry bubble, cobweb, green mould and wet bubble. All these diseases significantly reduce mushroom yields and quality and can cause browning.
- However, the damage caused by fungal diseases is usually catastrophic to infected mushrooms. These mushrooms are unlikely to be marketable, due to deformity and rapid breakdown. While browning may occur, it is unlikely to develop postharvest in packed mushrooms.

- Moreover, the management of fungal disease in mushrooms is reasonably well understood, and there are recognised experts in Australia who work actively in the industry to help growers manage disease.

2.5.3 Viruses

- Currently the most important virus is mushroom virus X (MVX). First reported in 1996, this has presented increasing problems over the last 10 years. The main symptom is cap browning, which can affect anything from a few mushrooms to up to 80% of a flush[54]. Symptoms also vary between flushes, with first flush mushrooms the most seriously affected[55]. MVX is not currently confirmed as present in Australia.
- Other symptoms include premature opening and distorted shape. These symptoms may worsen after harvest, particularly browning of the mushroom caps[56].

2.6 Nutrition and supplements

Key finding

Supplements may be added at spawning or prior to casing. A wide range of commercial formulations and agricultural by-products are available, and microbial inoculants are likely to be commercialized in the future. Although over 20% increases in yield have been reported, results are highly variable. This is likely due to interactions between supplement and compost.

There is little evidence that supplements improve mushroom quality or whiteness, and some may even have negative effects on colour. However, not all researchers measure quality attributes, and those who do rarely include postharvest assessments.

Research need

Examine the effects of different supplements on postharvest quality and storage life. Test whether adding supplement to casing (instead of compost) increases effects on quality.

- The practice of adding nutritional supplements to compost during either spawn run or casing has been practiced since the 1960s[57]. A wide range of commercial supplements are available. Examples include;
    - ProMycel Gold, Champfood E, MCSubstradd – mainly soy protein based
    - Natural Gold – a blend of lipids and protein
    - MycroNutrient – Carboxylic acid (casing supplement)
    - Micromax – mineral micronutrients
- In 2015, Burton and Noble reviewed supplement use in Europe. They found that >90% of phase 3 compost is supplemented, usually with a protein-based product. It was widely believed that supplements increase quality as well as yield. The products were usually applied during spawning at a rate of 1.2 – 1.5%.
    - It is likely that the majority (>90%) of Australian growers also supplement compost.
- Subsequent trials[58] examined the effect of supplements adding during spawning;
    - All of the tested protein-based supplements significantly increased yield (11.5%), while Promycel Gold and Champfood E significantly increased mushroom density.
    - Although ‘L’ values (whiteness) were not affected by the supplements, both ProMycel Gold and MC Substradd increased ‘b’ values (yellowness) (Figure 12). While this is clearly undesirable, the authors suggest this difference may not be detectable by consumers.
    - Although non-protein supplements had little effect in this trial, they had previously been reported as improving yield and quality in the US. This suggests the latter composts may be deficient in the elements these contain.

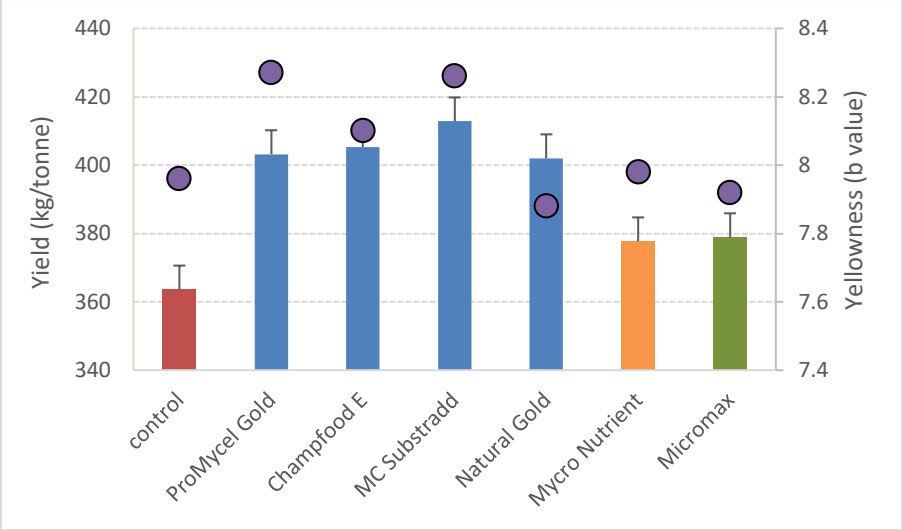


Figure 12. Effect of supplements on yield (columns) and yellowness (yellow dots) of white mushrooms. Products were based on protein or protein plus lipids (blue columns); carboxylic acid (green column) or micronutrients (grey column). From Burton and Noble (2015).

- While Spanish researchers have published prolifically on the effects of both commercial and low-cost supplements on yield and quality, effects are generally small;
    - Work published in 2012[59] did not find significant differences in either yield or quality between mushrooms grown with ProMycel Gold, Champfood S, Calprozime or various grapeseed extracts compared to non-supplemented controls.
    - ProMycel 600, up to 15g/kg defatted pistachio meal[60] or 15g/kg defatted almond meal[61] failed to significantly increase yield or improve whiteness compared to non-supplemented controls.
    - Later work[62] found a 10% to 22% increase in yield when compost was supplemented with 0.8% ProMycel 480. Again, there were no significant or consistent effects on either 'L' or 'b' values, suggesting colour was unaffected.
    - The trials with ProMycel 480 were repeated in Brazil. Yield was increased by 10 to 16%, with no significant effects on mushroom colour or other quality parameters[63].
- An alternative approach, but not widely used commercially, involves supplementation of casing. An Iranian study by Adibian and Mami (2015)[64] examined the effect of supplementing casing (peat) with ground corn or soybean meal.
    - While all mushrooms appeared similar at harvest, differences emerged during storage at 4°C. Adding 51g of either material to 5kg of peat significantly reduced browning during storage (Figure 13). Adding 17g or 34g had intermediate effects.
    - The 51g/5kg soybean meal treatment also significantly increased protein content.

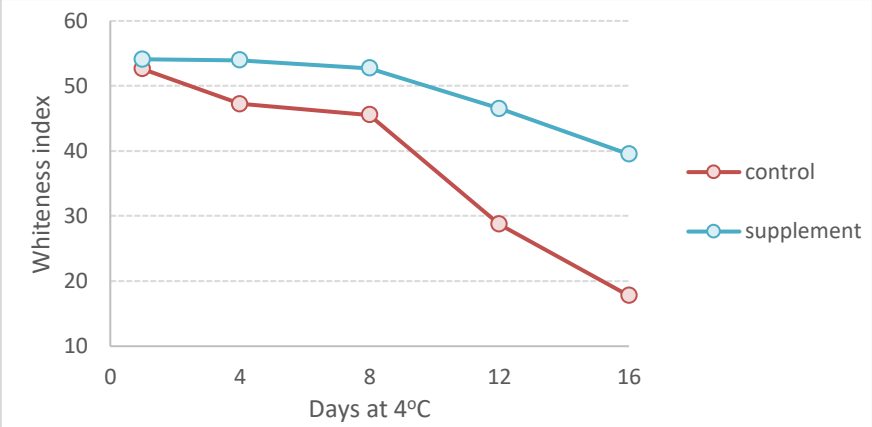


Figure 13. Effect of supplementing casing with 10g/kg corn or soybean meal (average of both treatments) on the whiteness index of stored mushrooms. Whiteness index calculated from presented data using the formula WI = L – 2b + 3a. Derived from Adibian and Mami, 2015.

- This effect is consistent with a report from 1991, which found that although mushrooms supplemented with 300ml safflower oil/tray at casing were similar to controls at harvest, quality retention during storage at 12°C was improved[65].

2.7 Choice of variety and breeding

Key finding

Susceptibility to browning and bruising differs between varieties. Research has identified numerous genes involved in browning reactions. However, deleting some browning genes reduced vigour of the hyphae. Work is progressing on using new genetic techniques to overcome issues with mushroom breeding and quench production of browning compounds.

- Differences in quality between strains of *Agaricus bisporus* can be observed, including colour, size, dry matter content and shelf life(Walton, 1987).
- Developing strains of *Agaricus bisporus* with reduced levels of either phenols or enzymes would be a clear way to produce less bruise-sensitive, longer lasting mushrooms.
- Researchers have attempted to define differences between 'bruising sensitive' and 'bruising tolerant' strains. This information could then be used in breeding programs to ensure new strains have good agronomic properties. For example;
    - Weijn et al.[68] identified two specific compounds (GHB, GDHB) associated with bruising sensitivity. These compounds were 15x to 20x higher in bruising sensitive strains compared to tolerant strains.
    - Indian researchers have developed two high yielding strains with low enzymic activity, so reduced browning after slicing [69].
    - Gao et al.[70] used PCR techniques to identify and locate quantitative trait loci (QTLs) in the mushroom genome, which were associated with browning sensitivity.
    - Sylvan has adopted next generation sequencing techniques to identify the locations of QTLs on the mushroom genome, with the aim of increasing the efficiency of new variety development (Loftus, 2016).

2.7.1 CRISPR-Cas9

- CRISPR stands for “clustered regularly interspaced short palindromic repeats”. The technique is highly targeted at specific genes, using the DNA cutting enzyme “Cas9” to delete targeted sections of DNA. As no new DNA is introduced, the transformed cell is not considered ‘transgenic’.
- If the areas of DNA responsible for browning can be identified and deleted, then it should be possible to produce a non-bruising mushroom.
    - In 2016 it was announced that Professor Yinong Yang, a plant pathologist with Penn State, had successfully deleted genes responsible for browning using CRISPR techniques. However, this variety has not been further promoted or commercially adopted
    - Mushrooms contain six different polyphenol oxidase (PPO) enzymes, these being responsible for browning reactions. Deleting the two main PPO genes has negative effects on mycelium growth
    - Other issues with using CRISPR for mushrooms include difficulties transporting the CRISPR particles through the cell walls, and presence of very large numbers of nuclei (up to 40) within individual cells; each nuclei would need to be transformed to ensure traits were retained.

