Final Report

Helping people to reduce fresh produce and dairy waste: **The impact of packaging and refrigeration on shelf life**

A report detailing shelf-life experiments to determine the impacts of packaging and storage conditions on the shelf life of fresh produce and dairy items.

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Written by: Tom Quested, Griff Palmer, Rachel Devine, Helen White, Estelle Herszenhorn, Jake Jasper (WRAP)

Front cover photography: Open fridge containing fruit and vegetables

Executive summary

This report is one of three describing a programme of research which investigated how the selling of fresh fruit and vegetables loose or in packaging could impact household food waste (HHFW). However, the research also encompassed other related facets of HHFW and packaging, including the impact of storing food items in ambient conditions versus in the refrigerator, the role of fridge temperatures, and people's interactions with date labels. Some of the research also examined these impacts on dairy products.

This report focuses on the shelf life of fresh fruit and vegetables and dairy products in different conditions.

Why are we doing this research?

Plastic pollution and food waste are prominent environmental issues that have risen up the social and political agendas in recent years. Plastic pollutes nearly every ecosystem on the planet, damaging wildlife and our life-support systems. With up to 40% of global food production being wasted, food waste is also an important challenge. The amount of land used to produce the total food wasted is equivalent in area to China and the wasted food has a greenhouse gas footprint larger than any nation bar the USA or China. Furthermore, in nearly every country with accurate data, *households* are the single largest source of food waste. Data for the UK, where this research focuses, indicates that approximately 70% of post-farm gate food waste (i.e., that from the supply chain excluding agriculture) comes from households.

One of the key barriers to removing plastic packaging from fresh produce items is that such a change could impact levels of food waste. One common narrative suggests that plastic packaging can extend the shelf life of uncut fresh produce and thereby reduce food waste. However, little scientific information in the public domain was found about the effect of packaging on the shelf life of fresh produce. Therefore, assessment of this narrative was difficult given the information publicly available. This is the main evidence gap that this project seeks to fill.

The research questions that this project investigates are:

- Does the presence of plastic packaging influence the shelf life of fresh fruit and vegetables?
- Does refrigeration influence the shelf life of fresh products commonly stored in ambient conditions in the home, but that could be refrigerated?
- Does the temperature of refrigeration (9°C vs 4°C) influence the shelf life of fruit and vegetables and dairy products that are typically refrigerated?
- How is the shelf life of dairy products influenced by when they are opened?
- Do products last longer than their Best Before or Use By date, and under what conditions?

What research was performed?

Experiments were conducted to assess the deterioration of certain food items over time under controlled conditions. These were performed on a range of fresh produce and dairy items, chosen for their high contribution to HHFW in the UK and to support other elements of this programme of work:

- Fresh produce: apples, bananas, broccoli, cucumber and potatoes
- Dairy items: hard cheese, milk, natural yogurt and fruit yogurt.

Comparisons were made between different conditions to assess the impact on shelf life of packaging, storage conditions and when items were opened. The conditions investigated varied between products and are summarised in Table ES1:

Table ES1: Conditions investigated for different products

Product conditions	Packaged vs. loose	Transparency of packaging	Refrigeration vs. ambient	Fridge temperature	Open life
Apple	✓		✓		
Banana	✓				
Broccoli	✓		✓	✓	
Cucumber	✓			✓	
Potatoes	✓	✓	✓		
Hard cheese*	✓			✓	✓
Milk				✓	✓
Fruit yogurt				✓	✓
Natural yogurt				✓	✓

* For hard cheese, the effect of 'temperature abuse' (keeping the cheese out of the fridge) was also investigated, alongside how well wrapped the cheese was after opening.

For all products, sensory evaluation was undertaken, forming the core output of this research. Trained assessors analysed samples in blind test conditions at scheduled intervals. Each sample was then scored against a predefined quality matrix covering aroma, taste, texture, and appearance. Product appearance was benchmarked against reference images. The sensory evaluation was carried out by injini laboratory with three trained assessors assigned to each product. The aim of the sensory evaluation was to identify:

- The point at which different levels of deterioration are observed, including when a product first shows signs of deterioration as well as when it is no longer of a sufficient quality to eat
- The extent to which these are influenced by the different test conditions.

Samples were graded using a Red, Amber, and Green (RAG) system for each sensory property (Table ES2) and the scores were then combined to create an overall score for each sample. RAG categories for sensory evaluation were:

Table ES2: Rating system for sensory evaluation of products

Colour rating	Evaluation	Descriptions*
Green	Optimal	Optimal product quality with minimal defects.
Amber	Acceptable	The majority of people would still consume, but minor defects.
Red	Unacceptable	Deemed inedible by the majority of people.

*Products were assessed against criteria in the quality matrix, covering aroma, taste, texture and appearance.

To aid analysis of the data from the sensory evaluation, a method to convert the RAG rating for each individual sample to numerical values was required. The numerical version of the RAG rating is referred to as the 'deterioration score', ranging from 0 to 1. A score of 0 means that all samples were rated as Green and a score of 1 means all samples were rated as Red (refer to Appendix 1 for more details).

Key comparisons were made at a deterioration score of 0.3. This is approximately the point when around 60% of the assessments are Amber (acceptable) and 40% Green (optimal). Few / none are Red (unacceptable) at this point. Therefore, a deterioration score of 0.3 can be seen as a mid-point in the deterioration journey of a product, suitable for making comparisons between conditions.

In addition to sensory evaluation, pressure testing and microbiological tests were undertaken for some of the products. These results from these tests were generally in line with the sensory-analysis results. Pressure and microbiological results can be found in the main body of the report.

What were the findings for fresh produce?

Packaged vs. loose: Figure ES1 and Table ES3 provide summary results for the fresh produce items, comparing experiments involving packaged and loose items. Of the 10 comparisons made, eight had no detectable difference in shelf life between the packaged and loose options. For cucumber, the shrink-wrap packaging did not increase shelf life for either of the two storage temperatures tested.

For two conditions, the packaged product had a longer shelf life than the loose product. These conditions were:

- bananas at room temperature (1.8 days or 23% longer), and
- broccoli in the optimal fridge, 4°C (7 days or 35% longer)

Figure ES1: Comparison of packaged and loose shelf life for different product / condition combinations. % difference shown for those where results are substantial.

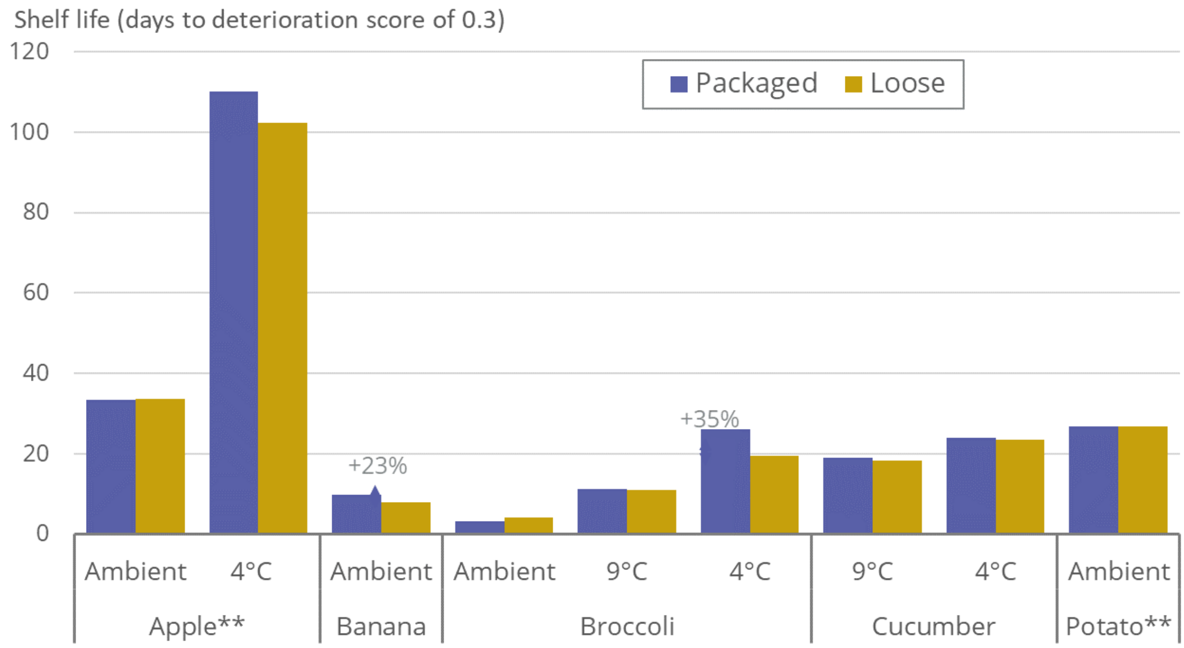

Table ES3: Comparison of packaging and loose on shelf life

Product	Condition	Impact of packaging on shelf life
Apple	Ambient	No impact detectable
	4°C fridge	No impact detectable**
Banana	Ambient	Increase of 1.8 days (+23%)
Broccoli	Ambient	No impact detectable
	9°C fridge	No impact detectable
	4°C fridge	Increase of 7 days (+35%)
Cucumber	9°C fridge	No impact detectable
	4°C fridge	No impact detectable
Potato	Ambient	No impact detectable
	4°C fridge	No impact detectable **

**For refrigerated apples and potatoes, there was considerable scatter in the sensory assessment data. Further investigation demonstrated that differences seen between packaged and loose conditions could have been due to this scatter, rather than being a real affect. More data would have needed to be collected to determine any difference relating to the presence of packaging (Appendix 3 contains further analysis on this point).

In reality, any modest differences in the shelf life of refrigerated apples and potatoes (e.g., between packaged and loose) will have limited impact on HHFW: if they last months in these conditions, then there is plenty of opportunity for households to use them before they start to deteriorate.

It should be noted that, for all products bar potatoes, loose variants were created by depackaging packaged products on their receipt by the retailer. For potatoes, the same variety was supplied loose and in a range of packaging types directly from the packer. In both cases, this allowed comparison of the same variety from the same source. Therefore, any differences between the packaged and loose varieties that are statistically significant can be attributed to the absence or presence of packaging in the home.

However, by obtaining loose samples in this manner, there are two important caveats. Firstly, with the exception of potatoes, the items tested as 'loose' had travelled through the supply chain as packaged items. Therefore, these tests are not comparing any difference in damage picked up in the supply chain. Secondly, the varieties and specifications (e.g., item size) sold loose in the UK often are different from those sold packaged. The testing in this research, therefore, does not seek to determine the effect on shelf life of these differences in variety and specification.

Therefore, it is important to note that the comparisons in these experiments are the effect of keeping the item in its packaging or removing from its packaging *after purchasing.*

Fridge vs. ambient storage: It is perhaps no surprise that, of the foods tested – apples, broccoli and potatoes – those stored in the fridge lasted longer than in ambient conditions. In all conditions, the shelf life was at least tripled (Figure ES2 and Table ES4).

Figure ES2: Comparison of shelf life for optimal fridge (4°C) and ambient conditions for different product / condition combinations

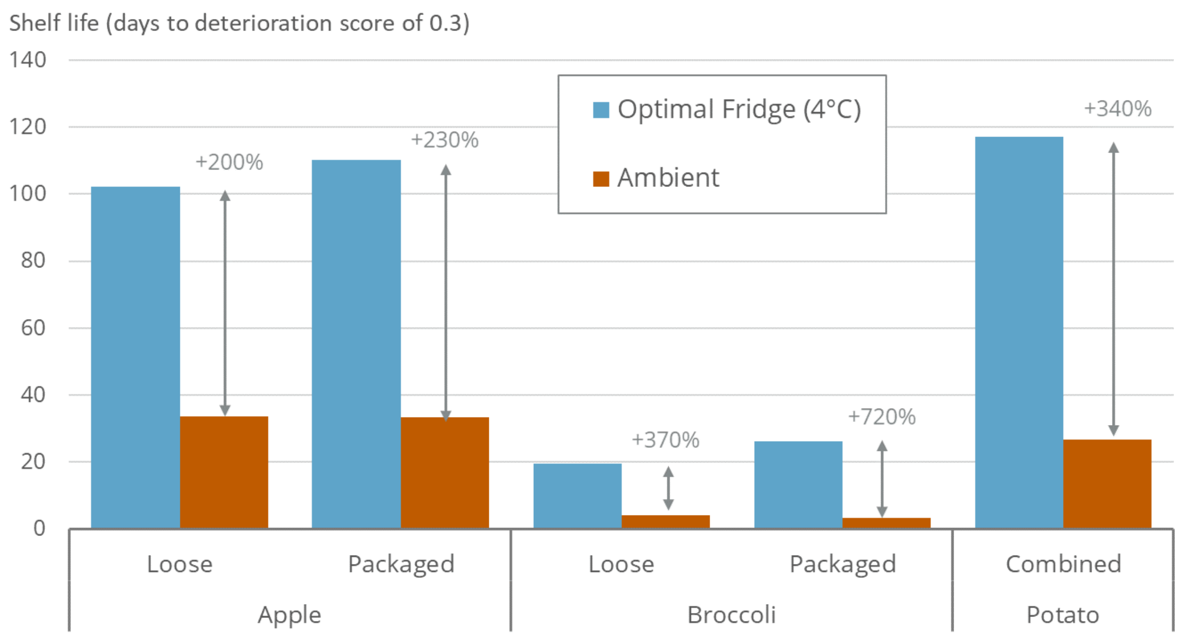

Table ES4: Comparison for fridge (4°C) and ambient storage on shelf life

Product	Condition	Impact of fridge storage on shelf life
Apple**	Loose	Increase of 69 days (+200%)
	Packaged	Increase of 77 days (+230%)
Broccoli	Loose	Increase of 15 days (+370%)
	Packaged	Increase of 23 days (+720%)
Potato**	Average of all packaged and loose conditions	Increase of 90 days (+340%)

**There is considerable scatter in shelf-life results for refrigerated apples and potatoes. For this reason, an average of all four conditions (three packaged and one loose) was made. There is clear evidence of the shelf-life extension of fridge storage for these items, but the exact amount of additional shelf-life conferred is approximate.

