Improved postharvest management of chestnuts

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Final Report

CH13005

Contents

1 Media Summary

This research has evaluated cooling times for chestnuts under a range of different, currently used practices including room cooling, room cooling with improved ventilation, forced air and hydrocooling. We have also determined the effects on chestnuts of different freezing times and temperatures and evaluated quality following long term storage at 0 or 5oC.

The results indicate that forced air systems can provide extremely rapid cooling to whole chestnut bins. In contrast, lined bins were extremely slow to cool and negatively affected chestnut quality. Freezing damage in chestnuts was associated with exposure time as well as temperature, with temperatures below -2.5oC potentially damaging fruit. There were no obvious differences between chestnuts stored at 0oC and those at 5oC, with both showing similar symptoms of deterioration after 15 weeks storage.

Unlike other tree nuts, chestnuts are quite perishable and need to be kept refrigerated after harvest. Growers usually store harvested nuts in bins, with rooms set as low as -3^{o}C in order to optimise storage quality. However, this raises a number of questions;

- How quickly do chestnuts cool after harvest?
- How low can chestnuts go before they freeze?
- Is the cost of cooling justified by improved outturn quality

A series of trials were conducted examining how quickly chestnuts cool in different systems. These compared cooling in polypropylene bags, mesh bags, wooden bins and plastic bins as well as room cooling in a lined bin or a bin with inserted ventilation pipes. Hydrocooling and forced air cooling, both technologies which may be used to speed up postharvest cooling rates, were also tested.

Freshly harvested chestnuts packed into a lined bin in cold room took more than 3 days to cool. Chestnuts placed directly into open wooden or plastic bins cooled more quickly, although rates were still relatively slow at the centre of each bin.

Perhaps surprisingly, the simple technique of adding a system of home-made ventilation pipes through the stack significantly increased cooling rate. The fruit at the middle of the ventilated bin actually cooled faster than those on the top layer. This low-tech, low cost solution could make a useful technique for growers who are leaving harvested chestnuts in bins but want to speed up the rate at which they chill.

Forced air cooling was by the far the fastest way to cool chestnuts. Whereas fruit in the centre of an unlined plastic or wooden bin took around a day to cool, those in a forced air system took only 60 – 100 minutes. This system is relatively inexpensive and can be used in an existing cold room, making it an excellent choice for medium or larger scale growers.

Freezing causes kernel darkening, softening, weight loss and development of off odours and flavours. Freezing appears to be a combination of time and temperature, with the critical temperature around -3^{o}C. As little as 2 hours below -3^{o}C can result in significant damage, especially in stored fruit.

Storing at a too low a temperature may not only cause damage but also provide little improvement in storage quality. A comparison of chestnut storage life at 0^{o}C and 5^{o}C found little difference between samples stored for up to 8 weeks. Differences between the samples could only be seen at longer storage times, and not for every variety.

It is concluded that storage at close to 0^{o}C can extend chestnut storage life without risking freezing injury or adding extra, unnecessary costs for growers. Colder temperatures should only be considered if fruit is to be stored for two months or more.

2 Technical Summary

Unlike other tree nuts, chestnuts are quite perishable and need to be kept refrigerated after harvest. Growers usually store harvested nuts in bins, with rooms set as low as -3^{o}C in order to optimise storage quality. However, this raises a number of questions;

- Do current practices, particularly room cooling in bins, cool chestnuts efficiently?
- What is the critical temperature at which freezing injury can occur?
- Can storage temperatures be reduced to reduce costs without jeopardizing quality?

A series of trials were conducted measuring cooling rates inside chestnut fruits with different, currently used commercial systems. Three grower packers (small, medium and large operations) were used for the trials, which compared cooling rates in polypropylene bags, mesh bags, wooden bins and plastic bins as well as room cooling in a lined bin or a bin with ventilation pipes through the load. Other technologies that can be used to speed up cooling rate were tested, including hydrocooling and forced air cooling.

Freshly harvested chestnuts packed into a lined bin and simply placed in a cold room failed to cool in reasonable time and resulted in rapid mould growth. While chestnuts placed in open wooden or plastic bins cooled more quickly, lack of air circulation through the centre of the bin meant cooling rates were still relatively slow. While plastic and wooden bins were not compared directly, there was no obvious benefit derived from the additional venting in the plastic bin.

The simple technique of adding a system of home-made ventilation pipes through the stack significantly increased cooling rate. In this case chestnuts at the middle of the ventilated bin cooled faster than those on the top layer. This low-tech, low cost solution would appear a useful technique for growers wishing to improve cooling rates for room cooled bins.

Forced air cooling was by the far the fastest way to cool chestnuts. Whereas fruit in the centre of an unlined plastic or wooden bin took 23 – 25 hours to ¾ cool after harvest, those in a forced air system took only 60 – 100 minutes. This system is inexpensive and can be used in an existing cold room, suggesting it could make an excellent choice of technology for medium or larger scale growers.

Freezing of chestnuts caused kernel darkening, softening, weight loss and development of off odours and flavours. Freezing appears to be a combination of time and temperature, with the critical temperature around -3^{o}C. As little as 2 hours below -3^{o}C was found to result in significant damage in stored fruit. As time below -3oC increased so did weight loss, darkening and rancidity.

Not only can storing at a too low a temperature cause damage, but it may provide little improvement in storage quality. A comparison of storage at 0^{o}C and 5^{o}C found little difference between samples stored for up to 8 weeks. Variation due to storage temperature between the samples could only be seen at longer storage times, and not for every variety.

It is concluded that storage at close to 0^{o}C can extend chestnut storage life without risking freezing injury or adding extra costs for growers. Colder temperatures should be used with caution, and only if fruit is to be stored for an extended period.

3 Keywords

Chestnuts; Postharvest; Storage; Handling

Cooling; Hydrocooling; Forced air cooling; Pressure cooling; Bin; Temperature; Humidity

Freezing; Kernel; Damage; Kernel colour

Quality; Storage life; Shelf life

4 Introduction

In 2013 Chestnuts Australia commissioned Applied Horticultural Research to conduct a study of harvest and postharvest practices currently used by growers in NSW and Victoria. The primary purpose was to add additional information to the new chestnut growers guide, as well as link with a survey of market quality in Sydney and Melbourne.

Although market quality was good, a number of inefficiencies were observed in the system;

- Growers often place full bins of chestnuts in cool rooms to chill. This type of cooling can be very slow, especially if bins are not well vented. Chestnuts in the centers of the bins may therefore be taking a long time (possibly several days) to cool.
- Some growers insert ventilation tubes into the loads to improve cooling, but the effectiveness of such systems is not known.
- A few growers hydrocool fruit before storage. While this was expected to cool fruit within minutes, whether this affects outturn quality is not known.
- Cool rooms are usually set at -3°C. Given the storage characteristics of chestnuts, this appears to be unnecessarily low and may even cause freezing damage on some fruit.
- It is common practice to line bins before use to reduce moisture loss. However, liners will reduce cooling rates while possibly providing little benefit. Liners also add extra complication if fruit need to be re-dipped in chlorine during extended storage to control surface moulds.

4.1 Cooling rates

Information on cooling rates in different systems is surprisingly limited. Some published data is available on citrus and apples, as shown below. Tests comparing wooden to plastic bins found that plastic bins with 8 – 10% open area cool fruit twice as fast as wooden bins, which have more limited air circulation (approx. 1.5% open vents)[1].

[1] Patchen, G.O.,Sainsbury, G.F. 1962. Cooling apples in pallet boxes. Marketing Research Report No. 532. Agricultural Marketing Service, U.S. Department of Agriculture, U.S. Government Printing Office

Table 1 - Cooling times for apples (top) and citrus (below) in different bin types.

	Half cooling time (h)
One apple in a room	0.5
Apple loose in an open box	7
Apple packed in a lidded box	23

	Half cooling times for central fruit (h)	
	Freely exposed	*Tightly packed*
Lidded bin, no vent	30	55
Lidded bin, 8% vents	23	43
Open bin, no vents	18	
Open bin, 10% vents	5	

No data on cooling rates or methods could be found for chestnuts. In Europe, the source of most published research on chestnuts, it is common practice for fruit to be "water cured" after harvest rather than placed directly into storage. This involves storing the chestnuts in cool water, usually 14 – 18^{o}C, for a minimum of 5 days and up to 10 days. The aim is to reduce development of internal and external fungi as well as control insect pests[2]. This practice is still apparently widely used, even though the process takes significant space and time, results in partial fermentation, reduces the natural shine of the fruit and is still not totally effective against *Curculio elephas*[3]. Australian growers have not adopted this practice, mainly because the major internal pests of chestnuts are not present in this country. Instead, the focus is on simply cooling the product soon after harvest, then packing and marketing within a relatively short time frame.