3 Harvesting

Key finding

Mushrooms picked as buttons deteriorate more slowly during storage than mature mushrooms. Mushrooms are less likely to continue to develop during storage if they are picked at the start of the flush than at the end, and if the stipe is cut short instead of long.

Multiple systems are under development for robotic picking, transport, trimming and packing of mushrooms. Of these, it is the systems which aid human pickers, allowing them to work more efficiently, which are the most advanced and commercially adopted.

No independent reviews on the effects on mushroom quality and storage life of robotic or harvest-aid systems were found for this report.

Research need

Independently review whether new harvesting and packing systems affect storage life and quality of mushrooms.

3.1 Harvest timing and method

- Mushrooms harvested early, while still relatively small and immature (veils intact and tight) brown more slowly during storage than more mature mushrooms [14].
- Braaksma et al. (1999) harvested mushrooms of similar size and weight, on consecutive days of the flush. Mushrooms harvested on day 1 were most likely to remain closed after 4 days at 20°C. There was a major increase in the proportion of open caps between harvest days 2 and 3, while mushrooms harvested on day 4 opened rapidly.
- Trimming the stipe to 5mm immediately after harvest reduces browning during storage compared to leaving the stipe long (30-35mm)[72].
    - It is believed that this is due to inhibition of further physiological development, which is otherwise fueled by the stipe[14].
    - According to work by Mau et al (1993), combining short stipes with $CaCl_2$ irrigation increased storage life.
- However, removing more stipe effectively reduces yield. Trimming the stipe to 5mm compared to 35mm reduced the yield of mushrooms by about 10% [72]
- Mechanical harvesters are available which effectively 'mow' the bed of mushrooms.
    - The cut mushrooms are carried on a conveyor to the packing area, while a stump remover is passed over the bed so as to allow the next flush to come through.
    - The mushrooms are too heavily bruised and damaged for the fresh market, but are suitable for canning or processing.
- There are multiple robotic harvesting systems under development for fresh mushrooms by both academic and commercial interests.
- Chinese researchers have developed a laboratory scale robotic harvesting and trimming unit which uses a suction cap to pick the mushrooms[73].

- The unit could pick mushrooms that were growing straight in the bed but could not attach to ones at an angle.
- Circular marks form the suction cap were evident three days after picking, especially when high pressure had been used to remove mushrooms from the bed.

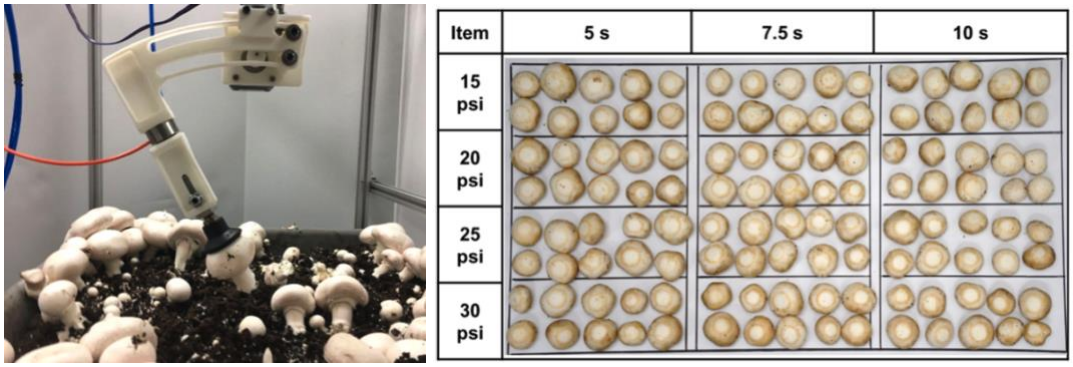


Figure 14. Robotic picking arm with suction cap and resulting marks on mushrooms after three days storage. From Huang et al., 2021.

- The Canadian company Mycionics have developed a robotic harvesting unit which can be hired out as a picking service (Figure 15). The system includes three machines:
  - A scanner which collects data on the bed, including mushroom size and location
  - A battery-operated robotic picker, with three gripper fingers operating off a solid robotic arm
  - A packing unit which fills punnets
  - Mycionics have conducted commercial trials of the robotic harvester in combination with the Christiaens Group™ Drawer System (Figure 16).

Figure 15. The Mycionics bed scanner (left) and robotic arm with picking fingers (right)

Figure 16. The Christiaens Group drawer system combined with Mycionics robotic harvester, and the picking fingers (right)

- While robotic harvesting has had limited uptake, new systems that make picking more efficient are increasingly integrated into new farms. These include tilting shelves (GTL Europe) and a moveable drawer system (Christiaens group).
- Several companies can install moving belts or chains to transport mushrooms out of the growing room, allowing harvest workers to pick with both hands at once. Mushrooms are transported past a trimming knife and into a centralized packing area.
- Automated packing units are now under development.
    - A prototype packer by GTL Europe allows mushrooms to be placed into punnets cap up
    - Other units eject mushrooms out of the belt or chain allowing them to fall into punnets
- While companies manufacturing such systems state that there are no adverse effects on quality (e.g. increased bruising, reduced storage life) from impacts incurred on robotic picking / packing machines, no independent data verifying this could be accessed for this review.

3.2 Handling during harvest and packing

Key finding

Mushrooms are easily damaged during harvest and packing. Bruising sensitivity varies by flush, mushroom size and maturity and increases after harvest. However, reported results are inconsistent. Damage may not become apparent for 24hrs, by which time the mushrooms have reached wholesale or the retail distribution centre.

Researchers have developed sensors which measure enzyme activity or directly detect browning; mechanization of harvesting and packing could potentially allow such sensors to be used in grading systems.

Research need

Examine whether the delay between harvest and cooling, and postharvest weight loss, affect susceptibility to bruising. Test whether mushrooms bruise more easily when cold or warmer, and examine the effect of firmness on bruising susceptibility.

- Mushrooms are easily physically damaged during harvest and packing. Even light squeezes or vibration can trigger browning reactions, which greatly reduce their market value[74].
- Browning in mushrooms is caused by polyphenol oxidases (PPOs) and peroxidases. Enzymic reactions lead to the formation of the brown pigment melanin. Selection of strains which have reduced amounts of PPO, or use of treatments that deactivate these enzymes, have the potential to greatly reduce bruising sensitivity and improve visual quality[75].
- Bruising sensitivity is higher in mushrooms with open caps and tends to be higher in first flush mushrooms than those from the third flush. In all cases, bruising sensitivity increases during the first 24 hours after harvest[76].
- One of the reasons mushrooms bruise so easily relates to their structure[29]. The cap surface overlays a relatively low cellular density zone with limited resistance to crush damage, compared to the higher density core tissue which determines texture (Figure 17).

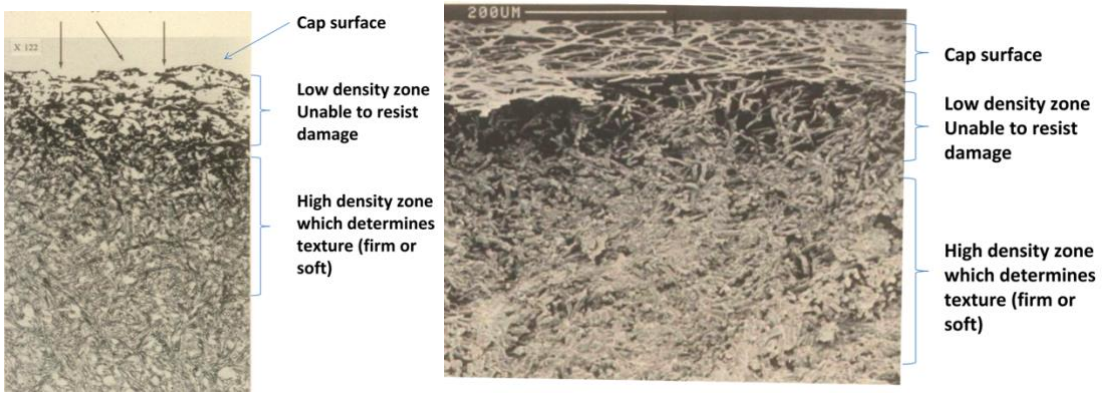


Figure 17. Mushroom cellular structure and density is a factor in bruising susceptibility. From Burton, 2011.

- Mushrooms are easily bruised during picking. Avoiding damage during harvest requires good supervision, effective training and well-motivated employees[77].
- Some growers have found that paying hourly rates results in better quality than paying by weight picked. Others pay picker team bonuses according to total marketable mushrooms per bed to discourage waste.

- Bruising was examined in some detail by Weijn et al, 2012[78]. The factors that increased bruise development included;
    - **Variety**; e.g. the variety Somycel X135 developed less severe bruising than varieties Darlington 735 and Horst U1 (Figure 18)
    - **Time**; bruises continue to develop and darken for more than 2 hours after damage has occurred (Figure 18)
    - **Storage interval**; as the time between harvest and damage increased, so did the degree of bruising, with mushrooms significantly more susceptible to bruising 24 hours after harvest than 2-4 hours after harvest (Figure 18)
    - **Size and maturity**; a trend was noted to increased bruising susceptibility in small mushrooms (25-35mm) compared to larger ones (55-70mm).
        - Small mushrooms with open caps were the most susceptible to bruising.
        - Large mushrooms with open caps were <u>less</u> susceptible to bruising than those with closed caps, so there was no significant effect on maturity overall (Figure 19).
        - It should be noted this is a different result to earlier researchers, who found that mushrooms harvested at earlier developmental stages are <u>less</u> susceptible to browning.
    - **Flush**; although first flush mushrooms were more sensitive to bruising than those from the second flush, the third flush was the most easily bruised – again, this is a different result to those reported previously, where first flush mushrooms were firmer so less easily bruised.