Fridge temperature: For the two vegetables tested, optimal (target temperature = 4°C) refrigeration increased lifespan by a significant amount over the warmer, sub-optimal (target temperature = 9°C) fridge (Figure ES3 and Table ES5). For cucumber, it extended the shelf life by 5 days, adding approximately one-quarter to its life. For broccoli, it added around 8-15 days, depending on whether the broccoli was packaged. For packaged broccoli, this more than doubled its shelf life.

Figure ES3: Comparison of shelf life for fridge temperatures (4°C vs 9°C) for different product / condition combinations

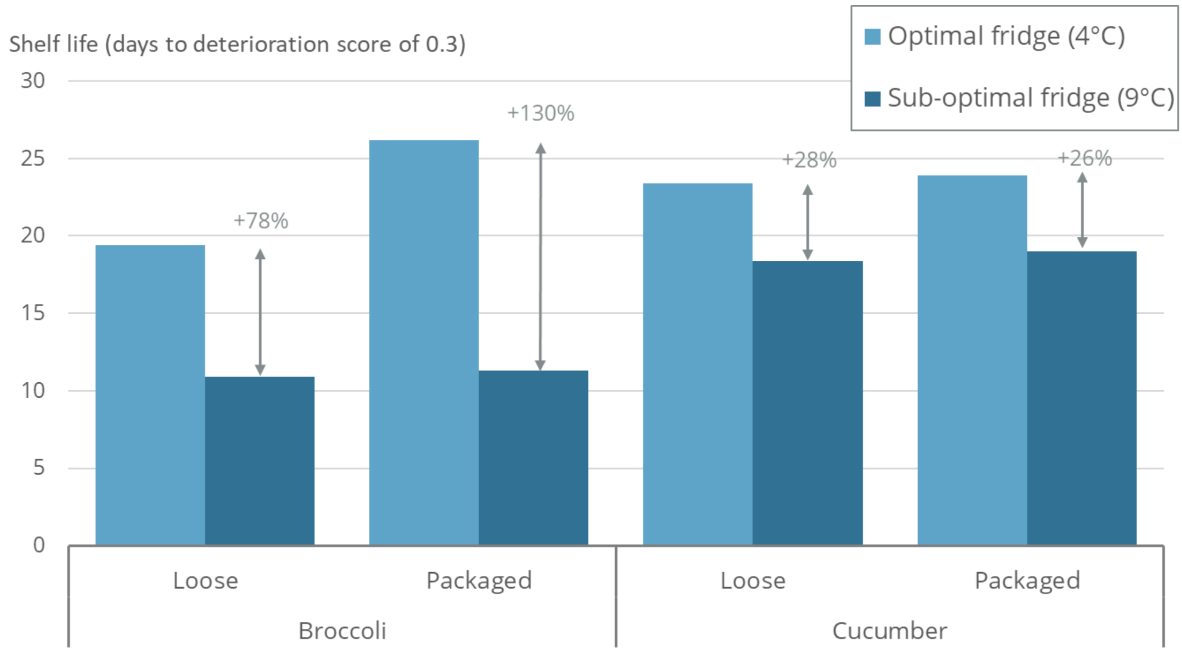

Table ES5: Comparison of fridge temperatures (4°C vs 9°C) on shelf life

Product	Condition	Impact of fridge temperature on shelf life*
Broccoli	Loose	Increase of 8.5 days (+78%)
	Packaged	Increase of 15 days (+130%)
Cucumber	Loose	Increase of 5 days (+28%)
	Packaged	Increase of 5 days (+26%)

*The differences quoted are at a deterioration score of 0.3. This is approximately the point when most products are rated 'amber' (acceptable), but few / none have been given a 'red' assessment (unacceptable).

How long do products last relative to their Best Before date? To answer this question, a comparison is made between the Best Before (BB) date and first signs of deterioration (Table ES6). This differs from results quoted above in the Executive Summary, which focus on a deterioration score of 0.3 – a mid-point in the deterioration journey. With two exceptions, the first signs of deterioration occurred after the Best Before date for packaged fresh produce items.

For packaged fresh produce items stored in sub-optimal conditions, this was often soon after the BB date. However, for some of the items stored in optimal conditions, no signs of deterioration were seen until well after the BB date: e.g., 15 days afterwards for broccoli and 74 days afterwards for apples when stored refrigerated at 4°C.

Table ES6: Comparison between the Best Before date and the *first signs* of deterioration for **packaged fresh produce**. All dates are relative to the number of days after packing.

Product	Condition	BB date	Date of 1st sign of deterioration	Difference between BB date and 1st sign of deterioration
Apple	Ambient	14	17	3 days after the date (+21%)
	4°C		88	74 days after the date (+529%)
Banana	Ambient	6	7	1 day after the date (+17%)
Broccoli	Ambient	6	2	4 days before the date (-67%)
	9°C		7	1 day after the date (+17%)
	4°C		21	15 days after the date (+250%)
Cucumber*	9°C	17	17	0 days – no difference
	4°C		18	1 day after the date (+6%)
Potato**	Ambient	10	14	4 days after the date (+40%)
	4°C		30	20 days after the date (+200%)

**For Cucumber, there was no Best Before date on the product. Instead, the retailer had a product life, which has been used in the same way as the BB date in this table.*

***Estimate for packaged potato uses an average of results for the three types of plastic packaging.*

These results suggests that Best Before dates for these specific products were set as 'markers of quality'. They appear to have been determined for sub-optimal conditions, with a low threshold for deterioration.

What were the findings for dairy products?

Fridge temperature: For the dairy products tested, all four showed a marked increase in shelf life when stored in the optimal fridge (target temperature 4°C) compared to the sub-optimal fridge (target temperature of 9°C), Table ES7. This is consistent with previous research findings and likely reflects slower growth of spoilage bacteria at lower temperatures.

Table ES7: Comparison of fridge temperatures (4°C vs 9°C) on shelf life for dairy items

Product	Notes	Impact of fridge temperature on shelf life (days, % change since bottling / packing)
Milk	Average over four different opening times	+1.5 days shelf life (+8%)
Natural yogurt	Average over three different opening times	+3.7 days shelf life (+12%)
Fruit yogurt	Average over three different opening times	+3.0 days shelf life (+12%)
Hard cheese	Average over four different conditions	+8.8 days shelf life (+19%)

* The differences quoted are the boundary between Amber (acceptable) and Red (unacceptable) ratings. Similar patterns were seen for the Green/ Amber transition.

It should be noted that the averages presented in Table ES7 are approximate, due to the inherent scatter in the data. More data would have been needed to determine the exact shelf-life extension of lower refrigeration temperatures, and to allow for comparison between products. However, the general trend is clear from this data.

Effects on product shelf life of when items were opened: The experiments conducted for dairy products as part of this research allowed the shelf life to be compared for products from the same batch opened on different dates (but otherwise subjected to the same conditions). For most of the products tested, trends were identified, but not exact differences relating to when items were opened, due to the scatter inherent in the data.

For milk, the shelf life did not appear to be influenced by when it was opened. Instead, the important factor in determining shelf life was the length of time since bottling.

In contrast, natural and fruit yogurt and cheese tended to last until a later date if opened later:

For yogurt, items opened on their Best Before date usually lasted several days longer – relative to the day of purchase – than those opened on the day of purchase.

Cheese opened on the day of purchase lasted 29 days **after the purchase date**, whereas cheese opened on the Best Before date (62 days after the purchase date) lasted until 73 days after purchase. In this case, opening the cheese on the Best Before date led to a difference in shelf life of around a month and a half.

Restating the same data with regard to how long cheese lasts **after opening**, cheese opened on its purchase date lasted 29 days after opening, whereas cheese opened on its Best Before date only lasted 11 days after opening.

Results for cheese also showed that wrapping cheese tightly extended shelf life by 8 days. Reducing the amount of time that cheese was left out of the fridge on test days from 60 minutes to 10 minutes increased the shelf life by 11 days. Tightly wrapped involved folding the original packaging over and wrapping the entire block with cling film. Loosely wrapped involved putting the cheese back into its original position in the packaging, but not folding the packaging over or securing in any way. One end of the cheese was therefore open to the air.

Storing hard cheese in optimal conditions can double its shelf life after opening: cheese opened on the day of purchase and stored in optimal conditions (well wrapped, refrigerated at 4°C, tightly wrapped and only left out of the fridge for 10 minutes for each test day) was still in optimal condition 36 days after opening, and acceptable quality 44 days after opening; in contrast, cheese stored in the least optimal way (loosely wrapped, 9°C and left out of the fridge for 60 minutes) was in optimal condition until 16 days after opening and acceptable quality 22 days after opening.

What are the implications of the research?

The findings of this research could have multiple implications regarding efforts to prevent HHFW and reduce plastic packaging:

Selling fresh produce packaged or loose: These results challenge the common narrative that packaging extends the shelf life of a wide range of fruit and vegetable products. Out of the ten combinations of products and storage conditions tested, there was evidence of shelf-life extension for only two. For the two products where packaging was associated with a product-life extension – bananas stored in ambient conditions and broccoli stored at 4°C – this could potentially reduce food waste, all other factors being equal.

However, for the remaining eight combinations of products and storage conditions, there was no discernible shelf-life extension[1]. Therefore, a conclusion of this study is

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[1] Out of these eight combinations, two conditions (refrigerated apples and refrigerated potatoes) were close to the threshold, but high levels of scatter in the results meant that there was a high degree of uncertainty around any conclusions.

that packaging should not be assumed to automatically increase shelf life and reduce food waste in the home. Experimental evidence is needed to make any conclusion relating to packaging and shelf life.

Furthermore, sensory evaluation (also known as organoleptic assessment) should be used to determine the rate of deterioration of fresh produce, rather than solely using proxy measures such as moisture loss.

The products selected for this research were identified as a representative range of items to determine impacts on shelf life and excluded items that would be sold packed for other reasons, such as being small and susceptible to damage (such as berries). However, were the experiments to be repeated on other varieties and / or those sourced at different times of year and through different supply chains, the conclusions may differ from those in this report. Nevertheless, these results provide a solid evidence base that can be built upon to facilitate decision making to reduce HHFW and the use of plastic.

For the five fresh produce items included in this research, the results have been used in one of the accompanying Modelling Report to assess quantitatively the impact on HHFW of the presence or absence of packaging. This includes modelling the effect of any changes in shelf life, as determined in the current report. The modelling also includes other effects relating to selling items packaged or loose: the ability to buy an amount appropriate to a household's needs and whether a date label is present.

Fridge storage: This research quantifies the additional shelf life provided by refrigerating apples, broccoli, and potatoes, in the home. This shelf-life extension is considerable, at least tripling the shelf life in all cases investigated.

For apples, the results indicate that Royal Gala apples could last in an acceptable condition in the home for at least three months if stored in the fridge – two months longer than if stored in ambient conditions. Currently around one-quarter of the UK population stores apples in the fridge, with the majority storing them in fruit bowls or other ambient conditions. Therefore, there is an opportunity to influence where apples are stored – especially for people not using their apples before they go off – to maximise the shelf life of apples.

Fridge temperature: Alongside previous studies, this research demonstrates that there is substantial shelf-life extension from storing fresh produce and dairy items at 4°C, compared to 9°C. For the comparisons undertaken in this research, the shelf-life extension ranged from adding 5 days for cucumbers (approximately an additional 25% to the shelf life), to more than doubling the shelf life of packaged broccoli. For dairy products, the shelf-life extension varied from 1.5 days (milk) to 8.8 days (hard cheese).

These results suggest that there could be considerable reduction in food waste for many refrigerated items if a higher percentage of fridges were run at the recommended temperature. Previous studies have indicated that the average temperature of fridges in the UK is approximately 5°C and that around half of fridges are running above the recommended range (0-5°C). These studies also suggest that around 3% to 9% of fridges run above 9°C (see Section 2.7).

This area of research would also benefit from an updated comparison of the impacts of the increased energy requirements of running a fridge at the recommended temperature (rather than a higher temperature) with the impacts of less food waste resulting from these longer shelf lives.

Presence of date labels on fresh produce: The results illustrate that deterioration is greatly affected by storage conditions in the home. Nearly all products had no signs of deterioration until after the Best Before date: in the case of optimal storage conditions, substantially after the BB date. Therefore, it is challenging to set a Best Before date for fresh produce that indicates when a product will start to deteriorate in the wide range of conditions found in people's homes. It should be noted that a sizeable minority of the UK population use the Best Before date as an indicator of when to dispose of food items, which suggests that Best Before dates could be responsible for a large amount of HHFW. From this perspective, food waste could be prevented by their removal from fresh produce items. This effect is further explored (and quantified) in the two accompanying reports.

Open-life guidance of dairy products: Many dairy products carry an 'open-life statement', e.g., 'once opened, use within 3 days'. In 2019, nearly all fresh, pasteurised cow's milk sold through UK supermarkets carried an open-life statement, with a duration of 3 days. However, this research demonstrated that the time of opening had no measurable impact on how long milk lasted for. Instead, the important factors were the length of time since bottling and the storage temperature.

These results therefore suggest that the open life statement is not a useful indicator of the product's quality. Open life statements are typically applied to some products because of poor handling and cross contamination, or drying out / hardening if not stored properly. As these are more closely linked to people's behaviour in the home, alternative approaches to target these behaviours could be a more appropriate solution, as opposed to a blanket open life policy.

In contrast to milk, for hard cheese and the two varieties of yogurt tested, when the product was opened does appear to influence how long it lasts. In 2019, 89% of hard cheese sold through UK supermarkets had a 'use within' statement, with the length of time stated to use the cheese given as between 5-7 days. The results in this study suggest that cheese may last much longer than this window: even hard cheese stored at 9°C (i.e., above the recommended temperature range), left out of the fridge most days for one hour and poorly wrapped was still of rated as 'acceptable' 22 days after opening.