4.2 Freezing point

Chestnuts are commonly stored below 0^{o}C, both in Australia and in Europe. According to the UCDavis recommendations for retaining quality of chestnuts, the optimum storage temperature for chestnuts is -1 – 0^{o}C. They advise that the freezing point for European chestnuts is -2^{o}C whereas Chinese chestnuts can be cooled to -5^{o}C without freezing[4]. This recommendation is likely originally sourced from a 1957 USDA – ARS report[5] which gave freezing points as shown in Table 2.

In France, chestnuts are usually stored at -1 to -3^{o}C[6], often after the "water curing" process described above. As water curing induces ethanol production in the fruit, it seems possible that these fruit will have a lower freezing point that those freshly harvested.

[2] Botondi R. *et al*. 2009. Technological parameters of water curing affect postharvest physiology and storage of marrons (*Castanea sativa* Mill. Marrone fiorentino). Postharvest Biol. Technol. 51:97-103.
[3] Blaiotta G. 2014. Optimization f water curing for the preservation of chestnuts (*Castanea sativa* Mill.) and evaluation of microbial dynamics during process. Food Micro. 42:47-55.
[4] Kader AA. 2003. Chestnut: Recommendations for maintaining postharvest quality. postharvest.ucdavis.edu/PFfruits/Chestnut/. Accessed November 2014.
[5] Whiteman TM. 1957. Freezing points of fruits, vegetables, and florist stocks. Marketing Research report no. 196. USDA-ARS.
[6] Breisch H. 2008. The chestnut industry in France. Acta Hort 784:31-36.

Table 2 - Freezing points of different chestnut types according to 1957 USDA-ARS data

	Freezing point ^{o}C		
	Lowest	*Highest*	*Average*
American chestnut	-7.5	-5.7	-6.5
Chinese chestnut	-5.6	-5.3	-5.4
Italian chestnut	-1.8	-1.7	-1.8

Chestnut fruit, as the mechanism of tree reproduction, have clearly evolved to survive through winter. The fruit may be buried in snow for months, subjected to sub-zero temperatures, yet remain able to germinate during the spring thaw.

Most horticultural products are unable to tolerate more than 1-2 degrees below zero, the formation of ice crystals rupturing cell membranes and resulting in total cellular breakdown. The symptoms of freezing damage are immediately obvious, with cell contents leaking and the plant structure collapsed. However, the dense, starchy structure of the chestnut flesh is comparatively resistant to such forces. Certainly the symptoms of freezing damage are subtler in chestnuts than in other products.

4.3 Storage temperature

The nominal optimal storage temperature for chestnuts has been stated to be -1^{o}C and 90% RH[7]. This appears to be based purely on the lowest temperature tolerated by the fruit. Researchers have commonly stored chestnuts at 0-2^{o}C[8], or higher temperatures, purely for practical purposes. No information could be located detailing the effects of different temperatures on quality of the fruit.

This may be partly because of the difficulties in objectively measuring chestnut quality. One researcher compared the effect of modified atmospheres on chestnut storability by measuring respiration, water content, starch content and, subjectively, marketable fruits. No differences were found in either water content or starch, despite differences in respiration rate, with minimal changes in marketable fruit[9].

Cold storage can be described as “value adding with electricity”. The lower the temperature the more expensive both the equipment and the power required becomes. In Australia, chestnuts are rarely stored for more than 2-3 months, and more frequently they are stored for only a few weeks. For relatively short storage times such as these, cooling to the minimum temperature may add cost without any obvious improvement in quality.

[7] Cecchini M. *et al.* 2011. Effects of controlled atmospheres and low temperature on storability of chestnuts manually and mechanically harvested. Postharvest Biol. Technol. 61:131-136.
[8] Jermini M. 2006. Influence of fruit treatments on perishability during cold storage of sweet chestnuts. J. Sci. Food Agric. 86:877-885.
[9] Peano C. *et al.* 2014. The use of a modified atmosphere for the storage of chestnut fruits. Italian J. Food Sci. 26:74-80.

5 Cooling rates

5.1 Aim

To determine the rates of cooling of chestnuts under different, currently used commercial cooling systems.

5.2 Method

Three growers agreed to participate in the trials. One was a small, family run business, the second a medium sized operation and the third a very large producer who grows and packs a range of horticultural products.

5.2.1 Temperature measurement

Three different types of temperature data loggers were used during the trial. These were;

- Logtag recorders with external probes, both thermocouple and metal probe types. (LOGEXT, resolution 0.1^{o}C)
- Hobo logger (UX120, 4 channel and single channel, resolution 0.1^{o}C) with external Type T thermocouples.
- Tinytag Ultra 2 splashproof air temperature and humidity logger

External probes were inserted into the core of fruit by first drilling a small hole to size using a small handheld electric drill. Thermocouples were secured snugly inside a single fruit. Where metal probes were used, a number of chestnuts were loaded onto the probe, similar to a kebab (Figure 1). All data loggers were checked for calibration and accuracy before use.

Figure 1 - Temperature dataloggers used to measure cooling rates. These included Logtags (top row), Hobo data loggers (centre row) and Tinytags (bottom left). Chestnuts with probes inserted were placed in mesh bags containing approximately 1kg of fruit, secured and marked with flagging tape (bottom right)

5.2.2 Grower 1

Grower 1 was a small, family business operated solely by the owners. Chestnuts are mechanically harvested, loaded into onion bags and simply placed in the small coldroom to chill. To pack, they are removed from the cold, sized, weighed and sorted into standard PPE bags. These are then placed back in the cold room for several hours or up to 3 days before dispatch to market.

Loggers were placed in freshly harvested fruit immediately on return to the packing shed. Chestnuts were either left in the light mesh onion bags as usual or packed into PPE bags (Figure 2). They were then placed in the cold store for 3 days, after which the loggers were removed.

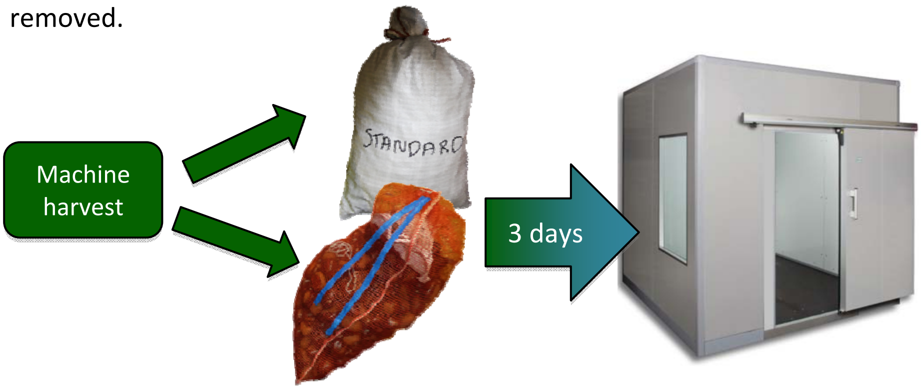


Figure 2 - Method for Grower 1

5.2.3 Grower 2

Grower 2 is a medium sized business, family owned but with a significant number of casual as well as regular employees and substantial infrastructure investment. Chestnuts are usually machine harvested and returned to the packing shed in bins. They are normally air legged to remove debris, washed, dipped in chlorine and then stored in wooden bins until packing. Liners are used, but only normally to store fruit that is already cooled. Ventilation pipe systems manufactured on farm are often installed into the bins to help freshly harvested fruit cool more quickly.

Bags of chestnuts were prepared using fruit which had been harvested that morning, cleaned and prepared for cold storage. Each bag contained approximately 1kg of fruit, but was weighed to within 1g. A data logger probe was inserted into the core of an additional chestnut, which was then also placed in the bag. Each bag was labeled, knotted shut and marked with flagging tape for easy removal.