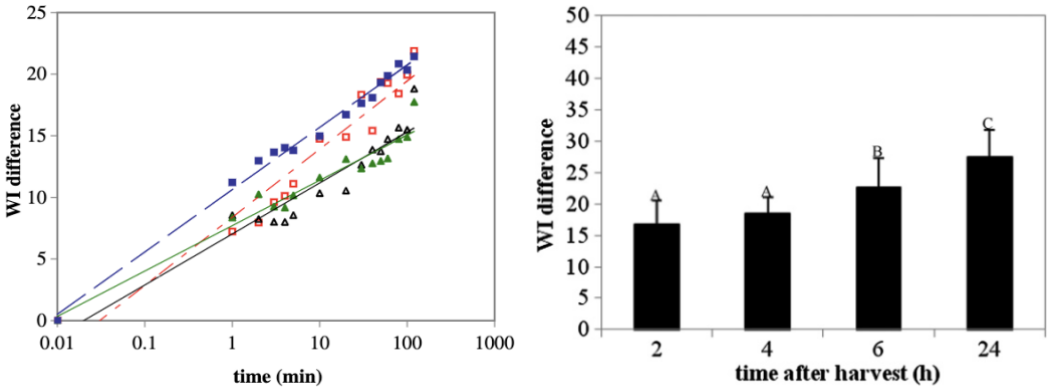


Figure 18. Bruise development of four mushroom varieties over time (left) and the effect of the time interval between harvest and damage (right). Bruising was measured in terms of the whiteness index (WI), being the difference between bruised and non-bruised parts of the mushroom cap. From Weijn et al., 2012.

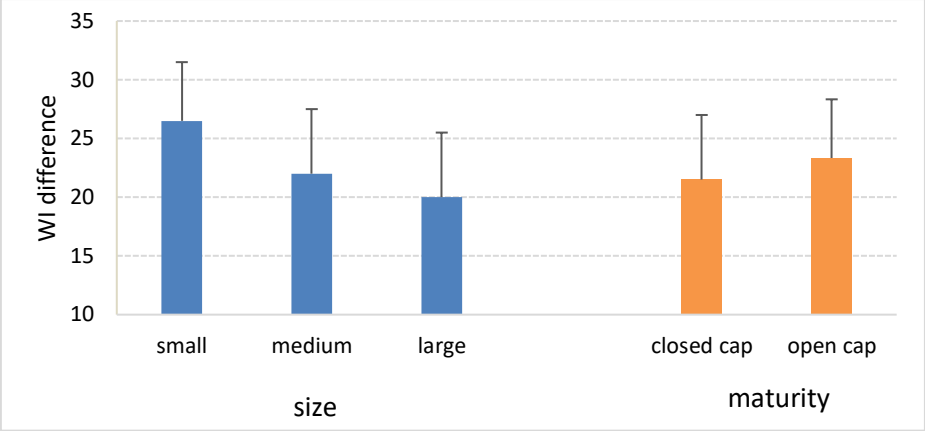


Figure 19. Average bruise development according to mushroom size and maturity. Bars indicate the approximate std. deviation of each mean value[. Derived from Weijn et al., 2012.

- Two compounds (GHB, GDHB) are associated with bruising sensitivity. These compounds are 15x to 20x higher in bruising sensitive strains compared to bruise tolerant strains[78]
- Considerable recent research has tested using near infrared (NIR) imaging to either determine enzyme activity in mushroom caps or measure browning reactions. It seems possible that new robotic packing systems, where mushrooms are moved on a belt or chain, could allow such sensors to play a role in grading. For example;
    - Gaston et al[79] tested NIR for predicting PPO activity and, therefore, the likelihood of browning.
    - O'Gorman et al[80] used NIR to evaluate damage on freshly harvested mushrooms.
    - Esquerre et al[81] also used NIR to detect bruising damage.

3.3 Cleaning and washing

Key finding

In some countries mushrooms are washed, especially if they are going to be processed. A wide range of products have been tested. A patented two stage process is used commercially in the USA. More recent research has focused on plasma activated water and electrolysed water, both of which have anti-microbial properties.

- In some countries mushrooms are washed before sale, especially if they are going to be processed[82]. Washing solutions can be used not only to remove casing and compost, but also whiten and sterilize, reducing food safety risks as well as blotch development.
    - Two-stage washing processes have been developed in the USA (Beelman-Duncan, US Patent no. 5,919,507) and are used commercially to reduce browning and improve food safety of mushrooms.
    - Sapers et al[83] determined that the optimum process involved a pre-wash with 0.5% hydrogen peroxide (H_2O_2), followed by a 30 second dip in 5% H_2O_2 then a spray with 4% sodium erythorbate + 0.1% NaCl.
    - Tarlak et al (2020)[84] replaced sodium hypochlorite (bleach) with sodium chlorite, and reported good results washing for up to 60 seconds in 1g/L solution
- Other authors have tried to improve on washing using different processes e.g.:
    - Mushrooms washed in electrolyzed water (chlorine content ≥25mg.L^{-1}) for 3 minutes retained whiteness and texture better than mushrooms washed in water alone[85]. Note this trial did not include an unwashed control.
    - Soaking mushrooms in plasma activated water (PAW) for 5 or 10 minutes reduced external pathogen populations, slowed weight loss and improved firmness during storage. Unfortunately, the washed mushrooms were browner than unwashed controls [86]
    - Other researchers have reported that immersion in PAW reduced both browning and weight loss, although in this case a 20 minute dip was used [87].
- While washing can have benefits, it adds cost and complexity and potentially increases disease, as well as reducing nutritional value, of mushrooms[82].

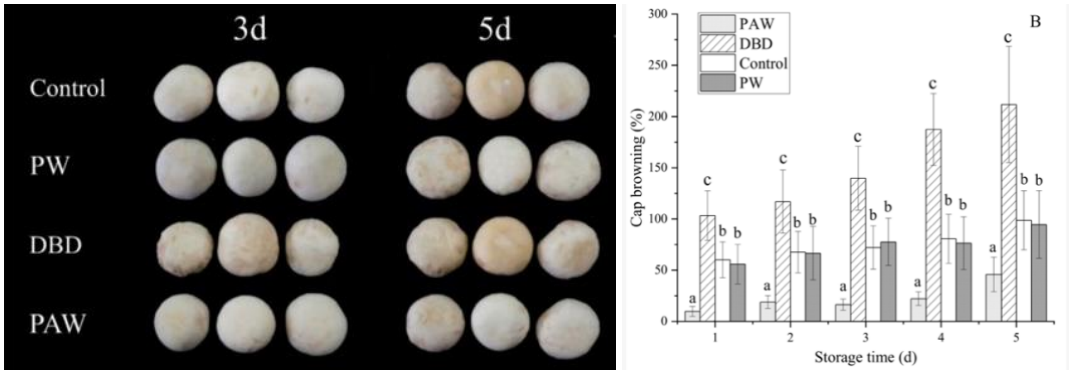


Figure 20. Mushrooms were untreated (control), immersed for 20 minutes in water (PW), immersed in plasma activated water (PAW) or exposed to atmospheric plasma (DBD). From Zheng et al., 2022.

4 Postharvest treatments

4.1 Postharvest dips

Key point

There is considerable research interest in using anti-browning reaction dips to extend storage life of mushrooms. While some results appear impressive, trials often do not include an undipped control, use mushrooms with high bacterial populations and store mushrooms at higher than optimum temperatures. It is unclear which of these would be suitable for commercial application and could potentially be applied without registration through APVMA.

Research need

Determine which dips are worthy of further investigation. Consider whether they could be applied pre-harvest in irrigation water rather than as a postharvest dip.

- A significant number of papers describe the effects of novel postharvest dips and washes. Many claim to reduce browning by deactivating enzymes such as polyphenol oxidase or tyrosinase.
- Australian mushroom farms are highly unlikely to adopt dips or washes, particularly for fresh, whole mushrooms. However, these products may have potential as part of a pre-harvest spray or irrigation program, so some selected examples are as follows:
    - Soaking whole mushrooms in 40g.L^{-1} citric acid or 50ml.L^{-1} H_2O_2 for 10 minutes increased shelf life of sliced mushrooms from 11 days to 15 and 14 days respectively at 4°C [88].
    - Simon and Gonzalez-Fandos[89] combined citric acid with 1.5% sodium ascorbate. Dipping in citric acid reduced the population of *Pseudomonas* bacteria by 99.8%, increasing storage life to 13 days at 5°C.
    - Two-minute dips in citric acid combined with calcium chloride and sorbitol were shown by Khan et al[90] to retain antioxidants during storage, but effects on quality were minor.
    - Hu et al tested a 60 second dip in 4 methoxy-cinnamic acid; this naturally derived extract has been shown to inhibit tyrosinase, involved in browning reactions. Treatment inhibited enzyme activity, reducing browning, cap opening and weight loss [91].
    - Treatment with 250µM salicylic acid (aspirin) reduced cap browning [92]. Note this work was un-replicated.
    - One-minute dips in 1 or 3 µM solutions of the natural plant hormone brassinolide, protected cell membranes from oxidative damage and halved the rate of browning in storage[93] (Figure 21).
    - Enzyme activity can also be reduced by the amino acid L-arginine. A 10 minute dip in 10mM L-arginine reduced PPO activity and improved cohesion in the outer layer of the mushroom cap[94] (Figure 28).