Contents

Glossary

Best Before (BB) date: A type of date marking applied to many food and drink products in the UK (in addition to many other countries). It is generally applied to products where food safety is a lower concern and is presented as an indicator of the quality of the food[2]. Importantly for this project, BB dates are not legally required on fresh, uncut produce in the UK; however, many such products do carry BB dates. In addition, many dairy products, including the cheese tested in this project, carry BB dates.

Colony forming unit (cfu): A measure of the population of micro-organisms used in the microbiological testing.

Deterioration score: A scoring system for the sensory evaluation (below) used to average the results from multiple samples and assessors, aiding further analysis. A score of zero indicates optimal quality (Green assessments), a score of one unacceptable quality (Red assessments). Please refer to Appendix 1 for more information.

Fresh produce: fresh fruit and vegetables.

Household food waste (HHFW): covers any food or associated inedible parts disposed of via the following routes: the general waste bin (residual waste), separate food-waste collections, mixed food and garden collections, via the sewer and home composting.

Monte Carlo simulation: a technique used to understand the uncertainty in the results emanating from the scatter between sensory-evaluation datapoints. Please refer to Appendix 3 for more details.

Not used in time: food that has been thrown away because it has gone off (mouldy, mushy or rotten) or because it has passed a date label (e.g., 'use by' or 'best before'). Differences in shelf life usually impact this fraction of food waste.

Open life: the lifespan of a product after its packaging is opened. For the dairy products tested in this research, the products had statements referring to the open life of the product: e.g., "Once opened consume within X days". For these dairy products, the effect of when they were opened on their deterioration was tested.

Sensory evaluation: also known as organoleptic testing, trained assessors evaluate the flavour, odour, appearance, and texture of a particular food product. Sensory evaluation is commonly applied by retailers and manufacturers to ensure high and consistent quality of products. For this report, each sample was assessed as Green (optimal), Amber (acceptable) or Red (unacceptable) by each assessor (Section 2.3).

Shelf life: as used in this report, the length of time after purchase that an item is deemed acceptable for consumption. This varies by product, by storage location and between people (i.e., different people are prepared to eat items at different points of deterioration). Assessment of shelf life is made by sensory evaluation (Appendix 2).

UK: United Kingdom

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[2] Food Standard Agency: https://www.food.gov.uk/safety-hygiene/best-before-and-use-by-dates, accessed 14th July 2021.

Use By (UB) date: A date marking applied to many food and drink products in the UK (and many other countries). "A use-by date on food is about safety. [...] You can eat food until and on the use-by date but not after. You will see use-by dates on food that goes off quickly, such as meat products ..."[2] Many dairy products currently carry a UB date in the UK, including the milk and yogurt products tested in this project.

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1.0 Introduction

1.1 Why are we doing this research?

The food system accounts for up to 37% of global greenhouse gas (GHG) emissions and the issue of food waste has been gaining global prominence since the publication of the 2011 United Nations report on this subject[3]. It is now estimated that up to 40% of food produced is wasted[4,5].

Food production uses a significant amount of land, energy, and water, and when food is wasted, so are the resources that went into producing it. Even if food waste does not end up in landfill and is used to generate compost or create energy, the GHG emissions associated with its production, processing, transport, retail, and storage are still wasted. Reducing food waste is a key part of tackling climate change and the United Nations Sustainable Development Goal 12.3 has set a target to halve per capita global food waste at the retail and consumer levels by 2030.

Of note for this report, in nearly every country with accurate data, households are the single largest source of food waste[6]. Data for the UK, where this research focuses, indicates that approximately 70% of post-farmgate food waste comes from households[7].

Plastic pollution is also a prominent environmental issue. Since the airing of the BBC documentary series Blue Planet II in late 2017, images of plastic – often plastic packaging – polluting and damaging almost every ecosystem on our planet have been burnt on to the public consciousness.

Reflecting these challenges, programmes are in place to deliver solutions. The UK Plastics Pact is transforming the way that the UK makes, uses and disposes of plastic, moving away from a linear plastics economy towards a circular system where we capture the value of plastics material – keeping plastic in the economy and out of the oceans. Launched in 2018, the UK Plastics Pact brings together governments, businesses, local authorities, citizens and NGOs behind a common vision and commitment to a set of ambitious targets:

- Eliminate problematic or unnecessary single-use packaging through redesign, innovation or alternative (re-use) delivery models
- 100% of plastics packaging to be re-usable, recyclable or compostable
- 70% of plastics packaging effectively recycled or composted
- 30% recycled content across all plastic packaging

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[3] Global food losses and food waste: extent, causes and prevention. FAO (2011) http://www.fao.org/3/i2697e/i2697e.pdf

[4] *Driven to Waste: Global Food Loss on Farms, WWF and Tesco. https://wwf.panda.org/discover/our_focus/food_practice/food_loss_and_waste/driven_to_waste_global_food_loss_on_farms/*

[5] *UNEP Food Waste Index Report, 2021.https://www.unep.org/resources/report/unep-food-waste-index-report-2021*

[6] UNEP Food Waste Index Report 2021, UNEP (2021) https://www.unep.org/resources/report/unep-food-waste-index-report-2021

[7] Food surplus and waste in the UK – key facts, WRAP (updated 2021): https://wrap.org.uk/resources/guide/waste-prevention-activities/food-love-waste-data

In parallel, the UK has committed to achieving Sustainable Development Goal (SDG) 12.3, with Courtauld 2030 setting a target to reduce food waste (post-farm gate) by 50% per person by 2030 against a 2007 baseline. The Courtauld Commitment brings together organisations from across the UK food system to make food and drink production and consumption more sustainable. At the heart of this voluntary agreement is a commitment to identify priorities, develop solutions, and implement change to cut the waste and greenhouse gas emissions associated with food and drink and protect critical water resources. To help deliver the Courtauld food waste target, WRAP and IGD have developed and led the Food Waste Reduction Roadmap, which is an industry-wide programme of work to equip food businesses to work towards UN SDG 12.3.

In the UK, around 70% of post-farm gate food waste comes from households. WRAP estimates total annual household food waste (HHFW) arisings in the UK at 6.6 million tonnes, equating to 100 kg per person, or c. £500 per year for the average household[8]. 41% of food wasted from households that could have been eaten arises from products that are 'not used in time', where food is thrown away because it has gone off or has passed a date label[9]. The cost of purchasing this food is around £6 billion each year. Fresh produce and dairy are two of the most highly wasted food categories in UK homes, costing over £4.5 billion per year[9]. Food products in these categories are the focus of this research.

1.2 What is already known about shelf life?

This section details previous research detailing the shelf life of fruit and vegetables, with particular regard to the effect of packaging, storage location and storage temperature.

1.2.1 Effect of packaging on shelf life

This section describes literature on the effect of packaging on shelf life for the five types of fresh, uncut fruit and vegetables studied in this project: apples, bananas, broccoli, cucumber and potatoes.

For apples, the effect of individually shrink-wrapping apples has been investigated for Red Delicious apples[10]. At 21°C, shrink-wrapped apples lasted 6 weeks before they fell below a minimum quality standard. The research suggested this was 3 to 4 weeks longer than unwrapped apples in the same storage conditions. Although this is useful evidence on the role of packaging, it does not closely relate to the packaging used for most apples sold in the UK, which rarely includes individually wrapped apples (Chapter 3 of the Modelling Report).

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[8] *https://wrap.org.uk/sites/default/files/2020-09/UK-progress-against-Courtauld-2025-targets-and-UN-SDG-123.pdf*

[9] *Household food waste: restated data for 2007-2015.*

https://wrap.org.uk/sites/default/files/2021-03/WRAP-Household-food-waste-restated-data-2007-2015_0.pdf

[10] *Individual Packaging of Apples for Shelf Life Extension, Anzueto, C.R., Rizvi, S.S.H., (1985). J. Food Science, 50(4), 897-900, https://doi.org/10.1111/j.1365-2621.1985.tb12975.x*

The effects of packaging on the shelf life of bananas have been previously studied[11]. Four packaging materials were assessed: perforated low density polyethylene bag, perforated high density polyethylene bag, dried banana leaf, *teff* straw and no packaging materials (the control). The packaged bananas were all marketable for longer than the unpackaged bananas (the two polyethylene bag conditions were still marketable for 36 days, banana leaf and *teff* straw for 18 days, and 15 days for unpackaged). Weight loss was also more pronounced for unpackaged bananas, as was the speed of ripening. The authors concluded that packaging of banana fruits in high- or low-density polyethylene bags increased shelf life and improved the quality over other packaging materials or no packaging.

For refrigerated broccoli at 4°C, previous research has indicated that keeping broccoli in a loosely tied polyethylene (PE) bag did not extend the shelf life relative to broccoli kept loose[12]. However, that study noted that broccoli stored loose lost weight more quickly and affected turgidity, compared to broccoli kept in a PE bag. In a separate study, different polymer film packaging materials were tested for broccoli[13]. These indicate that all film materials measured decreased weight loss and loss of texture of broccoli compared to no packaging, when measured at either 4°C or 10°C. A review of evidence quoted a New Zealand study that found the most effective means of storing broccoli was to spray the head with water, wrap it in a paper towel and store it in a re-usable 'snap-lock' bag in the fridge[14].

For cucumbers, the effect of packaging has been studied for Padmini variety (a leading variety sold in India, but not sold in the UK)[15]. These were refrigerated at 12°C with one condition shrink wrapped and the other condition left 'naked'. The weight loss (due to moisture loss) was recorded. After 15 days, the wrapped cucumbers had an average weight loss of 0.66%; the naked cucumbers had lost 11.1% of their weight. The naked cucumbers also softened at a faster rate than wrapped cucumbers. Furthermore, sensory qualities (appearance, texture and flavour) were also assessed. The naked cucumbers had a more rapid decline in sensory qualities than their wrapped counterparts. There is also a webpage (without supporting report) that indicates that unwrapped cucumbers lose moisture more rapidly than shrink-wrapped cucumbers[16]. In addition, the unwrapped cucumbers were bendier than wrapped cucumbers.

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[11] *Effect of packaging materials on shelf life and quality of banana cultivars (Musa spp.) Hailu et al. (2014), Food Sci Technol.; 51(11): 2947–2963. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4571223/*

[12] *Helping consumers reduce fruit and veg waste report, WRAP (2011): https://wrap.org.uk/resources/report/helping-consumers-reduce-fruit-and-veg-waste-report*

[13] *Effects of type of packaging material on shelf-life of fresh broccoli by means of changes in weight, colour and texture, Jacobsson et. Al. (2004), European Food Research and Technology, 218, pp. 157–16: https://doi.org/10.1007/s00217-003-0820-2*

[14] *Evidence review: Plastic packaging and fresh produce, WRAP (2019): https://wrap.org.uk/resources/case-study/evidence-review-plastic-packaging-and-fresh-produce*

[15] *Effect of shrink wrap packaging for maintaining quality of cucumber during storage: Dhall et al. (2012), J Food Sci Technol.; 49(4): 495–499. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3550898/*

[16] *https://www.cucumbergrowers.co.uk/shrink-wrap-still-necessary-further-investigation-by-the-cga-september-2018:/ Accessed 11th August 2021.*

The effect of packaging has also been explored for the Beit Alpha type of cucumber[17]. Naked cucumbers were compared to a range of compostable and non-compostable packaging, with different levels of perforation. Cucumbers were subjected to simulated storage condition for the supply chain and people's homes. A wide range of tests were performed to assess the deterioration of the cucumbers. Generally, naked cucumbers lost more weight, had higher levels of shrivelling and pitting. However, they were comparable to some of the packaged varieties for flavour and development of warts. Their acceptance scores were generally lower than packaged varieties.

For potatoes, there is evidence that potatoes stored loose, although deemed acceptable quality, became 'spongy', whereas those stored in a loosely tied PE bag were of acceptable quality at the end of the study (21 days). This was irrespective of the storage temperature[12].

1.2.2 Effect of storage temperature on shelf life

This section reviews literature and evidence relating to the impact of storage temperature and storage location on the shelf life of both the fresh-produce and dairy products investigated in this report.

For apples, the influence of temperature has been studied for individually wrapped fruit[10]. This indicates that apples decay more quickly as temperature increases: individually wrapped apples stored at 3°C were still of 'good quality' after 3 months, whereas those at 21°C fell below a minimum standard at 6 weeks.

Several papers have noted that broccoli deteriorates at a slower rate at lower temperatures. This includes lower levels of weight loss and yellowing[18] and lower levels of weight loss and loss of texture[13]. However, one study found no difference between broccoli stored at 10°C for a week compared to broccoli stored for 3 days at 4°C followed by 4 days at 10°C[19].

For cucumbers, the effect of temperature was also studied for Padmini variety[15]. This compared a fridge at 12°C with ambient conditions (in India) of 29°C-33°C. The sensory quality of cucumbers stored in ambient conditions deteriorated at a rate twice as fast as those stored in the fridge. In a separate study, 'chilling injuries' to cucumbers were observed for cucumbers stored at 5°C and subsequently stored at 20°C for 2 days[20].

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[17] *Effects of Compostable Packaging and Perforation Rates on Cucumber Quality during Extended Shelf Life and Simulated Farm-to-Fork Supply-Chain Conditions, Owoyemi et al. (2021), Foods 2021, 10(2), 471: https://doi.org/10.3390/foods10020471*

[18] *MiAe, C. (2021). Effect of packaging film and storage temperature on quality maintenance of broccoli. Retrieved August 11, 2021, from https://www.cabdirect.org/cabdirect/abstract/20093100044*

[19] Jacobsson, A., Nielsen, T., Sjöholm, I., & Wendin, K. (2004). Influence of packaging material and storage condition on the sensory quality of broccoli. *Food Quality and Preference*, *15*(4), 301–310. https://doi.org/10.1016/S0950-3293(03)00070-3

[20] *Adamicki, F. Effects of storage temperature and wrapping on the keeping quality of cucumber fruits. Acta Hortic. (1985) 156, 269-272 https://doi.org/10.17660/ActaHortic.1985.156.33*

For potatoes, different storage temperatures have been compared, with regard to the texture and colour of potatoes cooked after storage[21]. Potatoes stored at 4°C had a firmer texture after cooking and changed colour less than potatoes stored at 20°C. No sensory evaluation of the potatoes was performed in this study.