Three different cooling regimes were tested (Figure 3). Fruit was loaded into either;

1. A standard wooden bin
2. Standard wooden bin plus ventilation pipes
3. Standard wooden bin with liner (placed over the top of the bin for simplicity, would normally be inside the bin

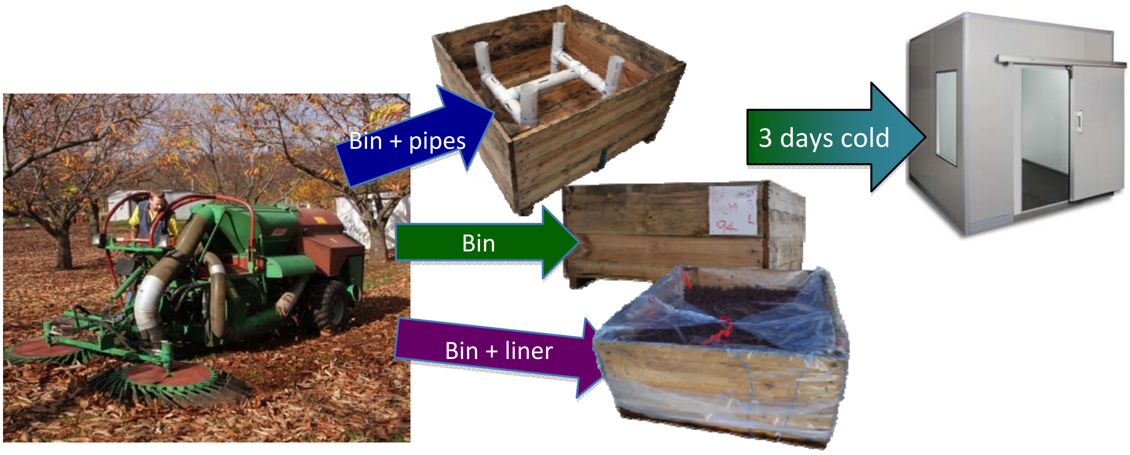


Figure 3 - Method for grower 2

Six sampling points were used for each treatment. Weighed bags, with (x2) or without (x4) loggers were placed at two heights (more than half way down through the load or on the top layer) and three positions (centre, corner and side wall) within each bin, as shown in Figure 4.

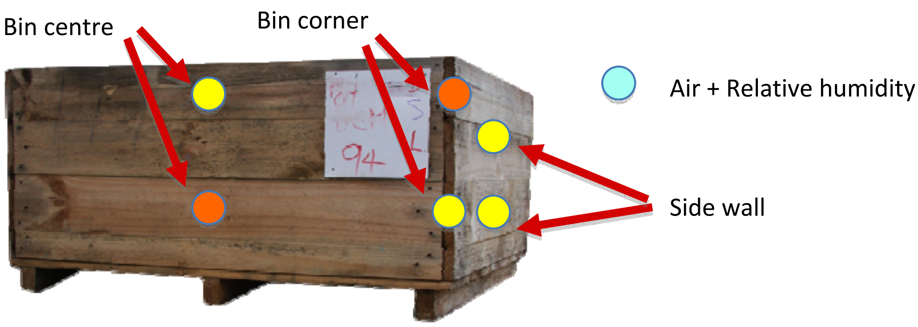


Figure 4 - Locations of weighed bags of chestnuts and loggers inside each bin. Yellow circles indicate bags of fruit only, orange circles signify bags which include fruit with inserted temperature probe.

Figure 5 - Installation of weighed bags of chestnuts and loggers in a standard wooden bin (L) and wooden bin with ventilation pipes.

Bins were loaded into a single stack inside the cold room and left to cool for 3 days before the loggers were retrieved, bags re-weighed, and samples taken for quality assessment.

5.2.4 Grower 3

Grower 3 is a large business. While still family owned, the company produces a range of horticultural crops and has multiple production locations. All harvested fruit are packed at the central packing facility. Chestnuts are usually air-legged then hydrocooled for 30minutes before storage in one of the larger cold rooms. The company has recently been trialing forced air cooling as an alternative. Once thoroughly cold chestnuts are either packed or moved to a more stable, long term storage room for up to 3 months.

Chestnuts were hand harvested at a farm near the packing shed and transported there early in the morning. Bags of 1kg chestnuts were prepared as previously, including a number of bags with data logger probes inserted into fruit.

A number of different cooling regimes were tested (Figure 6). Fruit was either;

1. Room cooled in a plastic, unlined bin
2. Hydrocooled using a tank of water placed in the cold room
3. Hydrocooled minutes using an actively refrigerated tank of water
4. Forced air cooled – loggers placed in the top, centre and bottom bins in a stack of three

Loggers and weighed bags of fruit were located in the room cooled bin in the positions indicated in Figure 7.

Chestnuts were placed in both hydrocooling systems for approximately 30minutes. They were then pulled out and restacked inside the general cold room to finish chilling.

The forced air system was constructed by wrapping three vertically stacked bins with pallet wrap and placing a fan + plenum on the top (Figure 8). This pulled the room air through the three bins from bottom to top. Each set of three bins was actively pressure cooled for three hours, then restacked inside the cold room.

The chestnuts were cooled for three days before re-weighing and removing the dataloggers as previously described.

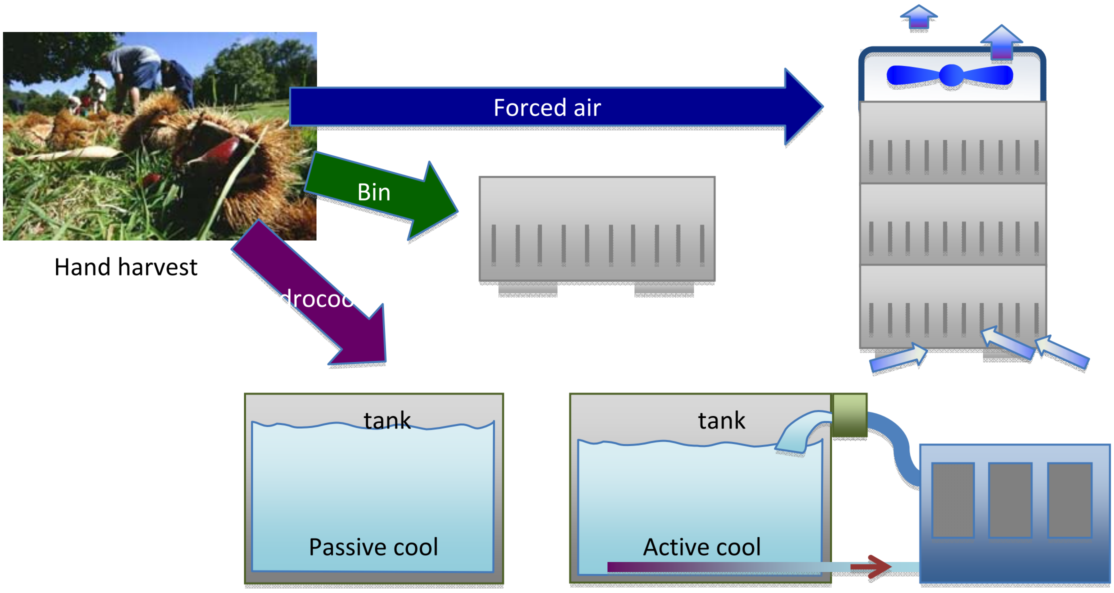


Figure 6 - Method for Grower 3

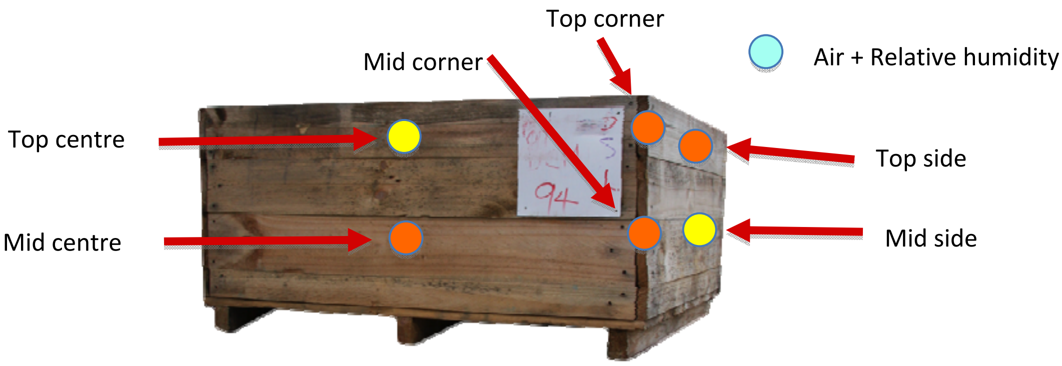


Figure 7 - Locations of weighed bags of chestnuts and loggers inside each bin. Yellow circles indicate bags of fruit only, orange circles signify bags which include fruit with inserted temperature probe.

Figure 8 - Cooling systems used by Grower 3 included; room cooling in plastic bin, hydrocooooling, and a forced air system

5.3 Results

5.3.1 Grower 1

Chestnuts in the open mesh (onion) bags cooled far more quickly than those in the PPE (woven polypropylene) bags, undoubtedly due to the better airflow. The core temperature of chestnuts in these bags barely differed from the temperature in the air inside the sack. In contrast, the significant gradient in temperature between the air and the chestnut pulp in the PPE bags demonstrates the lack of air circulation inside these packages.