- Zhu et al (2021)[95] found that a 5 minute dip in 100mg/L gibberellic acid (a plant hormone) improved quality and storage life compared to dipping in water alone. Unfortunately, there was no undipped control.

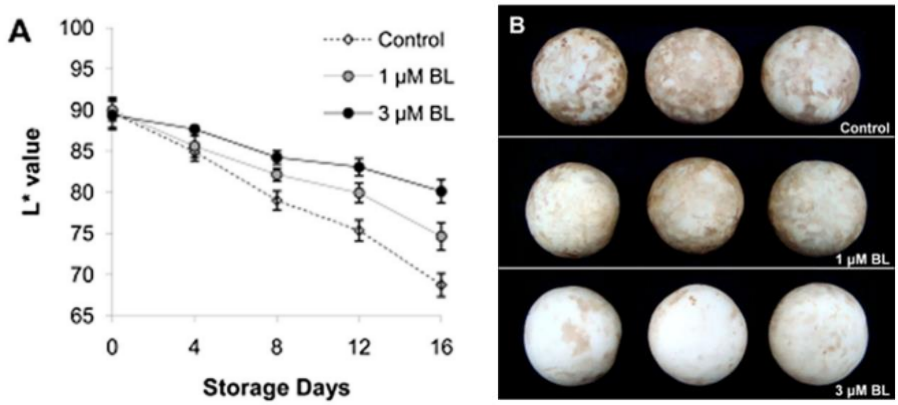


Figure 21. Changes in colour (A) and appearance (B) of mushrooms dipped for one minute in 1 or 3 µM solutions of brassinolide. From Ding et al, 2016.

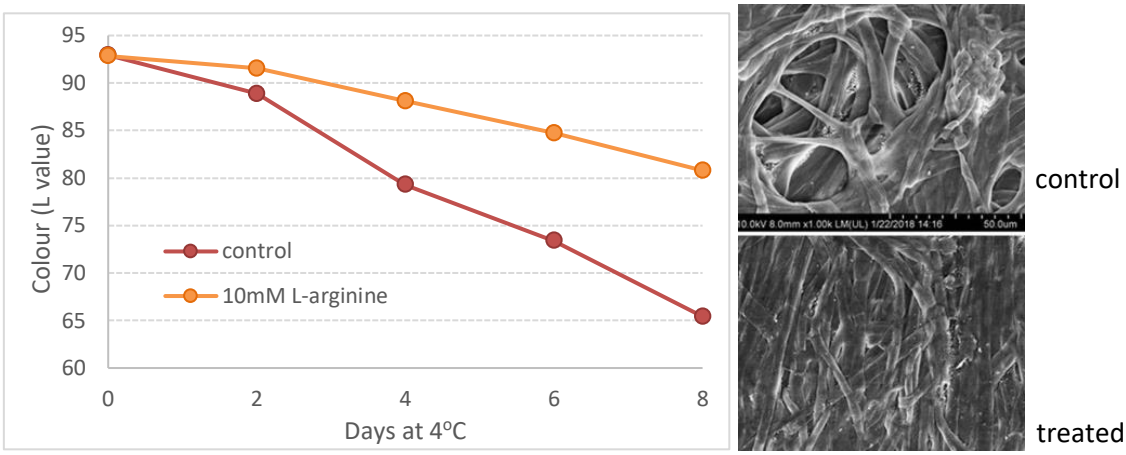


Figure 22. Changes in colour (left) and electron microscope image of surface structure (right) of mushrooms dipped in 10mM L-arginine or water. From Li et al, 2019.

- It seems possible some materials proposed as dips could be applied as pre-harvest sprays. For example, the plant growth regulator methyl jasmonate (MeJA) has been widely associated with improved plant defences.
    - According to Jahangir et al., (2011), application of MeJA as a postharvest dip reduces browning due to inhibition of oxidative enzymes.
    - Chinese researchers tested the effects of spraying developing pins (approx. 12mm) with 10, 100 or 200µm of MeJA. Although mushrooms were similar at harvest, all three levels of MeJA inhibited browning during storage at 4°C, with significant benefits after only two days. The best results were achieved with the 100µm treatment[96].

4.2 Edible coatings

Key finding

Researchers have tested a range of coatings, including chitosan, essential oils and even aloe vera, with mixed results. It seems unlikely that such treatments would be economic or acceptable to consumers.

- Chitosan, produced from shellfish waste, has anti-bacterial properties and has frequently been the subject of research. (Note that although chitosan should not contain allergenic proteins, it may be necessary to label treated products).
    - Abou-Elwafa et al (2023) reported that a 5 minute dip in 2% chitosan reduced weight loss and browning during storage at 1°C [97]
    - Eissa[98] reported positive effects from an edible chitosan coating on sliced mushrooms due to reduced bacterial growth.
    - When this work was repeated with better quality mushrooms, chitosan had negative effects on mushroom colour, although storage life was stated to be increased due to prevention of cap opening (Nakilcioğlu-Taş & Ötleş, 2020).
    - Other authors[100] have also found negative results from direct application of chitosan to mushrooms.
- A number of studies have examined the effects of coatings that include essential oils, with gums or other materials used as carriers.
    - For example, Xu et al (2022)[101] reported that coating mushrooms with 2% sodium alginate plus 0.2% ascorbic acid reduced respiration, weight loss and colour change
    - While such materials have been shown to affect enzyme activity and, in some cases, microbial growth, the effects on mushroom quality are not always presented[102] or may be negative[103].
- Coating mushrooms with a 50% aloe vera solution before storage reduced surface browning and inhibited weight loss[104]. The effects on eating quality or how this could be applied are not discussed.

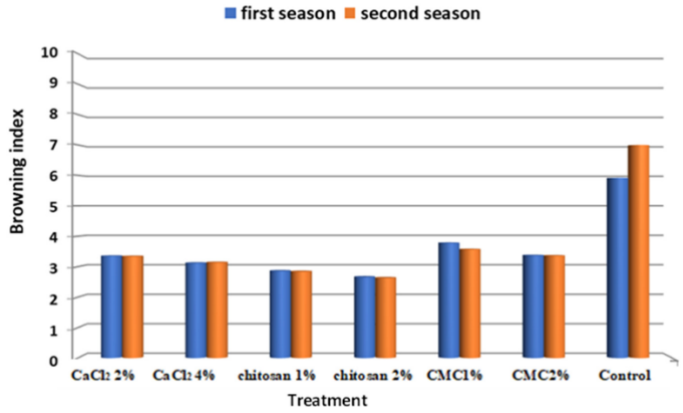


Figure 23. Effect of edible coating products on browning index following storage at 4°C. From Abou-Elwafa et al., 2023.

4.3 Fumigation in packaging

Key finding

Fumigants and other new compounds have not previously been a viable option for treating mushrooms postharvest. However new technologies can incorporate compounds directly into packaging materials or encapsulate them for slow release within packages. This could allow integration with normal packing practices. Cost, practical difficulty and effects on flavour and aroma are unknown.

- Numerous researchers have examined whether volatile compounds can be incorporated into packaging, effectively treating mushrooms as they move through the supply chain. Candidates include methyl jasmonate[105], essential oils [106], [107], sulphur dioxide (released from sodium metabisulfite pads) and even green tea extract[107].
- The use of essential oils was recently reviewed by Guo et al (2023) [108] who note the use of lemon, oregano, cinnamon, cumin, thyme and turmeric essential oils to preserve mushrooms.

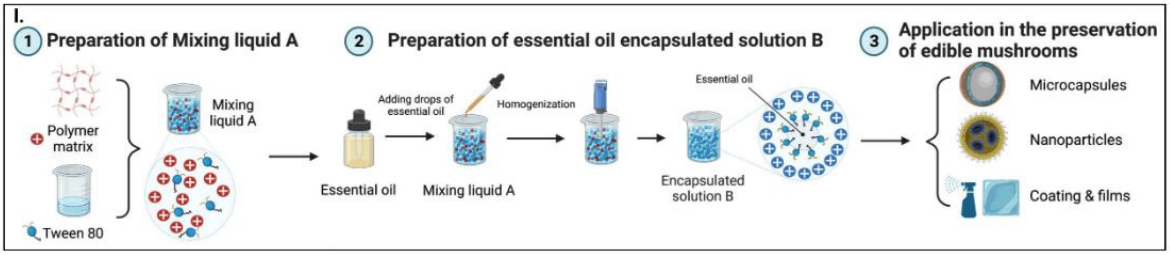


Figure 24. Edible oil slow release systems to preserve mushrooms; schematic summary by Guo et al., 2023.

- A popular methodology involves encapsulating the volatile into nano-particles of a compound such as chitosan, placing a drop onto absorbent materials and sealing inside a plastic package with the mushrooms. Many authors have reported good results from this technique:
    - Microencapsulated rosemary and thyme oil inhibited browning during storage[109].
    - Bitter orange[110] and cumin[111] essential oils were microencapsulated with chitosan; microbial growth and browning enzymes were suppressed, the cumin oil proving most effective (Figure 25).
    - Moradian et al[112] tested rosemary oil, as well as extracts of green tea and pomegranate peels. The compounds were incorporated into a biodegradable bacterial-cellulose based material. All three reduced browning and weight loss.
    - Qu et al[113] took a different approach, fumigating mushrooms with peppermint oil for 24 hours at 20°C before re-packing and storing at 4°C. Fumigation delayed browning as well as reducing weight loss and softening.