The rate of spoilage of milk increases with temperature due to growth of microbes, with one paper citing that, for every 2°C increase in temperature, the shelf life approximately halved[22]. Similarly, Schmidt et al.[23] found that pasteurised milk at 3°C lasted 21 days longer than at 7°C. Petrus et al.[24] estimated that the shelf life of HDPE-bottled, pasteurized milk was highly temperature dependent: at 2, 4, 9, 14 and 16 °C the microbial stability (their measure of shelf life) was 43, 36, 8, 5 and 3 days, respectively.

Unsurprisingly, similar trends with temperature were found for yogurt: deterioration was observed earlier for yogurts stored at higher temperatures compared to lower temperatures[25],[26].

1.2.3 Summary of previous research

In summary, there is some information on the role of packaging on the shelf life of the five types of fresh produce of interest. This generally suggests that packaging increases the shelf life of products. However, no information was found for potatoes. Furthermore, for some of the other products, the apple variety, storage conditions or packaging were not closely matched to situations in the UK: e.g., data for apples was for individually wrapped fruit, and the varieties of cucumber were different to those sold in the UK.

Therefore, to inform estimates of the impact of selling fruit and vegetables loose or in packaging on HHFW in the UK, there is a need for further experiments, as detailed in Sections 1.3 & 2.0. These allow the shelf life for fresh produce varieties frequently sold in the UK to be determined; where packaging is present, it is also typical of the UK market.

For the effect of storage location and storage temperature, previous evidence is also fragmented, with only some of the data relevant to the UK. Therefore, this area would also benefit from experiments designed to be relevant to the UK market, allowing the impact of storage location and storage temperature to be determined more accurately.

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[21] Nourian, F., Ramaswamy, H. S., & Kushalappa, A. C. (2003). Kinetic changes in cooking quality of potatoes stored at different temperatures. *Journal of Food Engineering*, *60*(3), 257–266. https://doi.org/10.1016/S0260-8774(03)00046-3

[22] *Rysstad, G., & Kolstad, J. (2006). Extended shelf life milk—advances in technology. International Journal of Dairy Technology, 59(2), 85–96. https://doi.org/10.1111/J.1471-0307.2006.00247.X*

[23] *Effect of pasteurization and storage conditions on the shelf life and sensory quality of aseptically packaged milk, Schmidt, D; Cromie, S J; Dommett, T W. Australian Journal of Dairy Technology; Melbourne Vol. 44, Iss. 1, (May 1989): 19-24.*

[24] *Petrus, R. R., Loiola, C. G., & Oliveira, C. A. F. (2010). Microbiological Shelf Life of Pasteurized Milk in Bottle and Pouch. Journal of Food Science, 75(1), M36–M40.* https://doi.org/10.1111/J.1750-3841.2009.01443.X

[25] *Mataragas, M., Dimitriou, V., Skandamis, P. N., & Drosinos, E. H. (2011). Quantifying the spoilage and shelf-life of yoghurt with fruits. Food Microbiology, 28(3), 611–616. https://doi.org/10.1016/J.FM.2010.11.009*

[26] *Jakubowska, M., & Karamucki, T. (2020). The effect of storage time and temperature on the quality of natural yoghurt. Acta Scientiarum Polonorum Zootechnica, 18(4), 29–38. https://doi.org/10.21005/ASP.2019.18.4.04*

1.3 What research did we do?

This research described in this report was initiated to help understand one area where the issues of food waste and plastic pollution intersect: the impact of packaging, usually plastic packaging, on HHFW. One of the primary purposes of the research is to support modelling work, published alongside this report[27], which seeks to identify and quantify the degree to which selling fresh fruit and vegetables loose or packaged influences HHFW. The current report assists the modelling work by providing information on the shelf life of relevant products, both in packaging and loose.

However, the current report goes further: it explores the impact on shelf life of storage location and temperature for not only fresh fruit and vegetables, but also a selection of common dairy products: milk, hard cheese and two sorts of yogurt. Section 2.1 explains the rationale behind these choices and the type of fresh produce included (apples, bananas, broccoli, cucumber, and potatoes).

Experiments were conducted to understand the impact of different temperature fridges. This allows a comparison of shelf life at 4°C (i.e., within the recommended range of 0°C - 5°C) and at 9°C, outside this recommended range. For selected products, comparison is made of the shelf life for refrigerated products and those stored at room temperature. Full details of the testing conditions can be found in Section 2.2. A range of testing methods were performed to quantify the shelf life of products, including sensory evaluation (Section 2.3), pressure testing (Section 2.4) and testing for microbiological organisms (Section 2.5).

In summary, the questions this research seeks to answer are:

- Does the presence of plastic packaging influence the shelf life of fresh fruit and vegetables?
- Does refrigeration influence the shelf life of fresh produce commonly stored in ambient conditions in the home, but that could be refrigerated?
- Does the temperature of refrigeration (9°C vs 4°C) influence the shelf life of fresh-produce and dairy products that are typically refrigerated?
- How is the shelf life of dairy products influenced by when they are opened?
- Do products last longer than their Best Before date or Use By date, and under what conditions?

The results from this research (Chapter 3.0, summarised in Chapter 4.0) have already been used as input data to the aforementioned modelling that aims to understand the impact of the presence or absence of packaging on HHFW. However, they also inform:

- Guidance for industry on food labelling
- Design of interventions aimed at influencing citizen's behaviour relating to storage and interaction with date labels
- Engagement with citizens via the *Love Food Hate Waste* and *Clear on Plastics* campaigns

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[27] *https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

2.0 Methodology

This chapter presents the methodological approaches and experimental parameters used in this research. It covers:

- The food items chosen to experiment upon (Section 2.1)
- The test conditions for the shelf-life experiments for each product (Section 2.2)
- Details of the:
  - Sensory evaluation (Section 2.3)
  - Pressure testing (Section 2.4) and
  - Microbiological testing (Section 2.5)
- Testing frequency (Section 0)
- Temperature and humidity parameters (Section 2.7)

2.1 Choice of food items

Nine fresh-produce and dairy products were selected for testing. The fresh produce items tested were apples, bananas, broccoli, cucumbers, and potatoes. These were primarily selected to provide data for modelling of the impact of the presence or absence of packaging on household food waste (HFHW)[28]. The five products were chosen to include items contributing greatly to HHFW in the UK[29], sold both packaged and loose, and have differing characteristics from one another: e.g., they have a range of shelf-lives, some are usually eaten cooked, one (potato) is often eaten as a starchy carbohydrate, etc.

The dairy products chosen were hard cheese (cheddar), milk (pasteurised, semi-skimmed), fruit yogurt (strawberry), and natural yogurt. These were also chosen as they contribute to HHFW in the UK and have relatively high footprints with regard to greenhouse gas emission. Consumers of these products frequently use the information on the date labels. Their shelf life can greatly influence the amount of waste[30].

Three types of testing were conducted - sensory evaluation, pressure testing and microbiological testing. Only relevant tests were applied to each product: all products underwent sensory evaluation, pressure testing was reserved for apples and potatoes, while only dairy products underwent microbiological testing (Table 1).

For each product type, one product was tested, as listed in Table 1. While it would have been useful to test a wider range of products, budget constraints did not permit more testing. For all product types, a product was selected to represent as much of the UK market as possible. For many products, the UK market is dominated by a particular

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[28]*Modelling the impact of selling products loose or in packaging, WRAP, 2022,* *https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

[29] *Household food waste: restated data for 2007-2015. WRAP, 2019.* *https://wrap.org.uk/sites/default/files/2021-03/WRAP-Household-food-waste-restated-data-2007-2015_0.pdf*

[30] *Kandemir et al. (2020), Using discrete event simulation to explore food wasted in the home, Journal of Simulation:* *https://doi.org/10.1080/17477778.2020.1829515*

variety / type of product: Cavendish bananas, Calabrese broccoli, slicing cucumbers, semi-skimmed milk, and cheddar cheese.

For apples, Royal Gala was selected as it is one of the most popular in the UK. In addition, expert advice suggested that it was similar to many other popular varieties in its shelf life and storage characteristics.

The Estima variety of potato was selected for these experiments. Estima is often sold as a generic 'white potato': a term under which different potato varieties can be sold throughout the year depending on availability. For this reason, it is a relatively higher seller within the UK, and had the advantage that it was available for these experiments. In addition, advice from industry suggested that it had a comparable shelf-life with other potato varieties.

Two types of yogurt were chosen – natural and fruit (strawberry) yogurt – to account for the fragmented nature of the UK market for this product.

Table 1: Summary of laboratory tests that were applied to each product.

Product	Variety	Type of laboratory test		
		Sensory	Pressure	Microbiological
Apples	Gala	✓	✓	
Bananas	Cavendish	✓		
Broccoli	Calabrese	✓		
Cucumber	Slicing	✓		
Potatoes	Estima	✓	✓	
Cheese	Mild cheddar cheese 400g	✓		✓
Milk	Semi-skimmed 2 pint	✓		✓
Fruit yogurt	Strawberry yogurt, low fat 450g	✓		✓
Natural yogurt	500g, regular fat level	✓		✓

2.2 Shelf-life testing conditions

A range of different experiments were conducted to understand the impact of different storage temperatures and packaging conditions on product deterioration and shelf-life. These are summarised in Table 2 & Table 3 and described in the text below. Not all conditions were applied to all products: comparisons were made where it was useful to the issues of food waste or plastic packaging. For each test condition on each product, a series of replicate samples were tested. The full details of test conditions applied to each product are outlined in chapter 3.0.

Table 2: Product conditions tested in this research for **fresh produce items**

Product conditions	Packaged vs. loose	Transparency of packaging	Refrigeration vs. ambient	Fridge temperature
Apple	✓		✓	
Banana	✓			
Broccoli	✓		✓	✓
Cucumber	✓			✓
Potatoes	✓	✓	✓	

Table 3: Product conditions tested in this research for **dairy items**

Product conditions	Fridge temperature	Open life	Degree of temperature abuse	Wrapping: tight vs. loose
Hard cheese*	✓	✓	✓	✓
Milk	✓	✓		
Fruit yogurt	✓	✓		
Natural yogurt	✓	✓		

Packaged versus loose: Comparison of shelf life was made in the presence or absence of packaging for fresh-produce items. This test was repeated for different types of packaging (for potatoes), in different storage locations (apples, broccoli and potatoes) and for different fridge temperatures (broccoli and cucumber).

For all products bar potatoes, loose variants were created by depackaging packaged products on their receipt by the retailer. For potatoes, the same variety was supplied loose and in a range of packaging types directly from the packer. In both cases, this allowed comparison of the same variety from the same source. Therefore, any differences between the packaged and loose varieties that are statistically significant can be attributed to the absence or presence of packaging in the home.

However, by obtaining loose samples in this manner, there are two important caveats. Firstly, with the exception of potatoes, the items tested as 'loose' had travelled through the supply chain as packaged items. Therefore, these tests are not comparing any difference in damage picked up in the supply chain. Secondly, the varieties and specifications (e.g., item size) sold loose in the UK often are different from those sold packaged. The testing in this research, therefore, does not seek to determine the effect on shelf life of these differences in variety and specification.

Therefore, it is important to note that the comparisons in these experiments are the effect of keeping the item in its packaging or removing from its packaging after purchasing. This is discussed further in Chapter 4.0.

The packaging formats in the study were:

- Apples: polypropylene flow wrap
- Bananas: polyethylene (PE) bags
- Broccoli: PE shrink wrap
- Cucumbers: PE shrink wrap
- Potatoes: PE bags

Transparency of packaging: This comparison was only used for potatoes, as the level of light can affect the shelf life of potatoes. Three types of packaging with differing levels of opacity were tested on potatoes: transparent, whitewash (70% opaque), and opaque.

Refrigeration versus ambient: Apples, broccoli, and potatoes were stored in ambient conditions at 21°C and refrigerated at 4°C. For the ambient condition, apples and broccoli were stored under light during the day and in the dark at night-time, simulating a fruit bowl or being left on a worktop counter. Potatoes were stored in the dark, replicating a cupboard. Due to budget constraints, it was not possible to test potatoes in light and dark conditions. Given that the majority of UK citizens (58%) claim to store their potatoes in a cupboard[31], dark conditions were chosen for the test.

Fridge temperature (optimal versus sub-optimal): Products typically refrigerated (broccoli, cucumber and dairy products) were tested at two different fridge temperatures: 4°C (optimal) and 9°C (sub-optimal) to measure the impact of different refrigeration temperatures on products' lifespans and deterioration. Section 2.7 provides the rationale for the specific fridge temperatures selected.

Open life: This refers to the lifespan of a product after its packaging is opened. This was tested by opening dairy products on different days throughout the testing. Details of when products were opened can be found in Sections 3.6 to 3.9.

Degree of temperature abuse: all dairy products were subject to 'temperature abuse' to simulate realistic conditions in UK homes (as described later in this section). For cheese, the level of temperature abuse was varied. In one condition, the cheese was left out of the fridge for the 'standard' 60 minutes on each test day. In the comparator condition, the cheese was left out for only 10 minutes on each test day.

Tightly versus loosely wrapped: This condition was only applied to cheese to observe the impact of re-wrapping the product once opened, in particular on how quickly the cheese might dry out. Two different types of wrapping were tested: tightly (good) and loosely (poor). For reference, the instructions for tight and loose wrapping for the experiments were:

- **Tightly wrapped**: Open pack by cutting along one end. Once opened, fold original packaging over and wrap entire block with cling film. During temperature abuse leave open for that time.
- **Loosely wrapped**: Open pack by cutting along one end. Once opened, put the cheese back into its original position in the packaging. Do not fold packaging over or secure in any way. One end of the cheese will therefore be open to the air.