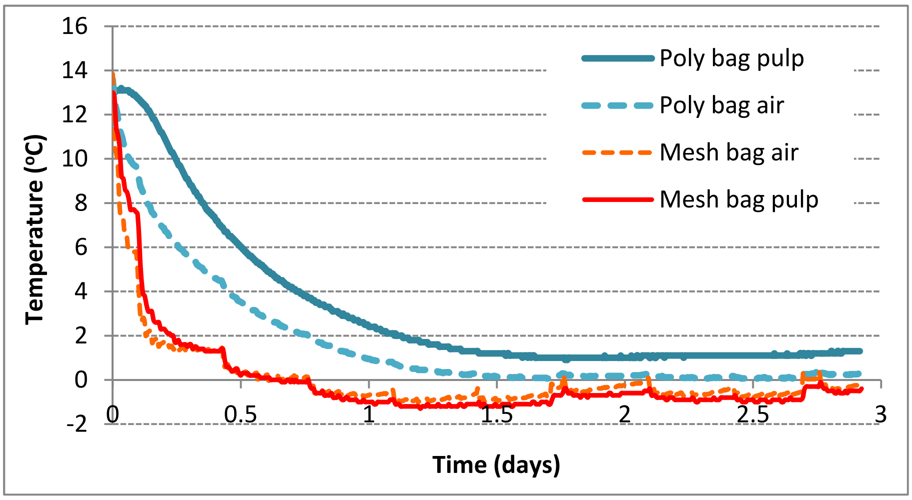


Figure 9 - Chestnut pulp (solid lines) and air temperatures (dashed lines) inside mesh sacks or sacks made of polypropylene (PPE)

The room itself was running at approximately 0^{o}C but with distinct defrost cycles every ~9.5 hours. Given a starting temperature of around 14^{o}C, this meant that the fruit were ¾ cooled in around 3.2 hours in the mesh bag compared to over 20 hours in the PPE bag.

Weight loss after 3 days was, however, higher in the mesh bags, these fruit losing an average of 1.5% moisture compared to only 0.2% weight loss in the PPE bags. This suggests that the optimum strategy for grower 1 is to harvest into the onion bags, cool for at least 4-5 hours, then pack into PPE bags for longer storage and / or marketing.

5.3.2 Grower 2

The room temperature for grower 2 was also set at close to zero, with room air temperatures falling to around -1^{o}C at times. After the room was loaded with warm fruit it took some hours to return to the setpoint, presumably due to the significant heat load of a large volume of warm product. Relative humidity was stable at close to 90%, which is likely to be suitable for chestnut storage.

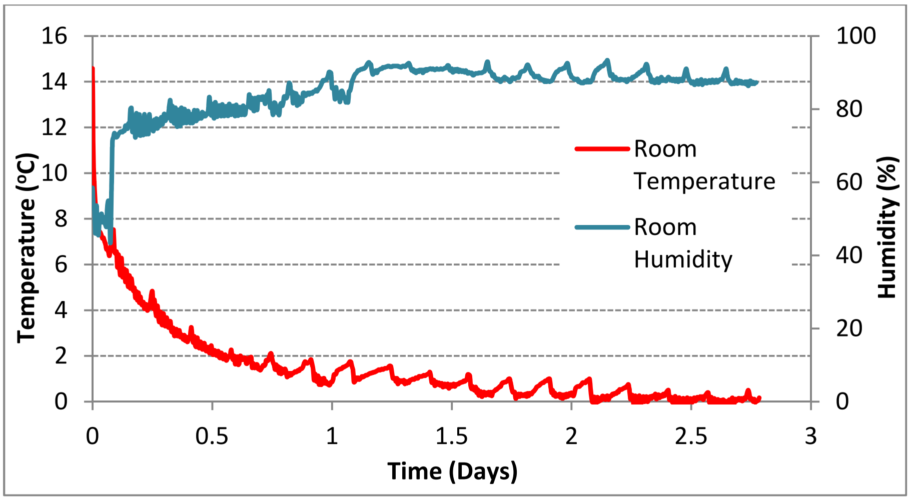


Figure 10 - Room air temperature and RH at Grower 2.

Perhaps surprisingly, the passive ventilation pipes installed into wooden bins significantly reduced cooling time at the centre of the bin. In this case, chestnuts were cooling from 16°C to 0°C, giving a ¾ cooling point of 4°C. Pulp temperature of chestnuts at the centre of the bin with pipes reached this point in around 12 hours compared to 24 hours for chestnuts in the bin without this insert. Chestnuts in the centre of the lined bin failed to reach 4°C during the 3 days allowed for the trial. However, given the rate of decrease, it was expected to take at least 6 days to reach this point.

In contrast, chestnuts at the top of the unlined bin and the bin with ventilation pipes cooled at extremely similar rates, falling to 4°C in 17.5 – 18.5 hours. Again the lined bin took longer, with even these topmost fruit taking nearly the whole 3 days of the trial to come down to this temperature.

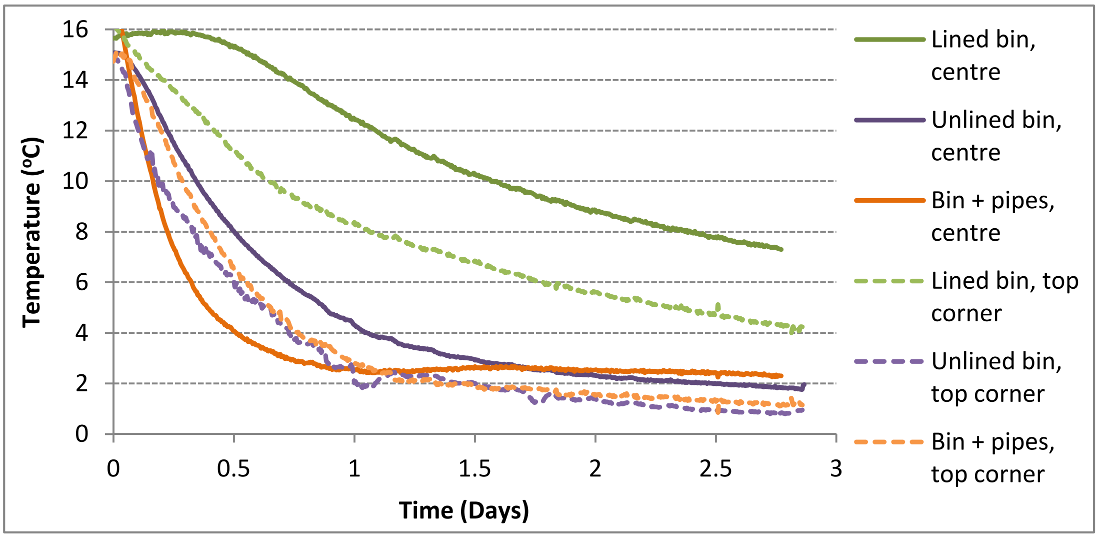


Figure 11 - Cooling rates in a lined wooden bin, unlined wooden bin, and wooden bin with ventilation pipes

Weight loss for all treatments and positions ranged from 0.03 – 1.0%. Differences between the methods were not significant, with average weight loss overall of 0.5%. There was, however, a major difference in quality between the chestnuts enclosed with a liner and those cooled by other methods. Due to the nuts staying relatively warm for several days, mould started to grow on some nuts with hilum speckling visible on others (Figure 12).

Figure 12 - Mould growth after 3 days on chestnuts cooled in a lined bin.

5.3.3 Grower 3

Room temperature at Grower 3 was also set to 0°C, with a range of ±0.4°C. The large size of the cold room ensured that little fluctuation was noticeable, even with loading and unloading of warm fruit. The room temperature returned to this level within half an hour of setting the sensor in place. Relative humidity inside the room approximated 100% throughout the trial.

It is not possible to directly compare cooling rates of plastic and wooden bins as the Grower 2 and Grower 3 cold rooms were very different in design, size and airflow rates. Significant temperature differences were previously observed between the centre and top layers of chestnuts room cooled in a wooden bin. It had been expected that increased venting in the plastic bin would reduce this differential. In this trial this was not observed. The chestnuts in the middle of the plastic bin still cooled much more slowly than those at the bin surface. This suggests that, in this case, little airflow was penetrating through the side vents and into the centre of the bin.

The cooling rates of fruit in the top layer of the plastic bin were initially faster than those observed for the wooden bin. This is most likely due to the airflow at that point in the cool store, the return to the temperature setpoint in the larger room, and the presence / absence of other bins stacked on top.