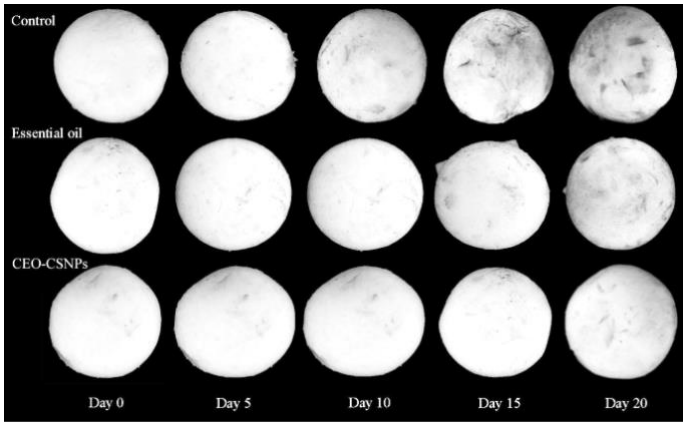


Figure 25. Appearance of mushrooms packed with water only, cumin essential oil (CEO) or CEO microencapsulated into chitosan nanoparticles (CEO-CSNPs). From Karimad et al., 2019.

4.4 Ethylene removal and 1-methylcyclopropene (1-MCP)

Key point

Ethylene has not previously been considered to create issues for mushrooms. However, there is some research suggesting that mushrooms are ethylene sensitive, so exposure may accelerate senescence, while blocking ethylene's effects (through 1-MCP fumigation) can increase storage life.

Research need

Determine whether mushrooms are sensitive to ethylene. If so, test whether the exposure times and concentrations that could occur within commercial supply chains are likely to be reducing storage life. Also determine whether the ethylene inhibitor 1-MCP is likely to provide commercial benefits for mushrooms.

- Mushroom mycelia are known to emit ethylene, with production peaks occurring in the compost in conjunction with the maturation of mushroom fruiting bodies(Ward et al., 1978).
- Harvested mushrooms are classified as low emitters of ethylene and are usually considered to have little sensitivity to ethylene. However, new research suggests that exposure to low levels of ethylene – as may occur during transport and storage – may accelerate deterioration.
    - Mushrooms treated with (the ethylene releasing compound) ethephon deteriorated more rapidly than water-dipped controls during storage at 20oC [115] (Figure 26).
    - Fumigation with the ethylene inhibitor 1-methylcyclopropene (1-MCP) slowed changes in quality during storage at 6^{o}C [115]
    - Fumigating mushrooms with 1-MCP before sealing in modified atmosphere packaging reduced changes in the atmosphere inside the bags (by reducing respiration rate) and resulted in less browning of the mushroom caps after 4 days or more at 5^{o}C [116].
    - The researchers suggest that the best results were obtained using the combination of 1-MCP and medium permeability film (Figure 27).

- Ethylene absorbers such as potassium permanganate have been incorporated in packaging materials, and delayed browning and softening (Ni et al., 2021).

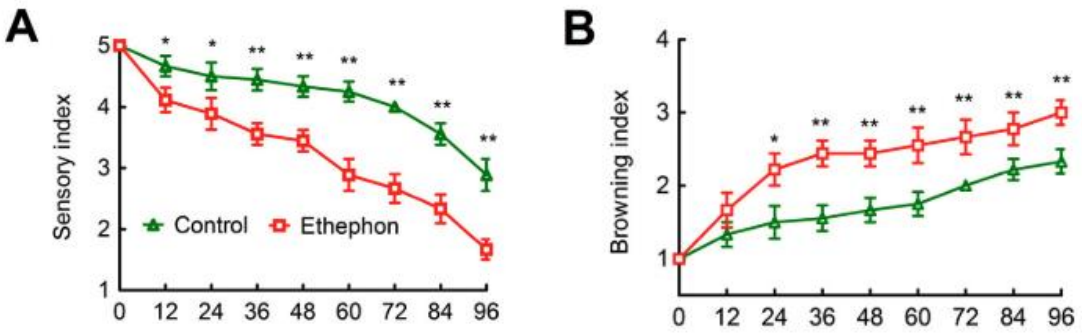


Figure 26. Changes in button mushroom sensory index (A) and browning index (B) treated with ethephon or water during storage at 20°C (Li et al. 2019).

	Film permeability	Control	1-MCP
After 4 days	Low		
	Med		
	High		
After 15 days	Low		
	Med		
	High		

Figure 27.Condition of mushrooms treated for 12 hours with 5µl/L 1-MCP then packed in films with varying permeability, following storage for 4 or 15 days at 5°C. From Sun et al., 2020.

- Note that the original Ward et al[114] research did not find any effect on stipe elongation or cap development from exposing mushrooms to 100ul/L ethylene.

4.5 Irradiation and pulsed light

Key finding

Irradiation with gamma radiation, electron beams and pulsed UV-C light have all been demonstrated to reduce microbial loads on mushrooms. This can increase shelf life by eliminating brown blotch causing bacteria. Cost and penetration into packed punnets may be issues with these technologies.

- Low dose irradiation can alter the expression of enzymes and other biochemical processes. It can be conducted using a huge range of different wavelengths of energy. Irradiation encompasses everything from exposing mushrooms to sunlight, a cobalt-60 source or with electron beams / x-rays (available through Steritech facilities in Brisbane and Melbourne).
    - Irradiation with 1kGy can delay or prevent cap opening, stipe elongation browning and softening without negatively affecting flavor or texture[118].
    - A 1kGy dose greatly reduces microbial counts, so was effective at extending storage life of sliced mushrooms [119]
    - Increasing the dose to 2kGy or even 4kGy has also been reported to increase storage and shelf life by reducing development and browning(Zhong et al., 2023).
    - For example, Mami et al found that exposure to 2kGy through electron beam irradiation retained whiteness of whole mushrooms(Mami et al., 2014).
- Exposure to UV-C light is well established as generating Vitamin D in mushrooms, with intense pulsed light sources creating value added products[122].
    - Although UV-C light can induce slight cap browning, it reduces bacterial populations, significantly lessening bacterial blotch after 21 days at 4°C[123].
    - After 2 weeks or more, UV-C light treated mushrooms may be similar to or whiter than untreated product[124].
    - Similar results with UV-C light have been reported for whole mushrooms by Lu et al[125] and Wu et al[126] as well as for sliced mushrooms by Oms-Oliu et al[127].
    - This last study found 0.6 to 2.2 log reductions in the natural microflora of mushrooms, resulting in 2-3 days extension of shelf life.

4.6 Other methods of extending storage life

Key point

Natural plant cytokinins can retard cap opening, but do not appear to have been studied for postharvest use since this was first reported in 2001.

Ozone can reduce spread of pathogens and there are reports it can improve mushroom quality. Note that high levels of ozone can damage equipment and are dangerous to human health.

- Cytokinins are plant (and fungal) growth substances that promote cell division, increasing shelf life of some products. Cytokinins, applied to cut stipes, have been demonstrated to retard cap opening[128].
- Ozone can be used as a sanitiser, and to control mould in storage environments. It is also thought to reduce activity of PPO and therefore browning reactions.
    - Exposure to ozone at rates of 2.8 or 5.3mg/L was demonstrated to achieve greater than 2 log (99%) reductions in bacteria inoculated onto the mushroom surface[129]. Unfortunately, the condition of the mushrooms was not reported.
    - Fifteen minutes ozone exposure, followed by packing in nano-particle film packaging (containing silver particles), was reported to extend storage life by 8 to 0 days at 4°C(Wang et al., 2021).
    - Yan et al[131] used high voltage electric fields (HVEF) to ionize the air, producing a range of active substances including ozone. Storing mushrooms in the presence of HVEF reduced browning and retained structural integrity after 12 days at 4°C .

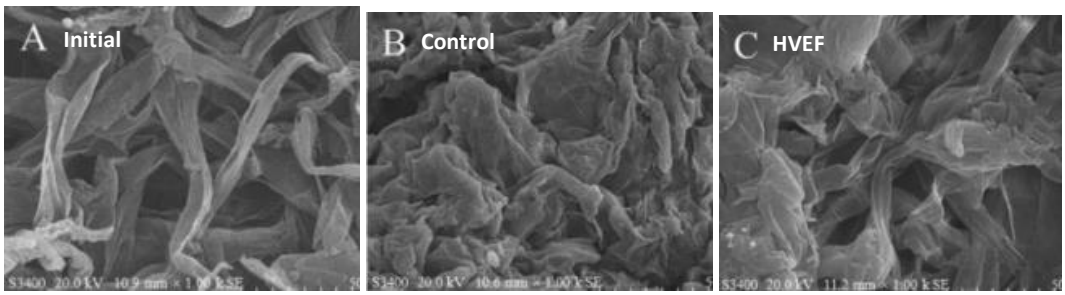


Figure 28. Microstructure of *Agaricus bisporus* when freshly harvested (A), after 12 days storage at 4°C (B) or after 12 days storage at 4°C in the presence of HVEF (C) From Yan et al., 2020.

5 Cooling and storage temperature

5.1 Cooling method and temperature

Key finding

Cooling mushrooms as quickly as possible after harvest is essential to minimise postharvest quality loss. Harvested mushrooms are cut off from their source of water and nutrients; the faster they are cooled, the less moisture they will lose. Cooling slows metabolic processes, reducing the rate at which mushrooms develop, senesce and use up their storage reserves.

Vacuum cooling is not only a fast and efficient way to cool mushrooms but may also reduce browning potential by disrupting browning enzymes in the caps. Forced air cooling can cool mushrooms 18x faster than room cooling, reducing moisture loss and browning. Mushrooms should be fully cooled before overwrapping punnets, as this interrupts airflow, slowing cooling during storage.

Research need

Survey farms to determine cooling methods used. Log temperatures of freshly harvested mushrooms to determine cooling rates and special variation within a load, with specific reference to packaging type. Test the effects of cooling delays and cooling rates on quality at retail as well as subsequent storage life.