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[31] *Food waste tracker survey, WAVE C - April 2020, WRAP. Unpublished.*

All dairy products were also subject to 'temperature abuse' – i.e., leaving the product at room temperature to simulate 'real-life' conditions, where products may be taken out of the fridge for extended periods of time. These products were left uncovered in ambient conditions (approximately 21°C) for one hour on test days. In addition, on Day 1, the products were left at ambient conditions for four hours to simulate the time between purchasing and storing the item at home in the fridge[32].

In addition, all yogurt samples were subject to contamination, similar to realistic conditions in the home. A clean (but not sterile) spoon was inserted into the product at specific intervals to test the impact on products' lifespans and speed of deterioration when using a spoon to serve it.

2.3 Sensory evaluation / organoleptic testing

The organoleptic properties of food are the aspects that a person experiences via the senses, i.e., taste, sight, smell, and touch. Sensory evaluation– also known as 'organoleptic testing' – involves assessment of the flavour, odour, appearance, and texture of a particular food product. Sensory evaluation is commonly applied by retailers and manufacturers to ensure high and consistent quality of products. In this report we use the term 'sensory evaluation' to describe the tests because it is a term that is more widely recognised and is synonymous with 'organoleptic testing'.

In a sensory evaluation, trained assessors use sensory-based quality indicators to describe a sample of food over time. Assessors analyse samples in blind test conditions at several scheduled intervals. Each sample is then scored against predefined quality matrices covering aroma, taste, texture, and appearance – with product appearance benchmarked against reference images.

Sensory evaluation forms the core output of this research whereas pressure testing and microbiological testing support and add further detail to the findings. The sensory evaluation is central to this report since it systematically records the information available to citizens to make sensory-based decisions on whether to consume or dispose of a product.

The degree to which citizens use their sense to make these decisions varies by product. Recent WRAP research[33] showed that for fresh produce, most citizens say that they use their own judgement to decide when to eat or throw products away. The proportion who uses 'entirely' or 'mostly' their own judgement is similar across the five fresh produce items in this study, varying from 66% for broccoli to 70% for bananas. In contrast, for dairy products, a minority of citizens stating that they use their own

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[32] Four hours represents longer-than-average period of temperature abuse, effectively simulating worst-case treatment of the product. This is standard practice for this type of test and was applied to all products equally.

[33] Citizen insights on food disposal, packaging, and date labels. WRAP 2022. https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste

judgment: 49% for cheese, 33% for milk and 28% for yogurt. Whilst a minority, a sizeable proportion of citizens do use their own judgement for consumption of dairy products[34].

Therefore, systematically recording the deterioration of products allows us to understand how long items last before deteriorating and when items might be rejected by people using their senses (rather than, for instance, date labels). This systematic approach also allows comparison between different test conditions such as different fridge temperatures or the presence / absence of packaging.

The sensory evaluation was carried out by injini laboratory with three laboratory-trained analysts assigned to each product. The testing was based on ISO 3972:2001. (Some elements of the method could not conform to the ISO standard due to Covid restrictions and the nature of the study.) Each of the sensory tests (appearance, aroma, texture, taste) were completed for each of the product conditions (Table 5). However, the 'taste evaluation' was not carried out on potatoes and broccoli as this would require cooking of these items.

Samples were graded using a Red, Amber, and Green (RAG) system for each sensory property (Table 4) and the scores were then combined to create an overall score for each sample.

Table 4: Rating system for sensory evaluation of products

Colour rating	Evaluation	Descriptions*
Green	Optimal	Optimal product quality with minimal defects.
Amber	Acceptable	The majority of people would still consume, but minor defects.
Red	Unacceptable	Deemed inedible by the majority of people.

*Products were assessed against criteria in the quality matrix, covering aroma, taste, texture and appearance.

Table 5 details the quality matrix[35] used to classify food samples as either Red, Amber, or Green for each of the sensory properties, using cucumber as an example (refer to Appendix 2 for the quality matrix for each product). Photographic standards were also used when assessing product appearance and assigning a RAG category[36].

Table 5: Quality matrix for sensory evaluation of cucumber samples.

Sensory property	Green	Amber	Red

[34] *Guidance from the Food Standards Agency is clear that food should not be consumed after their Use By date because you cannot always smell bacteria and other microbes. So, the food may appear fine to eat, but could still cause food poisoning.*

[35] *The quality matrices used were proposed by injini laboratory and approved by WRAP. They do not represent the acceptable product standards of injini and were designed for the purpose of this project and are owned by WRAP.*

[36] *The photographic standards are not available as permission to share these images has not been granted due to copyright and commercial confidentiality.*

Appearance	<2% affected by rot. Ideally all free from rot. Greenish-white flesh.	<5% affected by rots. Ideally all free from rot. Customer could easily remove rot.	>5% affected by rots. Ideally all free from rot. Significant darkening browning or yellowing seeds.
Aroma	Natural, fresh.	Parts of cucumber with a musty or stale aroma, easily removable.	Musty, stale aroma over entire cucumber.
Texture	Crisp and juicy. When fresh, cucumbers should feel firm.	Slightly soft, skin easily punctured. Soft spots dotted around the sample. <10-15% of the entire sample. Drying around open end of cucumber over life.	Excessively Soft and dry.
Taste	Clean, cool & fresh with a slight sweetness.	reduced sweet & fresh flavour, free from sour or bitter notes.	Musty, earthy, sour, astringent. Bitter or off flavours / taints detected.

On any given test day for a given product and condition, multiple assessments were made: 2 to 3 assessors each assessing each replicate sample. For fresh-produce items, there were usually three replicate samples on each test day (although occasionally, if samples were running low, two replicate samples were used on a given test day). For dairy items, generally one replicate sample was used on each test day, following industry advice.

To make comparisons between different conditions and to further analyse the data, two methods were developed to combine data from these multiple assessments. 'Deterioration scores' were used for fresh produce; 'Combined RAG' assessments were used for dairy. Each is described below, with further details in Appendix 1.

Deterioration score: On a given test day, there can be as many as nine assessments of a particular product in certain conditions (three assessors each assessing three replicates). To obtain a single 'score' for that test day, a 'deterioration score' is calculated. This involves converting the individual assessments into values according to:

- Green = 0
- Amber = 0.5
- Red = 1

The average of these scores is then taken. Therefore, a value of 0 means all assessments were Green (optimal); a score of 1 means all assessments were Red (unacceptable).

The conversion to a deterioration score enabled graphical representation of the RAG ratings and a line of best fit to be drawn for each condition. The line of best fit served two important purposes: to smooth out the scatter in the graph, and to compare the deterioration scores more easily between conditions.

This method allowed comparison of the time points when the lines of best fit hit a given level of deterioration. Three key points on the best-fit lines were recorded and can be found in Appendix 1 for all fresh-produce items in all conditions:

- **Linear fit moves above 0**: the first signs of deterioration – assumed most people would still eat this product.
- **Linear fit reaches 0.3**: Moderate signs of deterioration – a midpoint, useful for comparison.
- **Linear fit reaches 0.6**: Advanced signs of deterioration – assumed that most people would no longer eat this product.

Key comparisons were made at a deterioration score of 0.3, the midway between the point where the line of best fit first deviates from zero to a value of 0.6. Checks were made to ensure the conclusions would still be valid if comparisons were made at other levels of deterioration.

The full equation used to calculate the deterioration scores and the form of the line of best fit are provided in Appendix 1.

Combined RAG assessments: Commonly used in association with sensory evaluation, these combined Red-Amber-Green assessments provide thresholds for multiple RAG assessments from a single test day for a given set of conditions. The 'combined RAG' is calculated using the proportion of samples that fell into each of the sensory-based RAG categories:

- **Red**: >25% of samples are graded Red on a given test day (e.g., at least 3 / 9 samples are graded Red)
- **Amber**: >25% of samples are graded Amber on a given test day (e.g., at least 3 / 9 samples are graded Amber)
- **Green**: 75-100% of samples are graded Green on a given test day. (e.g., at least 7 / 9 samples are graded Green)

The combined RAG assessment forms the colour coding in results tables in Chapter 3.0 (e.g., Table 7 for apples). It was also found to work better for assessment of the results for dairy products. For these products, there was more scatter in the data, therefore, creating lines of best fit was problematic.

2.4 Pressure testing

Pressure testing measures the amount of force required to penetrate the flesh of a food sample. A decrease in the amount of pressure required to penetrate the skin of a product is associated with a change in texture and decrease in quality. Pressure testing supports the sensory evaluation since it provides objective data on the structural integrity or 'firmness' of the item. Pressure testing is most commonly used on apples or pears, though in this study, apples and potatoes were selected. This is because under certain storage conditions their visual appearance can remain consistent for prolonged periods of time and potentially a loss of ‘firmness’ may be an earlier indicator of deterioration.

The test is completed using a penetrometer, which measures the force required to push a metal measuring head, of a defined diameter, into a sample. The force taken to penetrate the flesh is measured in Newtons and converted to pressure (in kilopascals, kPa) by dividing by the cross-sectional area of the metal head[37]. The operator must peel the sample on both sides and take a pressure reading from the flesh of the sample, averaging the two results. Two different sized measuring heads were used: 8 mm for potatoes and 11 mm for apples.

For each product there are pre-defined upper and lower limits for firmness. The upper limit marks a sub-optimal level of firmness, and the lower limit marks the level of firmness at which most citizens would reject. The limits were chosen based on industry standards of general quality measures and were agreed between injini and WRAP for the purpose of this study. The upper limit is broadly consistent with the Green / Amber boundary from the sensory evaluation and the lower limit is broadly consistent with the Amber / Red boundary.

The pressure test results are compared to the results from the sensory evaluation in chapter 3.0. For apples (section 3.1) and potatoes (section 3.5) the time taken to reach the upper and lower pressure test limits are compared to the time taken to reach the Red / Amber stages in the sensory tests.

2.5 Microbiological testing

The presence and levels of micro-organisms in fresh and ready-to-eat products can affect the rate of deterioration in terms of both quality and safety. The speed of microbial growth in food is dependent on the physical and chemical states of the product, which are mainly influenced by pH, available water or oxygen, packaging, temperature, and the types of micro-organisms present.

In this research, microbiological testing of dairy products for spoilage and indicator organisms was completed to enable comparison between any increase in micro-organism colony counts over the course of the products’ lifespans. Differences in storage and packaging conditions and the effect this had on product quality were also observed.

All microbiological testing was completed by SGS, an external and independent UKAS accredited laboratory. All samples tested for micro-organisms and sensory evaluation originated from the same product batch to ensure results were comparable. Storage, temperature abuse and simulated contamination were consistent between the microbiological testing and sensory evaluation.

Three microbiological tests were selected for this study: Aerobic Colony Count (ACC), yeasts & moulds, and Enterobacteriaceae (EB). These tests were selected as the growth of these micro-organisms can be linked to the sensory properties and deterioration in

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[37] *One kilopascal is equivalent to 98 kg/cm^{2}.*

product quality. For example, microbial yeast and mould growth can relate to observable taints, off-flavours, and musty aromas.

The microbiological results in this report should not be used to assess the safety of a product or the risk to a citizen, as they only provide a potential indication of risk. However, higher counts of some micro-organisms such as Enterobacteriacea can indicate the presence of other micro-organisms that *are* a risk. Testing of relevant pathogens (e.g., *Listeria monocytogenes* or *Salmonella*) was not included within the scope. injini laboratory did not recommend testing pathogens as none should be present in the food at production. Additionally, if there were pathogens present, this would not greatly contribute to the deterioration in product quality that would be observed over a product's lifespan.

For all products, a sub-sample was removed and incubated allowing small microbiological colonies to grow into an observable count. For each product there are two quality thresholds for microbial growth: optimal and sub-optimal. These thresholds are based on industry guidelines, known historic data, and retailer specifications[38]. The following sections describe each of the microbiological tests alongside the test method and quality thresholds[39].

2.5.1 Aerobic Colony Count (ACC)

An Aerobic Colony Count (ACC) is a 'snapshot' of the total bacterial growth present in a product and can be a useful indicator of quality in ready-to-eat foods. ACC, also known as the 'Total Viable Count', is commonly used as a part of a shelf-life assessment to provide measurable changes in bacterial growth. High ACC counts are typically, but not exclusively, associated with poor temperature control and / or sub-optimal product quality. High ACC count may also relate to taints or discolouration and thus can be useful in supporting the sensory evaluation. This count must not be misused for estimating the entire microbial population in a sample.

Test Method: *Detection and enumeration (count) of aerobic Colony Forming Units (cfu) of bacteria, yeast and moulds – Aerobic Colony Count (ACC) at 30°C. Following method based on BS EN ISO 4833-1:2013.*

This method describes a procedure for the enumeration of micro-organisms by counting the colonies growing in a solid medium after incubation at 30°C. This method is applicable to products intended for human consumption (including sugars, syrups and soft drinks) and animal feeding stuffs, and environmental samples (swabs). Only those micro-organisms capable of forming colonies under the conditions of the test (time, temperature, nutrients etc.) are enumerated.

Quality thresholds:

- Optimal quality threshold: <10^6 cfu / g
- Sub-optimal quality threshold: >10^6 cfu / g (possibility of taints or discolouration).

[38] *The thresholds used were proposed by injini laboratory and approved by WRAP. They do not represent the acceptable thresholds of injini and were designed for the purpose of this project and are thus owned by WRAP.*

[39] *Further details of the microbiological testing, beyond those presented, cannot be shared due to commercial sensitivity.*

2.5.2 Yeasts and moulds

Yeasts and moulds are naturally occurring fungi, ubiquitous in the environment and in some food types. Yeast and mould counts frequently predominate when conditions for bacterial growth are less favourable (e.g., lower pH or lower temperatures). When yeast and mould counts are high, growth can occasionally be observed in the sensory evaluation as visible mould, off-flavours, or aromas. However, where they are imperceivable, a microbiological count can provide a useful measurement of their estimated growth.