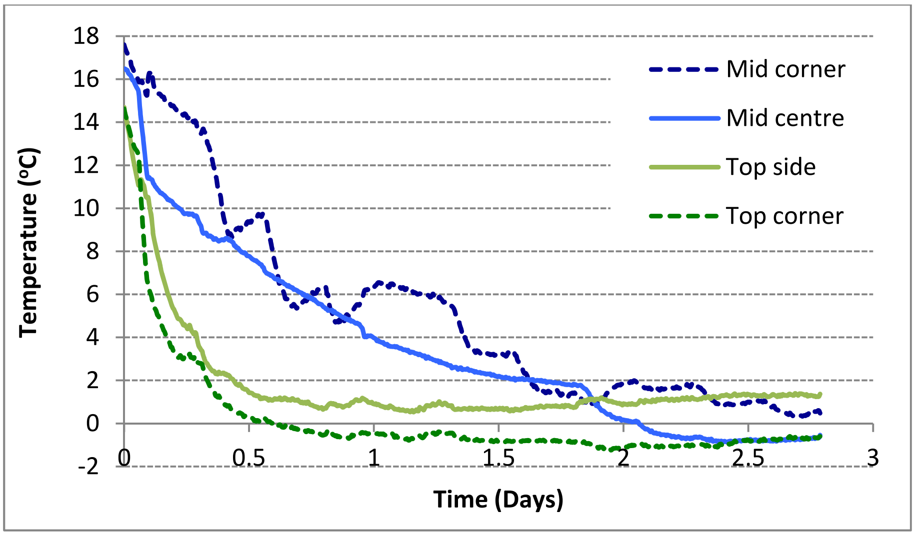


Figure 13 - Cooling rates in an unlined plastic bin, measured at different points in the middle and top layer of chestnuts

The aim was to cool fruit from an initial temperature of 17°C to a target of 0°C. It was therefore ¾ cooled when core fruit temperature fell to 2.1°C. The top layer of fruit took 4-7 hours to be ¾ cooled. However, chestnuts in the centre of the bin took 23 – 33 hours to cool to this point.

Several of the samples in the unlined plastic bin actually gained weight, with two samples gaining more than 2% weight over the three days of the trial. This is presumably due to the saturation humidity in the storage environment. Average weight gain was 1.3%.

The hydrocooling method had mixed results. While temperature fell rapidly in both the active (refrigerated water) and passive (tank in the cold room) hydrocoolers during the 30 minutes chestnuts were immersed, this was insufficient to fully remove all field heat from the fruit. After removal from the hydrocooler, the chestnuts were simply placed in the cold room. Their subsequent cooling rate depended on the heat still present in the surrounding fruit, their position in the room, and the position of the chestnuts with probes inserted within the specific bin.

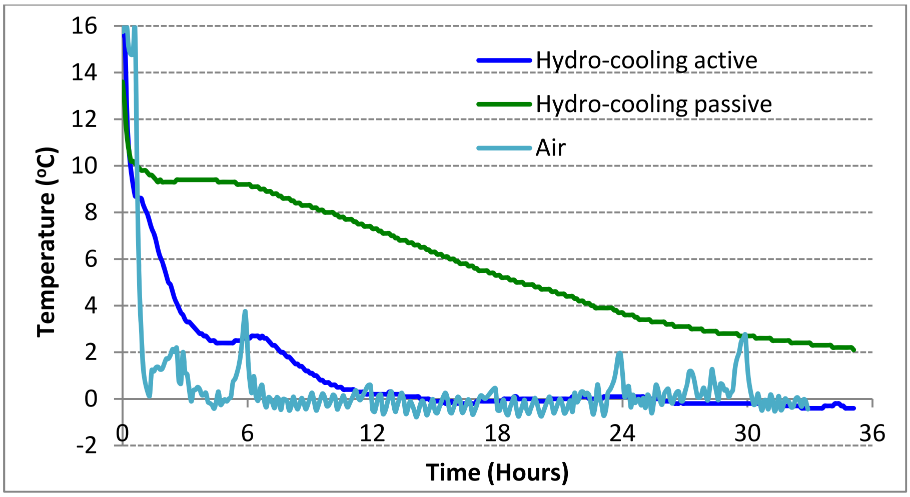


Figure 14 - Cooling rates of chestnuts immersed for 30 minutes in either an actively refrigerated hydrocooling system or a passive system involving a tank simply placed in the cold room. Light blue line indicates the air temperature on top of the bins.

As a result hydrocooled chestnuts took 3.5 to 27 hours (average values from 4 replications) to ¾ cool. It is notable that the cooling rate for the passive hydrocooling treatment closely resembled the results for the centre of the room cooled plastic bin, while the cooling rate for the active hydrocooling treatment closely followed those recorded for the top corner of the same bin. Essentially, after an initial rapid temperature drop, cooling rates were the same as those in a plastic, room cooled bin, with those at the top cooling faster than those in the centre.

The forced air cooling was by far the fastest of the cooling methods tested. The bottom bin cooled fastest, as this was the intake for cold room air. The centre and top bins cooled at a similar rate. The time to ¾ cooled was only 1 hour in the bottom bin and around 1.5 hours in the middle and top bins. Core temperatures in all of the bins fell below the room setpoint of 0°C in less than 3 hours. The results suggest that only 2 hours on the forced air system would thoroughly cool the fruit and allow efficient use of the equipment.

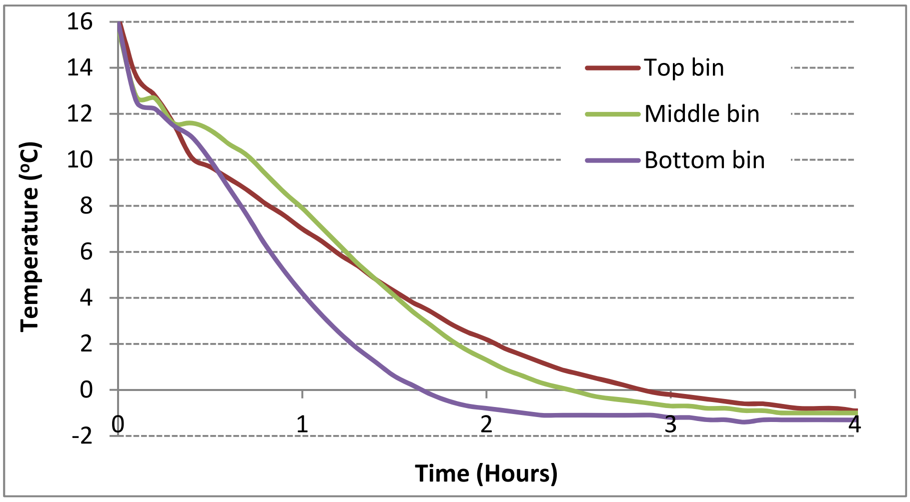


Figure 15 – Cooling rates of chestnuts in a 3 bin high stack with forced air cooling.

Weight loss of chestnuts in the forced air system was similar between all of the bins, averaging 0.3% following the three days of the trial. It seems likely that much of this weight loss occurred during cooling and that loss would have stabilized during subsequent room storage.

The differences between the three methods tested are illustrated in Figure 16. This indicates that the hydrocooling systems were excellent at reducing temperature initially but resulted in ¾ cooling times similar to simply leaving the chestnuts in a bin to room cool. Better results would undoubtedly been obtained had dipping times been longer. However, the need to handle large volumes of fruit during harvest this may not be operationally possible. In contrast the forced air system was effective at reducing core temperature in the fruit, which remained close to zero after destacking and placing in room storage.

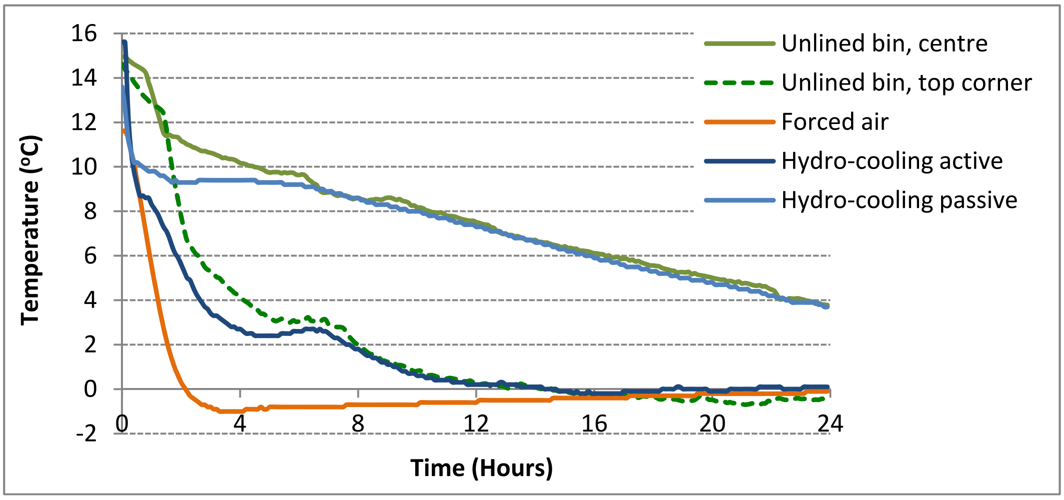


Figure 16 - Comparison of cooling rates in different systems at Grower 3

5.4 Discussion and Conclusions

The results are summarized in Table 3.