5.1.1 Vacuum cooling

- Vacuum cooling is capital intensive, but also fast and energy efficient. Cooling occurs as liquid water inside the mushrooms changes into vapour, a process that absorbs heat energy. Naturally, this results in some weight loss; Burton et al.[132] reported that mushrooms lost 1.7% of their weight during vacuum cooling. Newer 'hydrovac' systems provide misting, which can minimise this effect.
- Mushrooms that have been vacuum cooled remain in good condition for longer than those that have been cooled more slowly using conventional methods.
    - Although mushrooms that were cooled by different methods appeared similar during storage at 5°C, significant differences emerged after transfer to 18°C for retail sale[132]. The authors estimated vacuum cooling provided an additional 24 hours life after 4.5 days storage, a difference not explained by the total time taken to cool.
    - Tao et al[133] reported that mushrooms that were room cooled were twice as brown as those that were vacuum cooled after 4 days at 4°C, a significant difference that continued for up to a week (Figure 29).

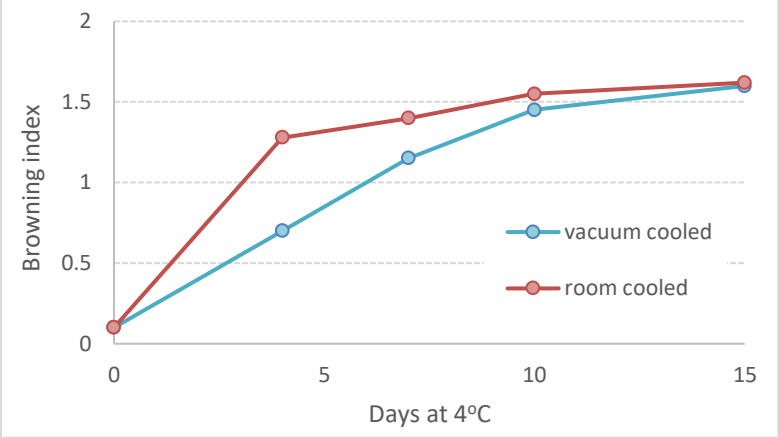


Figure 29. Increases in browning during storage at 4°C of vacuum cooled or room cooled mushroom. Derived from Tao et al., 2007.

- The effectiveness of vacuum cooling for mushrooms is not simply due to its speed, but to effects on enzyme activity. The activity of polyphenol oxidase was inhibited, while antioxidant enzyme activity increases in vacuum cooled mushrooms[133]. This may account for observed benefits even after transfer to warmer temperatures.
- Vacuum cooling effectively dries the surface of mushrooms compared to room cooling, and has been demonstrated to reduce subsequent growth of *P. tolaasi*[134].

5.1.2 Forced air cooling

- Mushrooms should be fully precooled to the desired storage temperature before room storage or transport. If not, there can be a long delay before the mushrooms reach the ambient storage temperature, which reduces quality.
    - Salamat et al. (2020)[135] forced-air cooled mushrooms to 10°C, 6°C or 2°C, and then stored in wrapped punnets at 2°C.
    - Mushrooms took 1.5 hours, 8 hours or 24 hours respectively to reach the target temperature when pre-cooled to 2, 6 or 10°C before overwrapping the punnets and placing in the storage room.
    - Weight loss increased and quality deteriorated when mushrooms were only partially cooled before punnetising; mushrooms were significantly softer and browner after 10 days storage (Figure 30).

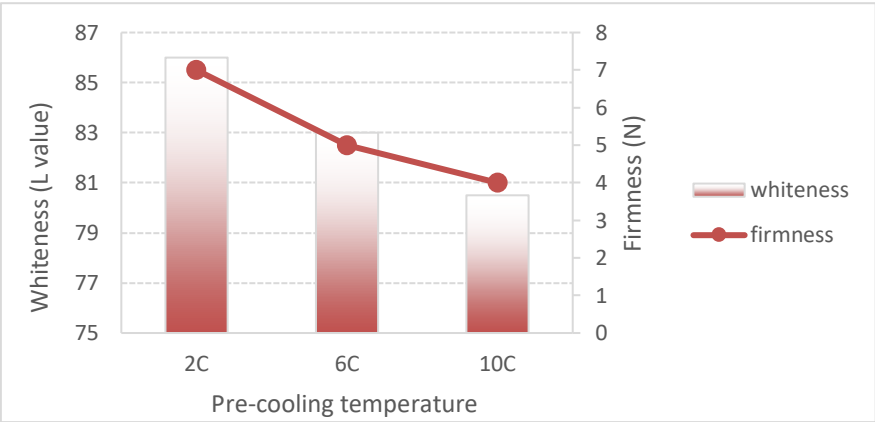


Figure 30. Effects on firmness and colour of pre-cooling to 2°C, 6°C or 10°C before overwrapping punnets and placing into storage at 2°C for 10 days. Derived from Salamat et al., 2020b.

- Large differences in cooling rate occur where air does not flow evenly across the mushrooms, as occurs during room cooling. The effect of local airflow over a single mushroom cap was modelled by Salamat et al [136], demonstrating that differences occur even on this small-scale.

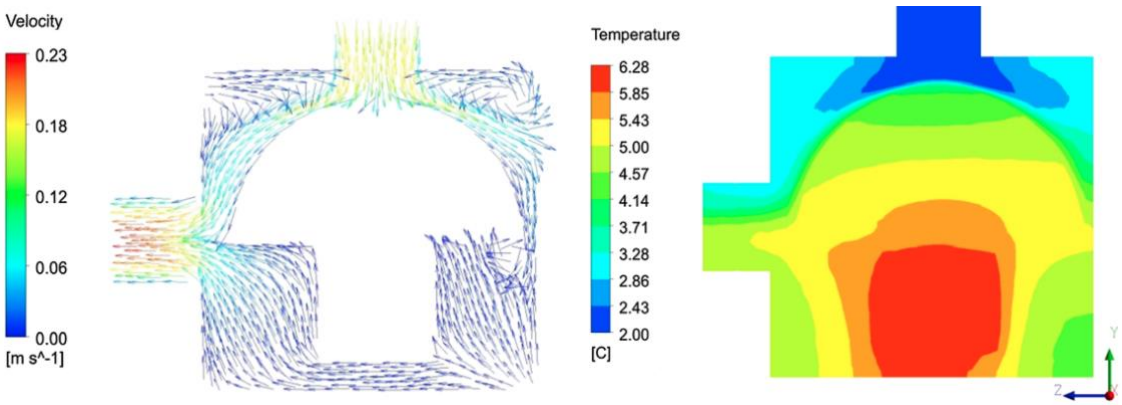


Figure 31. Air velocity contours and temperature contours inside a mushroom after one hour of cooling. From Salamat et al., 2020a.

5.2 Storage temperature

Key finding

Storage temperatures should be low and uniform to maximise mushroom storage life and avoid condensation. Mushrooms should be held at 0-2°C to minimise respiration, development, and water loss. As mushrooms freeze at approximately -0.8°C, mushrooms should never be placed directly under 0°C delivery air.

- As mushrooms are mostly water, their freezing point is approximately -0.8°C. Storage life is maximized at 0-2°C with 90-95% RH.
- There is a strong, non-linear relationship between temperature and storage life, with storage life falling to 0 to 1 days at 21°C, but frequently exceeding two weeks at 0°C. The greatest gains in storage life occur between 2 and 10°C (Figure 32).

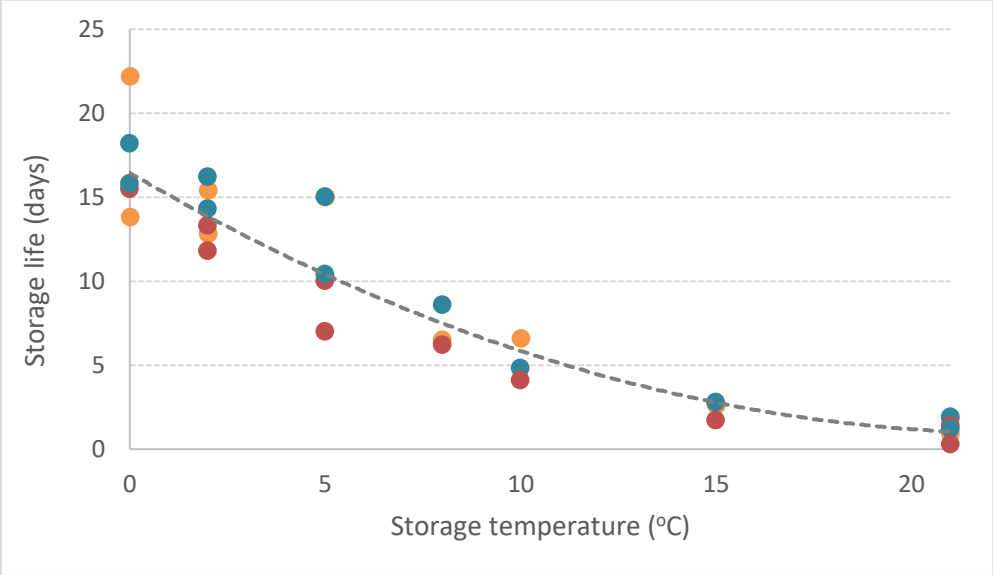


Figure 32. Relationship between storage temperature and marketable life for mushrooms. Line indicates average best fit. Data from two cropping cycles, divided into first ●, second ● and third ● flushes. Authors own data.