Test Method: *Detection and enumeration (count) of Colony Forming Units (cfu) of yeasts and / or moulds at 25°C, following method based on BS ISO 21527-1:2008.*

This method describes a procedure for the enumeration of viable yeasts and moulds in swabs and products intended for human consumption (including sugars, syrups and soft drinks), animal feed and environmental samples (swabs).

Quality thresholds:

- Optimal quality indicator: <10^4 cfu / g
- Sub-optimal quality indicator: >10^4 cfu / g (possibility of visible mould, off-flavours, and aromas).

2.5.3 Enterobacteriaceae *(EB)*

Enterobacteriaceae are a group of bacteria that predominantly inhabit the intestines of animals. The group includes a number of harmless bacteria, but also includes food-borne pathogens such as *Salmonella* and *E. coli* O157. The existence of these organisms does not guarantee the presence of a harmful pathogen, rather, their growth acts as an indicator or 'warning light' by highlighting any faecal and / or environmental contamination that may be present. As the samples in this project were exposed to regular temperature abuse and mock consumer interaction, regular EB counts can offer a useful indicator of the rate of contaminant growth relative to consumer interaction and storage conditions.

Test method: *Detection and enumeration (count) of presumptive* Enterobacteriaceae – *colony count at 37°C. Method based on BS ISO 21528-2:2017.*

This method describes a procedure for the enumeration of presumptive Enterobacteriaceae in products intended for human consumption and animal feeding stuffs, and environmental samples in the area of food production and food handling.

Quality thresholds:

- Optimal quality indicator: <10^4 cfu / g
- Sub-optimal quality indicator: >10^4 cfu / g (possibility of 'harmful' bacterial growth).

2.6 Frequency of testing

The frequency of testing for each condition was adapted for each product. The initial frequency was determined by the expected rate of deterioration and the availability of samples to test. Once deterioration was observed, e.g., more than three samples in the batch were given an Amber RAG rating, the frequency of testing increased to better capture the more rapid deterioration of the product. For example, cucumbers were initially tested every two days, but this was increased to every day once deterioration was observed.

Tests were usually scheduled for weekdays, with weekend testing reserved for when rapid deterioration in products being tested was likely.

In some instances, the frequency of testing had to be reduced in order to conserve the available samples. This occurred when they deteriorated at a slower rate than anticipated. This was especially the case for apples, potatoes, and cheese, which had a much longer shelf life than anticipated (particularly when refrigerated). In extreme circumstance, the number of replicates for fresh produce items was reduced from three to two to further conserve the samples available.

To enable reliable comparisons between the three types of test, the testing frequency was consistent across the pressure testing, microbiological testing, and the sensory evaluation. The actual test days can be seen in Chapter 3.0, e.g., Table 7 for apples.

For fresh-produce, in the majority of cases, new replicate samples were tested on each day in each product condition (i.e., once a sample was tested, it was removed from the experiment). This was to ensure that any samples which were handled, sliced into, or sub-sampled for sensory evaluation did not remain within the experiment since the deterioration rate might have been affected by being handled by the assessor. There was an exception to this rule: for apples and potatoes, one of the three replicate samples was the same throughout the testing; these two samples were not cut into, and were only assessed through visual inspection, touch and smell.

For dairy products, multiple samples were obtained from a given bottle of milk or pack of yogurt or cheese.

2.7 Temperature and humidity

The temperature and humidity of the storage conditions were monitored throughout each test. Three specific temperature targets were set:

- Optimal refrigeration: 4°C
- Sub-optimal refrigeration: 9°C
- Ambient: 21°C

The optimal fridge temperature was set to 4°C in line with the temperature that WRAP[40] and the Food Standards Agency (FSA)[41] recommend for both food longevity and safety. The sub-optimal fridge temperature was set to 9°C to simulate the domestic refrigerators that run at this higher-than-recommended temperature. Previous research

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[40] *'Reducing food waste through the chill chain. WRAP, 2010. https://wrap.org.uk/sites/default/files/2020-12/Reducing-food-waste-through-the-chill-chain-Insights-around-the-domestic-refigerator.pdf*

[41] *Chilling – How to chill, freeze, and defrost food safely. Food Standards Agency, 2020. http://food.gov.uk/print/pdf/node/195*

has suggested that somewhere in the region of 3% to 9% of UK fridges run at 9°C[42,43]. The same research suggests that around half of fridges (38% and 51% in the two studies) operate at a temperature higher than the recommended 5°C.

9°C was chosen as the higher fridge temperature so that it was in the range found in UK households, but sufficiently different from 4°C to be able to measure differences in shelf life. To understand the effects on shelf life of temperatures between these two test temperatures, it would be possible to interpolate between the results at these two temperatures; this has not been done in this report.

Both the optimal and sub-optimal temperatures were controlled throughout the tests. The target ambient temperature was 21°C as this is considered 'room temperature', however, this was not controlled. Humidity was monitored to check for variability over time but was not controlled. The average temperature and humidity of each condition is reported for each product in chapter 3.0.

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[42] *Temperature control in domestic refrigerators and freezers, Evans et al. (2014). https://openresearch.lsbu.ac.uk/item/8780x*

[43] *Temperature and energy performance of domestic cold appliances in households in England. Biglia et al. (2018). https://doi.org/10.1016/j.ijrefrig.2017.10.022*

3.0 Results

This chapter details the results of the different tests that were applied to each product. These include the sensory evaluation (all products), pressure testing (apples and potatoes) and microbiological testing (dairy products). The methodologies for these types of tests can be found in Sections 2.3, 2.4 and 2.5 respectively. The different temperature and packaging conditions that were applied are also outlined. The results section is structured by type of product, starting with the fresh fruit and vegetables, and then the dairy products.

3.1 Apples

To compare the impact of plastic packaging and different storage temperatures on acceptable shelf life, apples were tested under four conditions:

- Loose Stored in ambient conditions (target temperature 21°C)
- Packaged Stored in ambient conditions (target temperature 21°C)
- Loose Refrigerated in an 'optimum' fridge (target temperature 4°C)
- Packaged Refrigerated in an 'optimum' fridge (target temperature 4°C)

Where present, the packaging was polypropylene flow wrap.

Apples underwent both sensory evaluation and pressure testing: the former evaluating appearance, aroma, texture and taste, the latter measuring the amount of force required to penetrate the flesh of the sample. The descriptions that were used for the sensory evaluation are provided in Appendix 2.

The average temperature and humidity were monitored over the course of the sensory evaluation. The target temperature was 4°C for refrigerated and 21°C for ambient conditions, though ambient conditions were not controlled. There were no targets for humidity, but it was monitored.

Table 6: Apples: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Ambient	Refrigerated	Ambient	Refrigerated
Target	21.0	4.0	N / A	N / A
Mean	19.8	4.3	43.7	79.1
Min	9.0	3.0	19.6	64.3
Max	22.8	12.7	67.4	93.4

3.1.1 Sensory evaluation

Table 7 shows the 'Combined RAG rating' for each test condition in the sensory evaluation against the number of days after packing. There are some instances where the appears to be a reversal of deterioration: e.g., the overall assessment changes from Green to Amber, and then back to Green. This is because there is 'scatter' or 'noise' in the data – each apple will have started from a different level of deterioration and deteriorated at slightly different rates, as well as there being a degree of subjectivity in the assessment. Having three replicates and three assessors for most test points reduced this scatter, but, nonetheless, some remained. Furthermore, analysis using deterioration scores and lines of best fit allowed comparisons between conditions despite this scatter. Section 2.3 and Appendix 1 have more details.

Table 7: Combined RAG rating for sensory evaluation of **apples:** BB = Best Before date, PD = purchase date

Days after packing	Ambient		Refrigerated 4°C	
	Loose	Packaged	Loose	Packaged
2 (PD)	Test start	Test start	Test start	Test start
14 (BB)	Green	Green	Green	Green
18	Green	Green	No test	No test
21	No test	No test	Green	Amber
22	Green	Green	No test	No test
25	Green	Green	No test	No test
28	Green	Amber	Green	Green
31	Green	Green	No test	No test
33	Amber	Amber	No test	No test
35	Amber	Amber	Green	Green
37	Amber	Amber	No test	No test
39	Amber	Amber	No test	No test
42	Amber	Red	Green	Green
44	Amber	Amber	No test	No test
46	Amber	Amber	No test	No test
49	Red	Amber	Green	Green
52	Amber	Amber	No test	No test
56	No test	No test	Green	Green
59	Red	Amber	No test	No test
66	Test end	Test end	No test	No test
70	No test	No test	Green	Green
84	No test	No test	Amber	Green
98	No test	No test	Green	Green
106	No test	No test	Red	Red
112	No test	No test	Amber	Green
119	No test	No test	Amber	Green
127	No test	No test	Red	Amber
134	No test	No test	Amber	Amber
141	No test	No test	Test end	Test end

Key	Red	Amber	Green	No test

Overall, the two ambient conditions had a similar RAG rating over time, as did the two refrigerated conditions (Table 7). Apples in both ambient test conditions remained Green for the first month, were Amber for a further month and then turned Red a week later (two-and-a-half months in total).

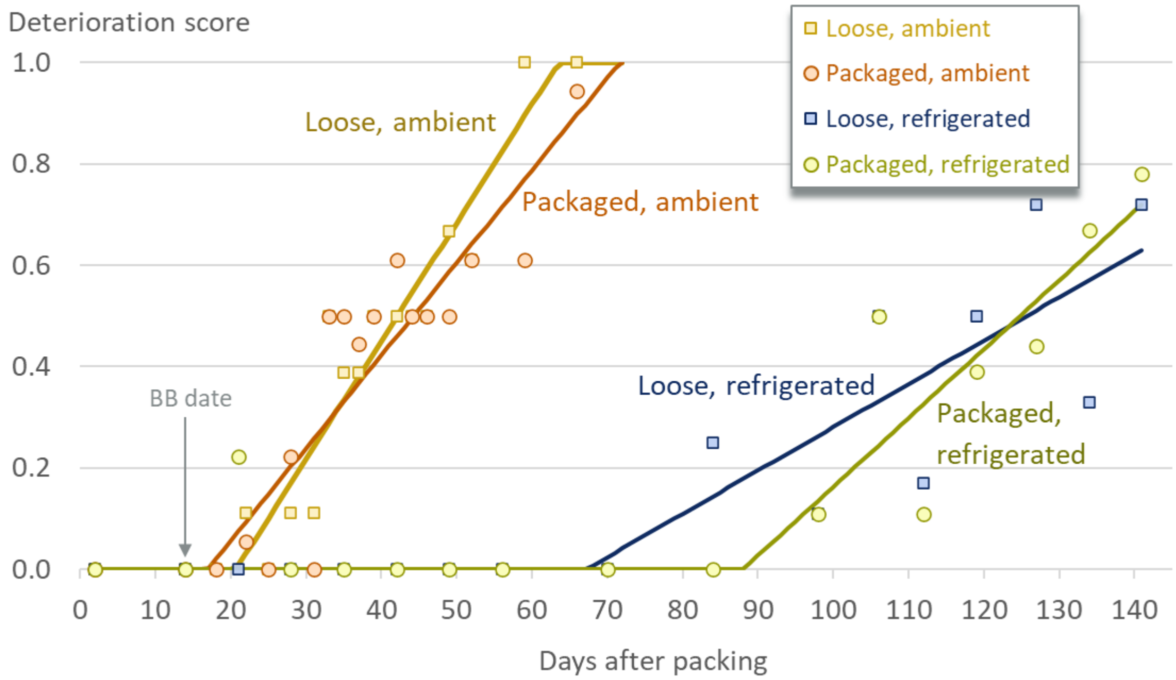
In both refrigerated test conditions, apples generally had a combined RAG rating of Green for around two-and-a-half months after packing. Refrigerated apples had their first Red ratings about a month later (three-and-a-half months after packing). This is an indication that, for refrigerated apples, the packaged condition lasted slightly longer than the loose condition.

For finer analysis of the results, the 'deterioration score' was calculated for each condition on each test day. Detailed in Section 2.3, the deterioration varies from zero (all assessments were green) to one (all assessments were Red). Lines of best fit were fitted to the data points to help navigate the scatter in the data. These are shown in Figure 1, representing the same behind data in Table 7, but in a different way. Comparisons were made at the point that the lines of best fit reached 0.3, as discussed in Section 2.3. Full details of the line of best fit for the deterioration scores can be found in Appendix 2.

It should be noted that in the case of refrigerated apples, the deterioration score does not reach 1, i.e., the point at which all samples were given a Red rating by all assessors. (A 'combined RAG rating' of red in Table 7 was reached for all conditions by day 106 or earlier; however, this only requires 25% of assessments on a test day to be Red for this to be triggered.)

Ideally, the experiment would have been run until all assessments were red. However, the experiment took longer than expected to reach this point and the number of apples allocated for these conditions were used up. Nevertheless, a deterioration score of 0.6, representing the point at which most citizens would likely throw apples away, was achieved with all experiments.

Figure 1: Deterioration scores for loose and packaged apples both ambient and refrigerated at 4°C



Ambient apples, packaged v loose: There was no detectable difference between the length of time that packaged and loose apples took to reach a deterioration score of 0.3 (<1 day). There were indications that the onset of deterioration (linear fit moving above zero) of packaged apples started earlier, around 4 days before loose, and then progressed more slowly. This resulted in the two lines of best-fit crossing over one another. However, given the scatter in the data, more data would have been required to be able to differentiate the gradients of these two lines.

Refrigerated apples, packaged v loose: At a deterioration score of 0.3, packaged apples lasted around a week (8 days) longer than loose apples – equivalent to an 8% increase in shelf-life. However, further analysis (Appendix 3) revealed that this difference was not significant and could have been the result of the scatter in the sensory-evaluation data, coupled with few data points with a deterioration score greater than zero. Similarly, the differences in onset of deterioration and the gradients of the lines of best fit could also be due to this scatter. Therefore, there is insufficient evidence to conclude that refrigerated apples last longer if stored packaged or loose.