Table 3 - Summary of cooling times and weight loss from different growers and cooling methods

Farm	Cooling method	Time to ¾ cool (hours)	Time to ⅞ cool (hours)	Weight loss (avg %)
Small	Packed in PPE bag	20	29	0.2
	Packed in mesh bag	3.2	5.7	1.5
Medium	Lined bin (top corner)	68	>70	0.5
	Lined bin (centre)	>70	>70	0.1
	Unlined wooden bin (top corner)	18	24	0.6
	Unlined wooden bin (centre)	25	59	0.6
	Unlined bin + ventilation pipes (top corner)	18	32	0.4
	Unlined bin + ventilation pipes (centre)	12	>70	0.2
Large	Unlined plastic bin (top corner)	3.9	7.9	-2.3 (gain)
	Unlined plastic bin (centre)	23	38	-2.8 (gain)
	Hydrocooled in the cold room	22	35	-0.8 (gain)
	Hydrocooled in refrigerated system	2.6	7.5	-1.1 (gain)
	Forced air top bin	1.6	2.0	0.3
	Forced air middle bin	1.5	1.8	0.3
	Forced air bottom bin	1	1.2	0.3

The forced air system was clearly significantly faster than any of the other methods tested. The mesh (onion) bag was also quite efficient at cooling, but resulted in slightly higher weight loss compared to other methods. It should be noted however this was an unreplicated trial, with the results likely due to the high rate of air exchange and resulting low humidity in the small cool room more than the actual bag itself.

The hydrocooling method was relatively disappointing, although this was due to the relatively short dip time which was used. Hydrocooling had been regarded by many as best practice for cooling chestnuts, and does have the advantage that chlorine or other surface sterilant can be added to reduce subsequent mould growth. These results suggest that the cost of such systems should be carefully considered in terms of their potential throughput, especially in comparison to a relatively inexpensive forced air cooling fan unit.

For smaller grower packers who lack the cool room space or infrastructure to use one of these systems, installing home-made ventilation pipes in the bin appears to have some clear advantages. While this made no difference to the top layer of the bin, it significantly increased cooling in the centre of the bin, which would otherwise be the slowest to cool.

Given the negligible cost of such a system, it would appear to be a useful addition for any grower currently using room cooling only.

The lined bin was evidently unsuitable, resulting in an extremely slow cooling rate and damage to the product. Based on this result, warm chestnuts should never be packed into a lined bin; liners should only be used once all chestnuts are thoroughly cooled with a core flesh temperature close to the room setpoint.

6 Measuring the freezing point of chestnuts

6.1 Aim

To clarify the symptoms of freezing damage in chestnuts and estimate the temperature at which freezing damage can occur in different chestnut varieties.

This will ensure that cold rooms are set far enough above this point to prevent accidental damage of stored fruit caused by sub-setpoint delivery air and / or evaporative cooling from the fruit.

6.2 Method

Three separate trials were conducted to determine both freezing damage symptoms and the temperature at which freezing occurs.

6.2.1 Trial 1

Chestnuts were placed in a freezer at -7^{o}C for 1 hour, 1 day, 2 days and 5 days. Temperature was recorded using a Hobo temperature datalogger with T-type thermocouples inserted into the centre of 4 separate fruits. Readings from the four probes was averaged to estimate the number of hours each group of fruit was below -3^{o}C.

After removal chestnuts were incubated at 22^{o}C for a further 3 days to allow symptoms of freezing damage to become evident. Measurements initially used to assess freezing injury included weight loss, mould, softening and appearance. The fruit were then scored and cooked for 2 minutes in the microwave (600W) before assessment of peelability, kernel colour, odour and flavor.

Digital photographs were used to record kernel colour. All photographs were taken on a standard black velvet background with bounce flash using a Canon EOS 40D SLR camera. A standard white tile was included in each photograph to act as a reference point for white balancing. The degree of lightness or discolouration (L or K value) of the kernels could then be analysed using Photoshop software.

6.2.2 Trial 2

Samples of chestnut varieties Red Spanish, April Gold, Di Coppi Marrone, Premium Delight and Purtons Pride were obtained and separated into 8 units of approximately 200-250g each. Weight was recorded to 0.1g.

To treat, one unit of each variety was placed inside a digitally controlled freezer unit for 24 hours. The freezer was set at 0 to -7^{o}C, with setpoint temperature changes in 1^{o}C increments for each 24 hour period. Containers of water were included inside the freezer to buffer variability in temperature control. Temperature for each ‘run’ was recorded using the Hobo datalogger and probes, as previously.

After removal, each sample was incubated for one week under ambient conditions (22^{o}C) to allow symptoms to develop. They were then assessed for weight loss, firmness, shrivel and the presence of mould. Each fruit was then scored and microwaved for 2 minutes before assessment of peelability and presence of off flavor and aroma. They were finally photographed, as previously described, to record kernel colour.

6.2.3 Trial 3

Samples of chestnuts cv. April Gold and cv. Red Spanish were divided into 7 units of approximately 200-250g each. These were weighed and placed in the -7^{o}C freezer along with four additional fruit with Type T thermocouples inserted.

Trays of fruit were removed at regular intervals, so as to expose each tray to approximately 1 to 6 hours below -3^{o}C. Actual exposure times are shown in Table 4. After removal each tray of chestnuts was incubated at ambient temperature for 3 days to allow freezing damage symptoms to develop. Weight loss, kernel colour and other attributes were recorded as previously.

Table 4 - Removal times and resulting hours below critical temperatures

Removal time	Time below -2.5^{o}C (hours)	Time below -3^{o}C (hours)	Time below -4^{o}C (hours)
10:15	0	0	0
14:10	2.5	1.1	0
15:20	3.7	2.3	0.6
16:15	4.6	3.2	1.6
17:10	5.5	4.1	2.5
18:00	6.4	5.0	3.3
18:55	7.3	5.9	4.2

6.3 Results

6.3.1 Trial 1

The main purpose of trial 1 was to identify the symptoms of freezing injury in chestnuts, as well as provide some preliminary data regarding sensitivity.

Chestnuts placed in the freezer for 1 hour appeared fresh and undamaged. While these fruit fell to -3^{o}C, this was only for a few minutes (approximately 10) before they were removed. In contrast, chestnuts exposed for 24 hours or longer suffered 6 – 8% weight loss and became noticeably softened. Cooked chestnuts had a rancid aroma and distinct off flavours. The outside colour of the kernel darkened, and the inside developed a dry appearance (Figure 17).

Figure 17 - Fresh (L) and frozen (R) chestnuts showing external discolouration of the kernel and internal cavitation and dryness

These criteria, particularly kernel darkening, were used in the following trials to determine the extent of freezing injury on the samples.

6.3.2 Trial 2

Internal temperatures inside the chestnuts did not fully equilibrate with the temperature setting on the digital freezer in the 24 hours allocated for each run. As shown in Figure 18, mean chestnut temperature fell below zero when the unit was set to 0°C, took over 15 hours to reach target temperature when the unit was set to -5°C, and failed to meet the target entirely when it was set at -3°C and -4°C.

The -3°C treatment stabilised at an average temperature of approximately -2.5°C during the trial, while the -4°C treatment stabilised closer to -3.5°C. Average values (n=4) did not fall below -3°C when the freezer was set to 0, -1, -2 or -3°C. A total of 13.8 and 19.8 hours below -3°C were recorded when the freezer had set points of -4 and -5°C respectively.

However, these mean values were calculated from 4 probes each in a separate unit of chestnuts. They include a range of different temperatures. The sample of cv. Red Spanish nominally stored for 24 hours at -3°C actually did drop below -3°C for several hours. Increased softening and internal dryness was observed in these fruit compared to the other samples.