- Minimising temperature fluctuations during storage and transport prevents condensation forming on either the mushrooms or their packaging. Condensation on packaging indicates moisture loss from mushrooms, while condensation on mushrooms leads to bacterial blotch. Both processes reduce whiteness. Uniform temperature control can be achieved by:
    - Reducing the gap between the high and low temperature setpoints (when the compressor turns on/off) for the coolroom.
    - Minimising the frequency with which doors are opened and using an air curtain to reduce ingress of warm air.
    - Ensuring cold rooms are well insulated, and that insulating materials are sealed against moisture.
    - Loading directly from cold rooms into pre-cooled trucks.

5.3 Effect of temperature on respiration rate

Key finding

Mushrooms are developing rapidly when harvested, as so have a high respiration rate. There is an inverse relationship between storage life and respiration rate; as respiration increases, storage life declines.

Respiration rate increases are most significant at warmer temperatures.

Damage such as bruising or slicing also increase respiration rate, but not by as much as occurs for some other products.

- Mushrooms have a high rate of respiration and few storage carbohydrates to sustain them after they have been removed from the parent mycelium. It may therefore be expected that respiration rate should mirror storage life; high respiration rate = short storage life.
    - Trials at CSIRO found that, in total, mushrooms respired approximately 5.8 ± 1.5 ml O_2/kg between harvest and the end of storage life. It was concluded that respiration rate was a moderate to good guide to expected storage life of mushrooms (authors own data).
- Respiration increases significantly as temperature rises (Figure 33). For example:
    - Iqbal et al (2009) measured respiration rates at 4, 12 and 20°C. At 4°C, the production of O_2 was 25 ml/kg/h, compared to 135 ml/kg/h at 20°C[137]
    - Similarly, Cliffe-Byrnes & O'Beirne (2007) identified a 5-fold increase in the CO_2 production between 4°C and 16°C[138]
- Note that whereas the data shown in Figure 33 shows a gradual increase as temperature increases, that in Figure 34 shows a steeper increase once temperature passes 12°C
    - This could indicate that degradation processes accelerate at these higher temperatures.
    - Iqbal et al suggest that this is due to continued development (cap opening, spore maturation) at higher temperatures, noting that respiration declines during storage at temperatures over 12°C [137].

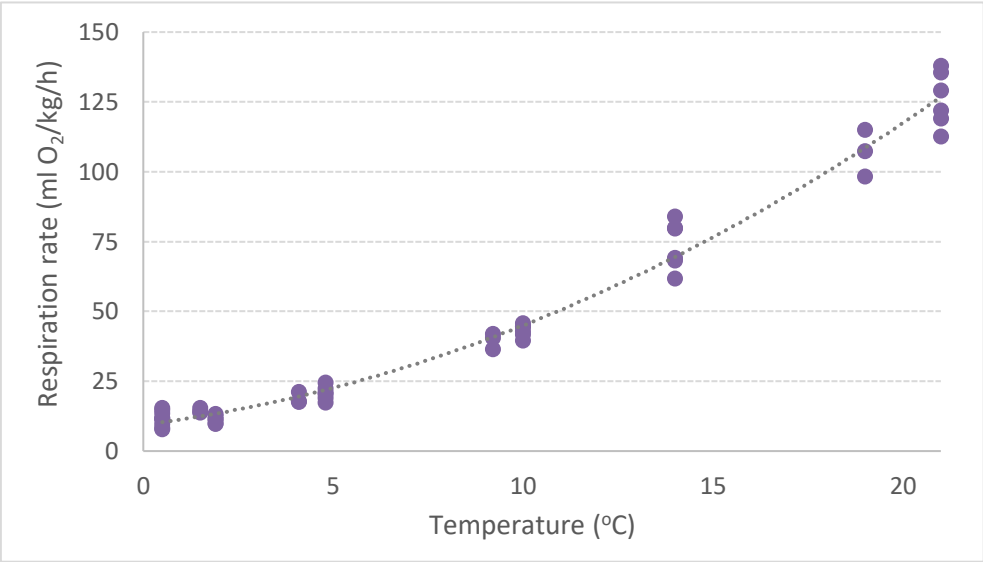


Figure 33. Effect of temperature on mushroom respiration rate. Authors own data.

- Damage due to bruising or slicing generally increases respiration rate and decreases storage life.
    - For some products, respiration rate can double due to slicing, as the increase in surface area relative to volume decreases gas concentration gradients within the flesh, as well as triggering a wound response.
    - Mushrooms are highly permeable when whole. This may be one reason respiration rate increases following slicing are relatively moderate, reported as approximately 20% [138] to 40% [137].

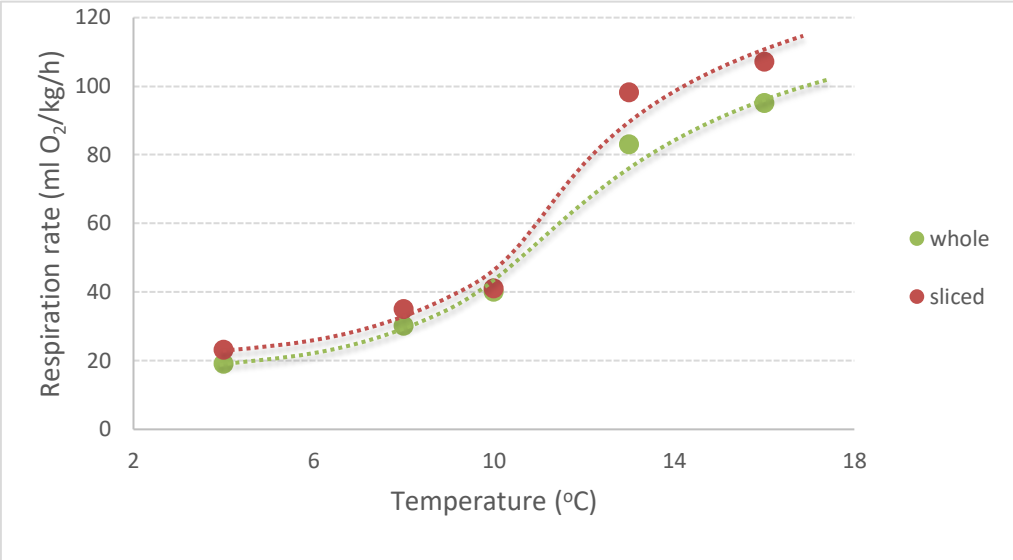


Figure 34. Effect of temperature on respiration rates of whole and sliced mushrooms. Derived from Cliffe-Byrnes and O'Beirne, 2007[139]**.**

5.4 Effect of temperature on water loss

Key finding

Mushrooms lose water easily. This is most rapid at higher temperatures, or where the pulp temperature of the mushroom is higher than the surrounding air. It has been estimated that loss of 10% of initial weight makes mushrooms unsaleable.

Research need

Quantify weight loss occurring in room cooled mushrooms, compared to those cooled using forced air or vacuum cooling, mushrooms being packed in punnets and cartons

- Mushrooms are mostly water, and the air spaces inside them are normally saturated with water vapour. Although the internal air spaces are effectively at 100% RH, the actual amount of water held as vapour (ml/cm^3) will be affected by temperature, warm air holding more water than cold.
- The difference in the amount of water vapour (Vapour pressure) in the air inside and outside the product is the vapour pressure deficit (VPD) – a higher VPD increases water loss.
- Water loss is likely to be most rapid when warm mushrooms are placed directly inside a cool room.
    - Mushrooms stored at 5°C lost 4% of their harvest weight after 4 days, compared to 19% of weight when stored at 18°C[140](Figure 35)
    - It is estimated that after mushrooms lose 10% of their initial fresh weight they become unsaleable[141]

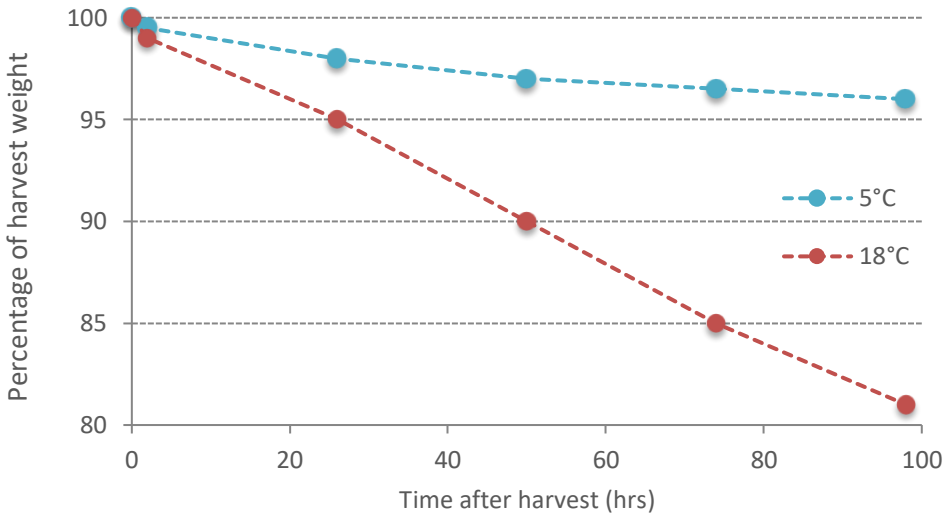


Figure 35. Average percentage weight loss of mushrooms during storage at 18°C versus 5°C (adapted from Burton et al., 1987)[140]

5.5 Monitoring temperature in supply chains

Key finding

The last study monitoring supply chains for Australian mushrooms was nearly 25 years ago: Much has changed since then, particularly the increases in punnetised and processed mushrooms, but also on-farm practices, retailer requirements and retail displays.

Research need

Determine the effects of transitory temperature fluctuations (as can occur during loading or unloading) on quality of punnetised / cartonised mushrooms and suggest critical limits for significant damage. Examine whether such a fluctuation is likely to impact the microbial safety of sliced mushrooms.