Ambient versus refrigerated at 4°C: The results indicate a large impact on shelf life of fridge storage on the shelf life of apples. Moderate deterioration (deterioration score of 0.3) occurred at around one month for ambient apples compared to three and a half months for refrigerated apples. Similar differences were seen at different levels of deterioration.

Best Before date versus minor signs of deterioration: WRAP research shows that most citizens say they would still eat apples with minor/moderate signs of deterioration[44]. In this study, moderate signs of deterioration (deterioration score = 0.3), were observed 33 days after packing for ambient apples, and 110 days after packing for apples refrigerated at 4°C. In comparison the Best Before date on-pack was the equivalent of just 14 days after packing.

The 14-day Best Before date can also be compared to the point at which the best fit line increases above zero. This is 17 days for ambient packaged apples, 21 days for loose ambient apples and between 67 days (loose) and 88 days (packaged) for refrigerated apples.

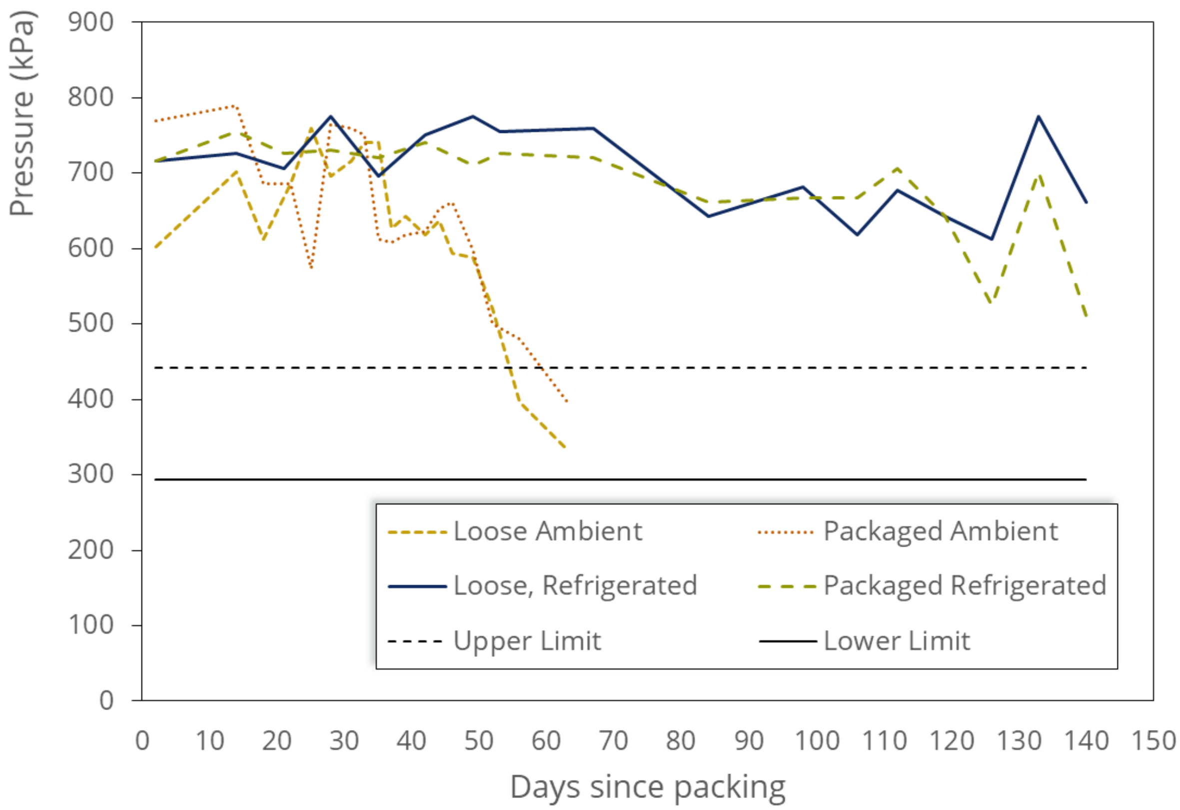
3.1.2 Pressure testing

Pressure testing was also applied to apples for all four conditions. The results are shown below in Figure 2.

For apples stored in ambient conditions, pressure readings were around 600-800 kPa for the first 45 days of testing. After this point, the pressure readings for both packaged and loose variants declined, dropping below the 'upper limit' of 441 kPa on day 56 for loose apples and day 63 for packaged apples. This similarity in readings for packaged and loose variants is broadly consistent with the sensory-evaluation results. Furthermore, the time at which the apples dropped below the upper limit is around the time the last Amber combined RAG assessment in the sensory evaluation (Table 7).

[44] *Citizen insights on the influence of packaging and date labels on disposal decisions, WRAP, 2022* *https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

Figure 2: Pressure testing readings for apples in four conditions



During the period of time when the pressure readings were dropping for ambient-stored apples, the deterioration score from the sensory analysis was around 0.5 to 0.6 (for 45 days) and 0.8 to 0.9 (for 60 days). Therefore, the drop in pressure readings occurred when the apples had already deteriorated to a moderate to high degree. At this point, comments in the sensory evaluation included notes of the change in texture: e.g., 'loss in textural quality' and 'partially shrivelled'.

There was little change in pressure when the deterioration score was 0 to 0.5. Therefore, in the case of ambient-stored apples, pressure testing is able to detect the later stages of deterioration relatively well. However, it does not provide a reliable measure of the early stages of deterioration for these apples.

For refrigerated apples, the pressure readings never reached the upper limit of 441 kPa, even when the sensory evaluation was a mixture of amber and red assessments (e.g., test day 141). This appears to be because issues other than texture were the main driver of deterioration in the refrigerated apples. Growth of mould and internal rot were frequently mentioned in the comments for deteriorated apples.

Taken together, these results suggest that pressure testing has some limited use in supporting sensory evaluation for apples. Specifically, it is useful in situations where changes in texture are observed during the deterioration process. However, these results suggest that that is not always the case, and therefore pressure testing would not be suitable for use by itself (i.e., without sensory evaluation) to determine the shelf life of apples.

Overall, the shelf life of apples was greatly affected by their storage location, with apples stored in the fridge lasting around two-and-a-half months longer compared to apples stored in ambient conditions. In contract, the presence of packaging had no measurable impact on the shelf life.

3.2 Bananas

This section contains results for the sensory evaluation of bananas, following the methodology in Section 2.3. No pressure testing or microbiological testing was performed, as discussed in the methodology section. The descriptions that were used for the sensory evaluation are provided in Appendix 2.

To compare the impact of packaging on acceptable shelf life, bananas were tested under two conditions:

- Loose Stored in ambient conditions (target temperature 21°C)
- Packaged Stored in ambient conditions (target temperature 21°C)

Where present, the packaging was polyethylene bags.

A refrigerated condition is not included as storing bananas in the fridge is not recommended. They are sensitive to the cold and the skins become blackened, hence not including a refrigerated condition.

The average temperature and humidity were monitored over the course of the sensory evaluation. The target temperature was 21°C, though ambient conditions were not controlled. There were no targets for humidity, but it was monitored.

Table 8: Bananas: temperature and humidity of storage conditions

	Ambient temperature (°C)	Relative humidity (%)
Target	21.0	N / A
Mean	20.4	41.3
Min	18.1	26.3
Max	22.8	54.5

3.2.1 Sensory evaluation

Table **9** shows the combined RAG rating for each test condition in the sensory evaluation against the number of days after packing. Overall, the two ambient conditions had a similar RAG rating for the early and moderate signs of deterioration, but loose bananas deteriorated to Red four days quicker than packaged bananas.

Converting the data underlying Table **9** into the deterioration scores, as described in Section 2.3, allows more subtle shifts to be determined. Comparisons were made at the point that the lines of best fit reached 0.3, as discussed in Section 2.3. Full details of the line of best fit for the deterioration scores can be found in Appendix 2.

Table 9: Combined RAG rating for sensory evaluation of **bananas:** BB = Best Before date

Days after packing	Packaged Ambient	Loose Ambient
3	Green	Green
4	Green	Green
5	Green	Green
6 (BB)	Green	Green
7	Amber	Amber
8	Amber	Amber
9	Amber	Amber
10	Amber	Amber
11	Amber	Red
12	Amber	Red
14	Red	Red
15	Red	Red
18	Test end	Test end

Key	Red	Amber	Green	No test

Figure 3: Deterioration scores for loose and packaged bananas in ambient conditions

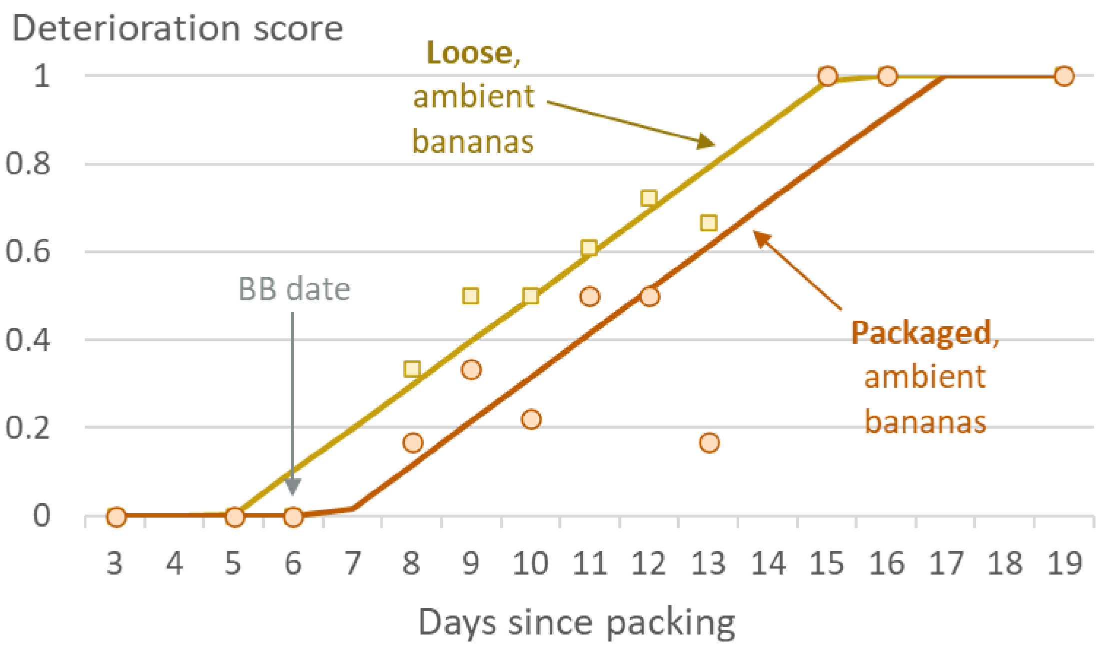


Figure 3 shows a systematic shift, with packaged bananas last 1.8 days longer than loose bananas, irrespective of where the comparison is made with respect to the deterioration score.

Best Before date versus earliest signs of deterioration: WRAP research shows that most citizens say they would still eat bananas with minor/moderate signs of deterioration[45]. In this study, moderate signs of deterioration (when the linear fit reaches 0.3), were observed 10 days after packing, with the line of best fit increase above zero 7 days after packing. In comparison the Best Before date on-pack was the equivalent of just 6 days after packing.

Overall, packaged bananas lasted 1.8 days longer than loose bananas, equivalent to a 23%-increase in shelf life. This finding was consistent throughout all stages of deterioration.

3.3 Broccoli

This section contains results for the sensory evaluation of broccoli, following the methodology in Section 2.3. No pressure testing or microbiological testing was performed, as discussed in the methodology section. The descriptions that were used for the sensory evaluation are provided in Appendix 2.

To compare the impact of plastic packaging and different storage temperatures on shelf life, broccoli was tested under six conditions:

- Loose — Refrigerated at 4°C (optimal fridge)
- Shrink-wrapped — Refrigerated at 4°C (optimal fridge)
- Loose — Refrigerated at 9°C (sub-optimal fridge)
- Shrink-wrapped — Refrigerated at 9°C (sub-optimal fridge)
- Loose stored — Ambient conditions (target temperature 21°C)
- Shrink-wrapped — Ambient conditions (target temperature 21°C)

Where present, the packaging was polyethylene shrink wrap.

The average temperature and humidity were monitored over the course of the sensory evaluation. The target temperature was 4°C for the optimal fridge temperature, 9°C for the sub-optimal fridge temperature, and 21°C for ambient conditions, though ambient conditions were not controlled. There were no targets for humidity, but it was monitored.

Table 10: Broccoli: temperature and humidity of storage conditions

	Temperature (°C)			Humidity (%)		
	Ambient	Optimal	Sub-optimal	Ambient	Optimal	Sub-optimal
Target	21.0	4.0	9.0	N / A	N / A	N / A
Mean	20.1	4.2	9.5	40.4	79.0	40.4
Min	18.9	3.7	8.0	19.6	64.3	19.6
Max	21.7	8.7	11.6	64.5	93.4	64.5

[45] *Citizen insights on food disposal, packaging, and date labels. WRAP 2022. https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

3.3.1 Sensory evaluation

Table 11 shows the RAG rating for each test condition in the sensory evaluation against the number of days after packing. There are some instances where the appears to be a reversal of deterioration: e.g., the overall assessment changes from Green to Amber, and then back to Green. This is because there is 'scatter' or 'noise' in the data: each head of broccoli will have started the tests with a slightly different level of deterioration, and will have deteriorated at different rates to each other. There is also a degree of subjectivity in the sensory assessment. Having three replicates and three assessors for most test points reduced this scatter, but, nonetheless, some remained. Furthermore, analysis using deterioration scores and lines of best fit allowed comparisons between conditions despite this scatter. Section 2.3 and Appendix 1 have more details.