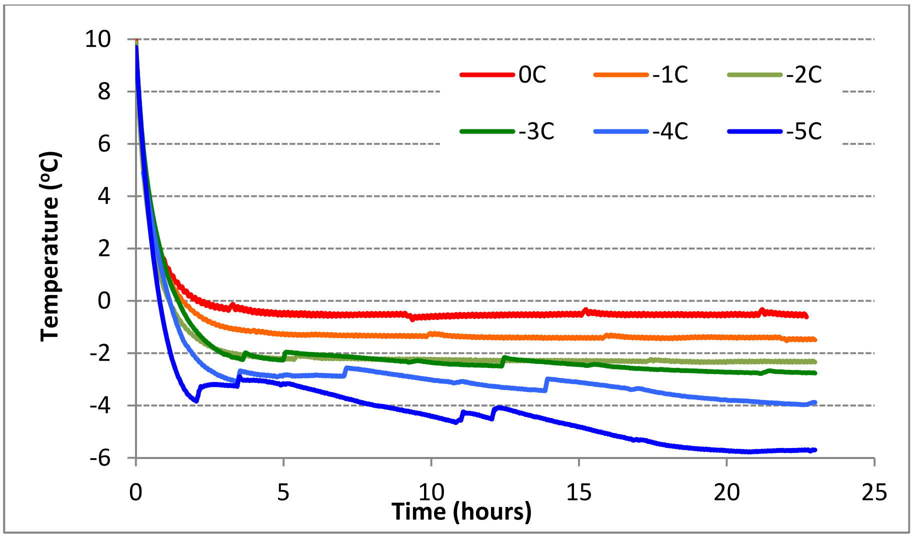
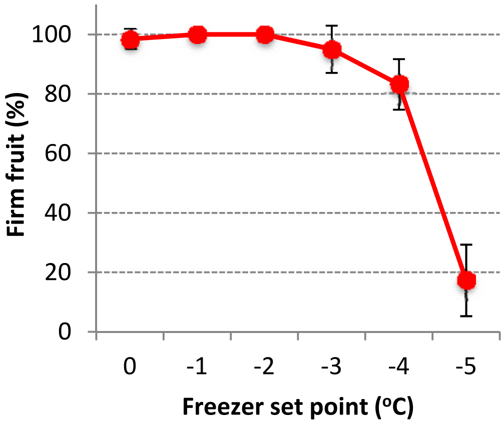


Figure 18 - Actual temperatures in chestnut pulp (mean values from 4 probes) at different nominal temperatures on the freezer unit used for trials

With this exception, all varieties reacted similarly to the different temperature regimes. No significant differences were noted between the cultivars. The data was therefore combined for analysis.

As shown in Figure 19, fruit kept for 24 hours in the freezer when set at -4°C or -5°C softened and lost weight.



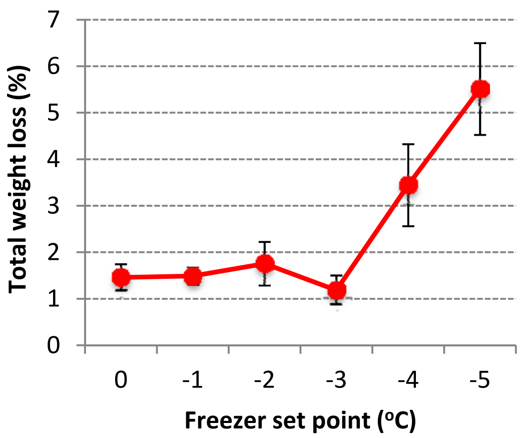


Figure 19 - Chestnuts remaining firm (L) and total weight loss after 24 hours sub zero temperatures followed by 3 days at ambient conditions. Error bars indicate the standard deviation of each mean value (n=5)

Chestnuts exposed to temperatures below -3°C also showed increasing discolouration and darkening of the outside of the kernel, and uneven colour in general. As shown in Figure 20, some discolouration started to occur in Red Spanish when stored at -3°C. As previously noted, this cultivar recorded a lower temperature during this treatment run than other samples. All varieties showed signs of injury when stored at -4°C. Mean temperatures during this treatment run fell below -3°C for nearly 14 hours.

Figure 20 - Kernel colour of five different chestnut cultivars following exposure to freezing temperatures. Top row is chestnuts stored at -3°C (actual core temperature -2.5°C) and bottom row is chestnuts stored at -4°C (actual core temperature -3.5°C).

6.3.3 Trial 3

The timing of the 7 removals provided a range of time / temperature combinations (Figure 21).

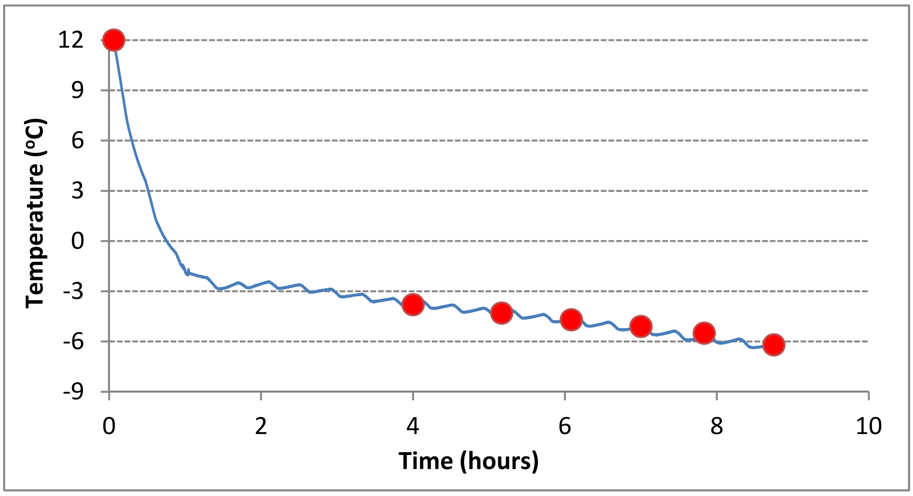


Figure 21 – Mean internal temperature (n=4) of chestnut fruit placed in a -7°C freezer. Dots ● indicate removals of sample units from storage so as to provide a range of time:temperature combinations.

The number of hours below -3°C was generally a good indicator of both kernel colour and rancidity. Kernel colour was reflected in the "L" or "lightness" value calculated from the photographs using Adobe Photoshop software (Figure 22). L values showed a response compatible with a visual assessment, as shown in Figure 23.

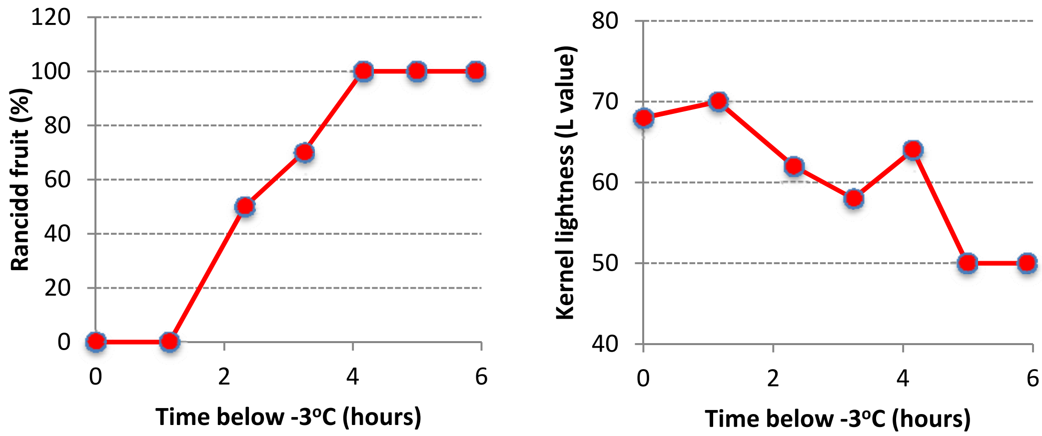


Figure 22 - Development of rancidity and darkening of kernel colour in chestnuts exposed to 0 - 6 hours below -3^{o}C

Figure 23 - Kernel colour of chestnuts stored for 0 - 6 hours below -7^{o}C

6.4 Discussion and Conclusions

The results suggest that more than 1 hour below -3^{o}C can be enough to induce freezing injury in some fruit. Chestnuts appear to become more sensitive as they age; freshly harvested Red Spanish exposed to below -3^{o}C for several hours in trial 2 only suffered very slight discolouration and softening, whereas fruit from the same batch tested some weeks later in Trial 3 had clear discolouration and rancidity after only 2 hours at this temperature.

In potatoes, cold induces transformation of starch to sugars. This raises osmotic potential and effectively decreases the freezing point in the liquid inside the cells. It is possible that a similar process may occur in chestnuts. However, such intense metabolic processes may be less easily induced as the fruit ages.