- In 1999 a national mushroom cool chain management project monitored twenty loads from farm to supermarkets and wholesalers, assessing quality at the end of each supply chain [141].
    - Mushrooms were mainly room cooled, resulting in inadequate chilling (average 9°C after 5hrs) before distribution.
    - Relative humidity (RH) inside mushroom farm cold rooms ranged from 65% to 85%
    - Mushroom temperatures averaged 7°C along supply chains.
    - Load consolidation during distribution to retail was an issue, as mushrooms were generally held at 10-12°C and 60 to 65% RH.
    - Mushrooms on retail display were stored at relatively high temperatures, together with low relative humidity (35 to 55%), which was likely to accelerate deterioration
- Extended increases in temperature (e.g. 12hrs at 20°C) can trigger cap development and increase formation of phenolic compounds, impacting quality[142]

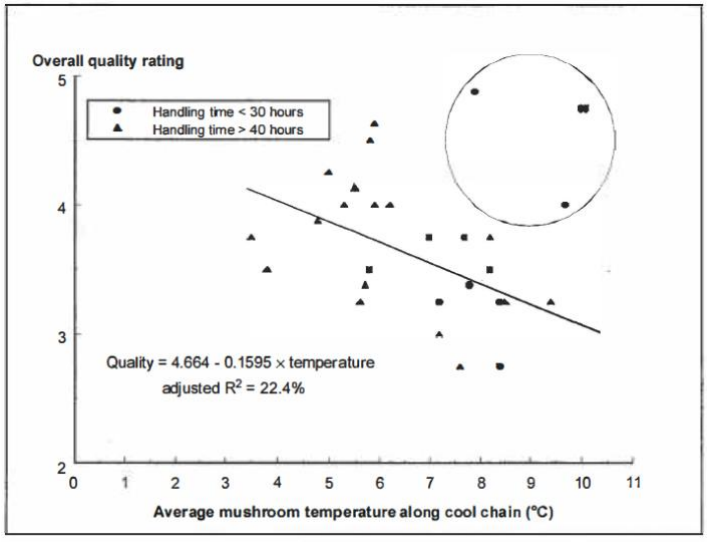


Figure 36. Effect of average mushroom temperature during distribution on overall quality of mushrooms assessed after at retail[141]

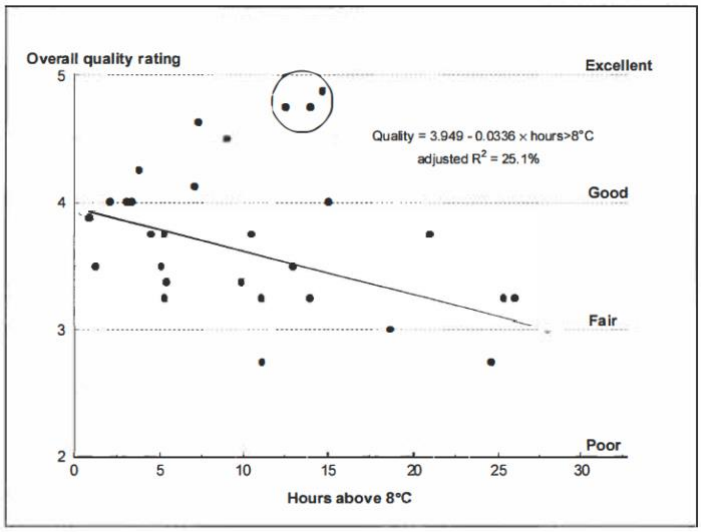


Figure 37. Effect of total hours above 8°C during distribution on overall mushroom quality assessed at retail [141]

6 Packaging and storage atmosphere

6.1 Package design and materials

Key finding

Packaging must provide enough ventilation to allow for effective precooling and removal of heat produced by mushrooms through respiration. However, pack types which allow high airflow potentially allow excess water loss.

A number of novel, biodegradable films have recently been tested. These can incorporate antioxidants and anti-bacterial compounds which inhibit browning and/or bacterial growth. This appears a particularly promising field for future commercial development as long as costs and consumer appeal are suitable.

Research need

Test the effect of biodegradable packaging options on storage life, quality and temperature management of mushrooms.

- Packaging should protect mushrooms from physical compression and be fully packed to minimise movement of mushrooms and pack units[143]. While cartons protect mushrooms well from compression, punnets over-wrapped with PVC film pack mushrooms more tightly to avoid movement.
- The optimum package design needs to be appropriate for the cooling method;
    - Forced-air cooling requires vents[143]
    - Vacuum cooling is more effective if overwrap film has perforations. No difference in vacuum cooling time was identified between 1.4kg cardboard and plastic trays, and 230g plastic punnets.[144]
- Recent papers have explored uses for chitosan, a product commonly extracted from shellfish waste. Chitosan can stimulate plant defences, has anti-microbial properties and can be manufactured into many different products including biodegradable film.
    - Mushrooms packaged using films made by blending 1:1 chitosan and zein (maize protein)[145] or chitosan and gallic acid[146] retained whiteness better than mushrooms packaged in standard PVC film during storage at 4°C.
    - The chitosan – zein result was further improved by adding the anti-oxidant alpha-tocopherol[147]. The (edible) film stimulated enzymes involved in anti-oxidant defence and inhibited bacterial blotch, reducing browning during storage.

6.2 Modified atmosphere packaging (MAP)

Key finding

Unlike other fresh products, the respiration rate of mushrooms is relatively unaffected by changes in O_2 and CO_2 concentrations in the surrounding atmosphere. High CO_2 and low O_2 can be detrimental to quality. Despite reports of benefits of MAP in the peer-reviewed literature, the author does not consider this to be a worthwhile option for Australian growers.

- Australian research on MAP[148] indicated that high CO_2 / low O_2 concentrations had little effect on the rate of O_2 consumption by mushrooms. Low O_2 levels (~10%) combined with low CO_2 increased stipe elongation, while high CO_2 increased browning and cap yellowing.
- These results were supported by Varoquaux et al[149], who confirmed that mushroom respiration was unaffected by CO_2 and O_2 concentrations within the range attainable through MAP. It was concluded no extension of shelf life is attainable through MAP, with management of RH far more important to storage life and quality.
- Lopez-Briones et al[150] found a linear relationship between CO_2 concentration inside packages and mushroom cap colour (Figure 37).

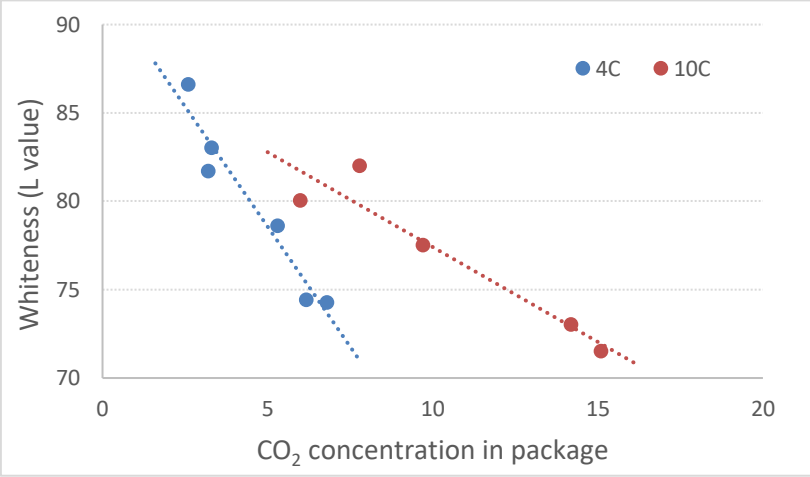


Figure 38. The effect of CO_2 concentrations inside the package on mushroom cap whiteness following 8 days at 4°C or 10°C. Derived from Lopez-Briones et al., 1993.

- Despite this, numerous researchers have continued to examine MAP for mushrooms, with many reporting apparent extension of storage life. Recent (since 2020) publications have recommended atmospheres containing up to 30% CO_2 and anything from 0% to 80% O_2 (Xia et al., 2023), despite it being likely that such atmospheres will negatively affect eating quality. For example, Salamat et al (2020)[151] reported that mushrooms pre-cooled to 2°C then placed in MAP (12 to 14% O_2 + 7 to 9%) CO_2 were whiter than controls

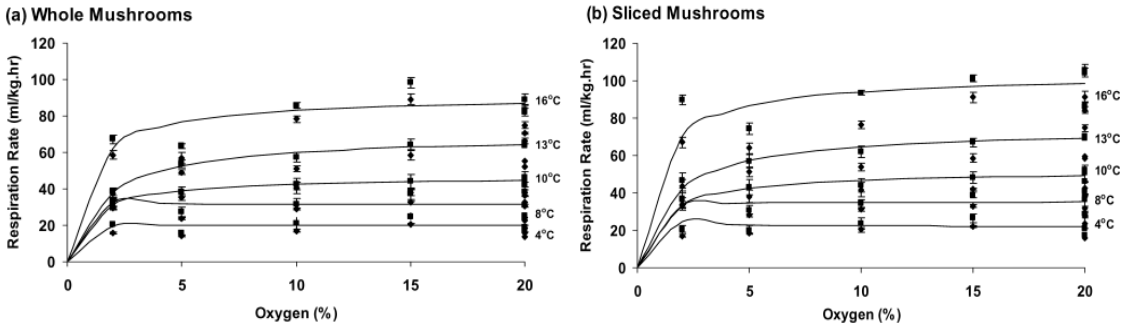


Figure 39. The effect of oxygen concentration on respiration rates of whole and sliced mushrooms. From Cliffe-Byrnes and O'Beirne, 2007.

- As changes in temperature have a greater effect on respiration rate than film permeability, packages need to be designed for very specific conditions; storage at lower than target temperatures may result in little atmospheric modification, whereas at higher temperatures packages can become anaerobic.

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