Freezing injury is difficult to precisely assess in chestnuts. Moreover, damage seems likely to be related to initial quality of the fruit, temperature and duration of exposure. No consistent differences between varieties were found in this trial, which is similar to other fruit. The results may be summarized as follows;

Temperature range	Result
0 ^{o}C to -1^{o}C	No damage
-1 ^{o}C to -2 ^{o}C	No damage observed
-2 ^{o}C to -3 ^{o}C	Slight damage possible, particularly on stored fruit
-3 ^{o}C to -4 ^{o}C	Moderate damage likely if exposed for 2 hours or more
-4 ^{o}C to -5 ^{o}C	Severe damage probable
-5 ^{o}C or lower	Severe damage inevitable

It has been common practice in the past for growers to set cold rooms at -3^{o}C. This is extremely close to the point at which damage can occur, suggesting this is a risky (and possibly unnecessary) strategy. It seems possible that the main reasons more severe damage has not been observed in chestnuts stored at -3^{o}C is that;

- Chestnuts may not actually reach the room setpoint due to self heating through respiration. When combined with low rates of air circulation inside some rooms and the use of liners – further restricting airflow - in stored bins, respiration may help prevent the damage observed.
- Freezing damage symptoms are subtle, mostly internal and not easily observed, particularly by the grower / packer. They are also not evident on initial warming, with off flavours and discolouration only becoming obvious after 2 or more days under ambient conditions. This may be well after product is sold.
- Freshly harvested chestnuts may be more resistant to freezing compared to the stored fruit used in this trial. Most chestnuts are not stored for long term but marketed soon after harvest.

Despite these considerations, the results suggest that cool rooms should be set no lower than -1 ^{o}C, with zero likely to be a safe option that still provides an excellent result in terms of extending storage life.

7 Storage temperature and quality

7.1 Aim

To determine the effects of storage temperature on quality of short and long stored fruit.

7.2 Method

The initial proposal was to compare -3^{o}C, 0^{o}C and +3^{o}C. However, no storage room or cabinet could be identified that could reliably provide a -3 ^{o}C environment. The trial therefore focused on comparing 0^{o}C and 5^{o}C; this would still provide some information on the relative importance of different temperature regimes.

Samples were obtained of 3 different chestnut cultivars; Red Spanish, April Gold and Bouche de Betizac. These were sorted into small trays, weighed to within 0.1g and loosely overwrapped with plastic bags. Three units were constructed per removal time for Red Spanish and April Gold, with 2 units per removal time for Bouche de Betizac.

All samples were then placed in storage at 0^{o}C or 5^{o}C. Removals occurred after 2, 4, 8 or 15 weeks of storage. After removal the fruit were immediately re-weighed, then incubated at 22^{o}C to provide 3 days shelf life before final assessment of weight loss, softening, shrivel and mould. Each sample was then scored and cooked for 2 minutes in the microwave before assessment of peelability and development of rancidity.

7.3 Results

Initial assessment of weight loss and external characteristics found no differences between the varieties tested. The data could therefore be combined to provide greater replication. Weight loss after 8 weeks or more was greater in the fruit stored at 0°C than it was for the fruit stored at 5°C. This demonstrates that often the storage conditions (humidity control, air flow etc) can have a greater impact on weight loss than the absolute temperature (Figure 24).

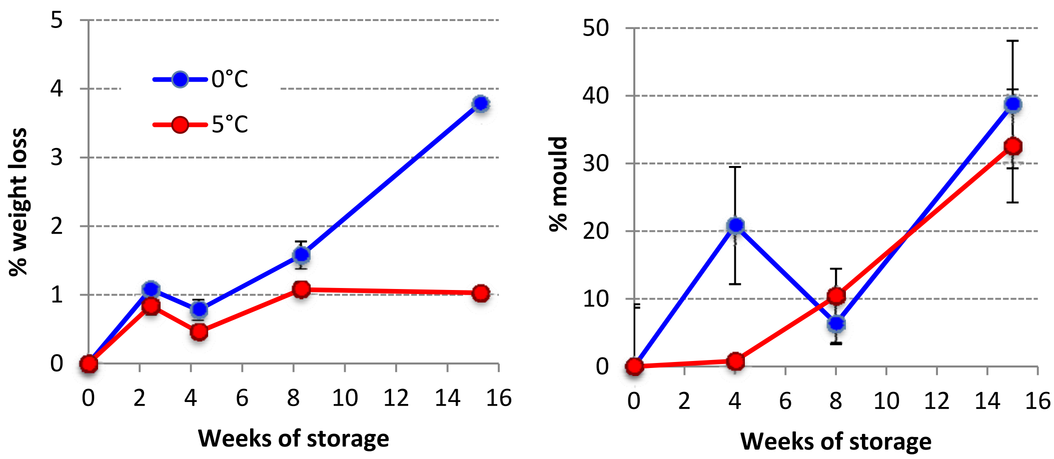


Figure 24 - Changes in weight loss and mould in chestnuts stored for up to 15 weeks at 0 or 5°C. Bars indicate the standard deviation of each mean value (n=8)

Very little deterioration in fruit quality was observed up until the 8 weeks storage assessment. At this point mould started to appear on a number of the samples. By 15 weeks fruit were starting to develop more severe mould, and kernels of the cooked fruit were noticeably darker (Figure 25), particularly the cv. Red Spanish (Figure 26).

Figure 25 - Condition of kernels of cv. April Gold following 4, 8 or 15 weeks storage at 0°C or 5°C.

Figure 26 - Condition of kernels of cv. Red Spanish following 4, 8 or 15 weeks storage at 0°C or 5°C

No differences were observed between the temperature regimes for storage times of less than 8 weeks duration. As may be seen in Figure 26, after this time cv. Red Spanish kernels appeared slightly darker in the fruit stored at 5°C. This difference was similar at the 15week assessment, with increased mottling and uneven kernel colour at the higher temperature. The difference was less apparent in the April Gold fruit, with 0 and 5°C apparently providing similar outturn quality even at the longer storage times tested.

No significant differences in shrivel, peelability, rancidity or softening due to storage temperature were observed for cvs. April Gold or Bouche de Betizac during the trial.

7.4 Discussion and Conclusions

It had been expected that chestnuts stored at the sub-optimal temperature of 5°C would suffer increased shrivel, mould growth and softening during storage compared to those stored under the close to optimal temperature of 0°C. However, differences were small, subtle, and only readily apparent in the Red Spanish cultivar. All samples were starting to deteriorate by the 15 week assessment, however this was true of both the lower and higher storage temperature regimes.

However, sample sizes in this trial were extremely small. In addition, laboratory storage conditions may have been significantly different (in terms of temperature fluctuations, humidity and airflow) compared to those that would normally be found in a large commercial storage facility.

Nonetheless, the results do suggest that changes in chestnut quality due to temperature are subtle and may occur quite slowly during storage. It seems likely that temperature control will only have significant impacts on outturn quality at longer storage times; if chestnuts are only being stored for 2-4 weeks, then higher storage temperatures may provide an economic alternative while still preserving freshness and quality of chestnut fruit.

8 Recommendations

Cooling rates

- Warm chestnuts should never be placed into a lined bin and simply placed in the cold room to cool.
- Ventilation pipes can increase the rate of cooling at the centre of a bin, so are a useful addition if growers are room cooling chestnuts in bins.
- Hydrocooling systems need to be checked to ensure that water temperatures are low enough and immersion times are long enough to thoroughly cool chestnuts (through to the core) before storage.
- Forced air systems can provide rapid cooling without increasing moisture loss. Simple, inexpensive systems may be developed which utilize a suction fan mounted on the top of up to three wrapped bins and are operated within the cold store. These may be a useful technology for growers with medium to large size cold rooms.

Freezing temperatures

- Freezing causes kernel darkening, development of off odours and flavours, weight loss and softening of chestnuts. However, these effects can be subtle. They are also internal, found mainly after shelf life and cooking and not easily quantifiable.
- Freezing damage is caused by a combination of time and temperature.
- Core temperatures around -2.5^{o}C may have the potential to cause slight damage to some fruit, especially if it is not freshly harvested.
- Core temperatures below -3^{o}C for 2 hours or more are likely to cause freezing injury to chestnuts.
- Even a short exposure to temperatures -4^{o}C or less can cause severe freezing injury.
- Room temperatures should not be set below -2^{o}C and may be more confidently set at close to 0^{o}C to avoid potentially damaging fruit.

Storage environment

- Few differences in chestnut outturn quality and shelf life were observed when comparing chestnuts stored at 0 or 5^{o}C for several weeks
- After nearly 2 months, slight differences could be observed in kernel colour between the two temperature regimes, but not for all varieties.
- Extending storage to 15 weeks decreased quality regardless of storage temperature.
- Storage temperature is not critical for chestnuts that are stored for a relatively short period of time. Growers may find they can run cold rooms at 0^{o}C or even slightly higher without compromising quality.
- If chestnuts are to be stored for more than two months then storage temperature is likely to have a greater effect on outturn quality – in this case growers may consider reducing temperature to approximately -1^{o}C.

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