The two ambient conditions deteriorated very rapidly and had a similar RAG rating over time to each other (Table 11), assessed as Red six days after packing.

Table 11: Combined RAG rating for sensory evaluation of **broccoli:** PD = Purchase Date, BB = Best Before date.

Days after packing	Ambient		Sub-optimal fridge (9°C)		Optimal fridge (4°C)	
	Packaged	Loose	Packaged	Loose	Packaged	Loose
2 (PD)	Green	Green	Green	Green	Green	Green
6 (BB)	Red	Red	Green	Green	Green	Green
7	Red – Test end	Red	Green	Amber	Green	Green
8	No test	Red	Green	Green	No test	No test
9	No test	Red – Test end	Green	Amber	Green	Amber
11	No test	No test	Amber	Green	Green	Amber
13	No test	No test	Amber	Amber	Green	Green
15	No test	No test	Amber	Amber	No test	No test
16	No test	No test	No test	No test	Green	Amber
18	No test	No test	Red	Amber	Green	Amber
20	No test	No test	Red	Red	No test	No test
22	No test	No test	Red – Test end	Red – Test end	Green	Amber
27	No test	No test	No test	No test	Amber	Red
29	No test	No test	No test	No test	No test	Red
31	No test	No test	No test	No test	Red	Red – Test end
34	No test	No test	No test	No test	Red	No test
37	No test	No test	No test	No test	Red	No test
46	No test	No test	No test	No test	Red	No test
56	No test	No test	No test	No test	Red – Test end	No test

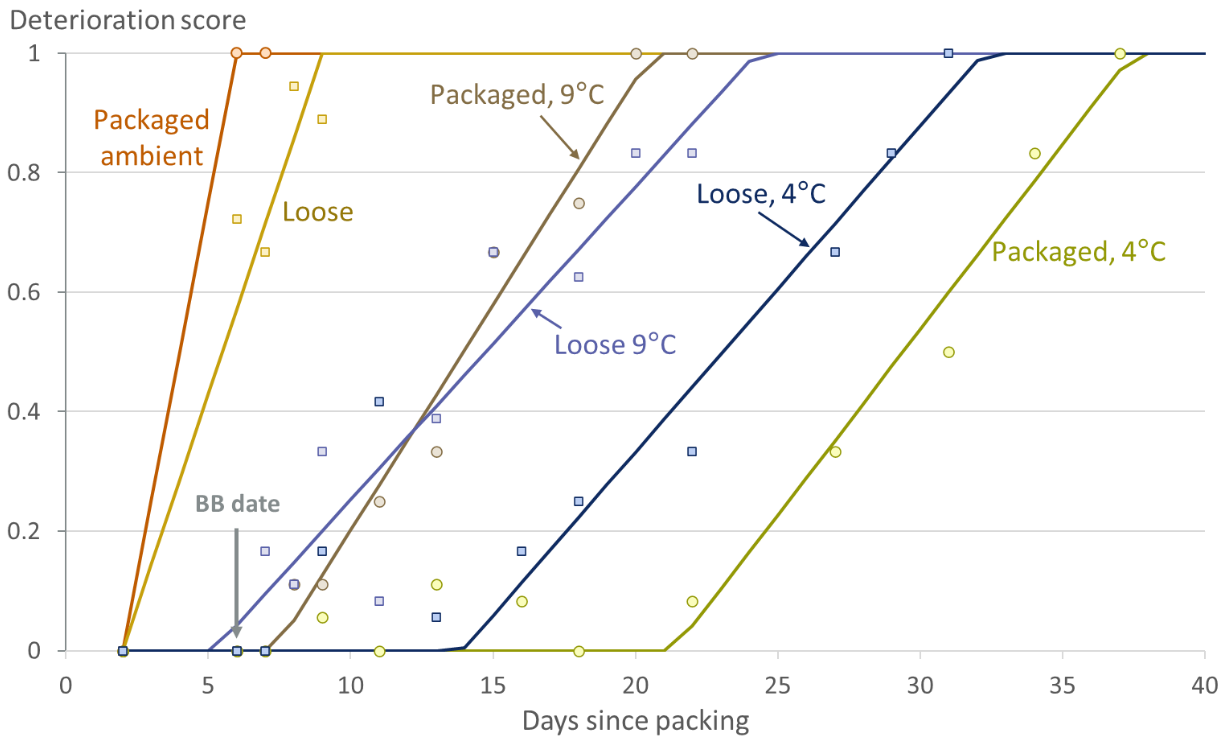
Key	Red	Amber	Green	No test

In both test conditions at 9°C (sub-optimal), broccoli had a Green rating for just over a week, was then Amber for a week, and then turned Red at around 18-20 days after packing. There was little difference between the whether the item was packaged or not.

For the test conditions at 4°C, there was a difference between loose and shrink-wrapped. Shrink-wrapped broccoli had a Green rating for around 3 weeks, was then Amber for a week and turned Red around a month after packing. In contrast, loose broccoli started deteriorated more quickly and had its first Red assessment 4 days before the shrink-wrapped variant.

Converting the data underlying Table 11 into the deterioration scores, as described in Section 2.3, allows more subtle shifts to be determined (Figure 4). The main comparisons were made at the point that the lines of best fit reached 0.3, as discussed in Section 2.3. Full details of the line of best fit for the deterioration scores can be found in Appendix 2.

Figure 4: Deterioration scores for loose and packaged broccoli in ambient conditions, and refrigerated at 4°C and at 9°C



Shrink-wrapped v loose:

- For broccoli stored in ambient conditions, there was minimal (<1 day) difference in the speed of deterioration between shrink-wrapped and loose.
- For broccoli stored at the sub-optimal fridge temperature, there was minimal (<1 day) difference in the speed of deterioration between shrink-wrapped and loose at a deterioration score of 0.3. There are indications that the onset of deterioration of loose broccoli started earlier – at around 1-2 days before shrink-wrapped – and then progressed more slowly. However, given the scatter in the data, more data would be required to demonstrate this with confidence.

- For broccoli refrigerated at 4°C, there *was* a difference in shelf life between shrink-wrapped and loose. Shrink-wrapped broccoli took 26 days to reach a deterioration score of 0.3, around 7 days longer than loose broccoli. This difference is equivalent to a 35% increase in shelf life for packaged broccoli compared to loose.

These results suggest that packaging only increases shelf life of broccoli at temperatures around 4°C, and not in ambient conditions or 9°C. These results could be explained by broccoli deteriorating in different ways (e.g., via different microbes) at different temperatures.

Ambient versus refrigerated at 4°C: These results demonstrate that storing broccoli in the fridge has a substantial effect on shelf life.

- Packaged broccoli stored in the fridge (at 4°C) took 26 days to reach a deterioration score of 0.3, compared to 3 days for broccoli stored in ambient conditions.
- Loose broccoli also lasted considerably longer in the fridge at 4°C compared to ambient conditions: 19 days versus 4 days to reach a deterioration score of 0.3.

Refrigerated at 9°C versus 4°C: The temperature of refrigeration also affected the shelf life of broccoli:

- For packaged broccoli stored at 9°C, a deterioration score of 0.3 was reached 11 days after packing. For refrigeration at 4°C, this level of deterioration was not reached until 26 days after packing.
- For loose broccoli, the equivalent shelf lives were 11 days at 9°C and 19 days for 4°C.

Best Before date versus earliest signs of deterioration: WRAP research shows that most citizens say they would still eat broccoli with minor/moderate signs of deterioration[46]. In this study, moderate signs of deterioration (linear fit reaches 0.3) were observed 11 days after packing when refrigerated at 9°C and 26 days when refrigerated at 4°C. In comparison the Best Before date on-pack was the equivalent of just 6 days after packing.

Considering the first signs of deterioration (linear fit moves above zero), for broccoli stored at 9°C, this was first observed around the BB date (just before the BB date for loose, just after the BB date for packaged). At 4°C, the first signs of deterioration were not seen until well after the BB date: for loose broccoli, 8 days after the BB date, for packaged broccoli 15 days after the BB date.

In summary, packaging had limited impact on the shelf life of broccoli stored in ambient conditions and at a sub-optimal fridge temperature of 9°C. However, when stored at an optimal fridge temperature of 4°C, shrink-wrapped broccoli lasted around 7 days (35%) longer than loose broccoli. Temperature impacts the shelf life of broccoli strongly, with broccoli stored in ambient conditions lasting the least time. Broccoli stored in the fridge at 4°C lasted between 8 and 15 days longer compared with refrigeration at 9°C.

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[46] *Citizen insights on food disposal, packaging, and date labels. WRAP 2022.* *https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

3.4 Cucumber

This section contains results for the sensory evaluation of cucumber, following the methodology in Section 2.3. The descriptions that were used for the sensory evaluation are provided in Appendix 2. No pressure testing or microbiological testing was performed, as discussed in the methodology section.

To compare the impact of plastic packaging and different storage temperatures on acceptable shelf life, cucumbers were tested under four conditions:

- Loose Refrigerated at 4°C (optimal)
- Shrink-wrapped Refrigerated at 4°C (optimal)
- Loose Refrigerated at 9°C (sub-optimal)
- Shrink-wrapped Refrigerated at 9°C (sub-optimal)

Where present, the packaging was polyethylene shrink wrap.

The average temperature and humidity were monitored over the course of the sensory evaluation. The target temperature was 4°C for optimal fridge temperature and 9°C for sub-optimal fridge temperature. There were no targets for humidity, but it was monitored.

Table 12: Cucumber: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Optimal	Sub-optimal	Optimal	Sub-optimal
Target	4.0	9.0	N / A	N / A
Mean	3.8	9.5	80.8	74.1
Min	1.9	9.0	43.9	57.1
Max	14.6	11.2	92.0	81.3

3.4.1 Sensory evaluation

Table 13 shows the RAG rating for each test condition in the sensory evaluation against the number of days after packing. There are some instances where there appears to be a reversal of deterioration: e.g., the overall assessment changes from Green to Amber, and then back to Green. This is because there is 'scatter' or 'noise' in the data: each cucumber will have started the tests with a slightly different level of deterioration and deteriorated at slightly different rate to other cucumbers. There is also a degree of subjectivity in the assessment. Having three replicates and three assessors for most test points reduced this scatter, but, nonetheless, some scatter remained. Furthermore, analysis using deterioration scores and lines of best fit allowed comparisons between conditions despite this scatter. Section 2.3 and Appendix 1 have more details.

It should be noted that the cucumbers used in this study did not have a Best Before date on-pack and so the Best Before date is inferred. The inferred date is based on a combination of information from the cucumber supplier that provided the samples for the experiments, and the average guaranteed product life (from purchase date to the Best Before date) stated on retailer websites. Both lines of evidence indicated that the Best Before date would be 17 days after packing, or 5 days after the estimated purchase date.

Overall, the was no measurable difference between the shrink-wrap cucumbers and those without shrink wrap (Table 13): the loose and packaged cucumbers in the optimal fridge (4°C) had a similar combined RAG rating over time, as did the loose and packaged cucumbers in the sub-optimal fridge (9°C). In the optimal conditions, cucumbers had a combined Green rating for three weeks after packing, which then became Red four-and-a-half weeks after packing. In the sub-optimal test conditions, cucumbers remained Green for the first two and a half weeks, Amber for a further 2-3 days and then turned Red at around three weeks after packing.

Table 13: Combined RAG rating for sensory evaluation of **cucumbers:** PD = purchase date, BB = Best Before date.

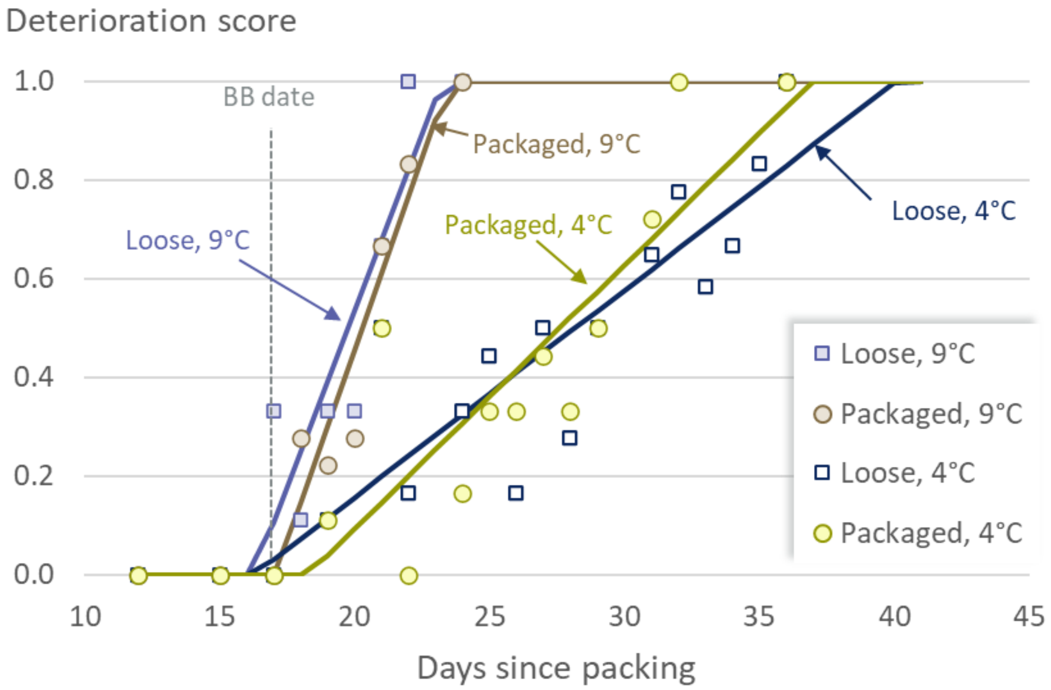
Days after packing	Sub-optimal (9°C)		Optimal (4°C)	
	Loose	Shrink-wrapped	Loose	Shrink-wrapped
12 (PD)	Green	Green	Green	Green
15	Green	Green	Green	Green
17 (BB)	Amber	Green	Green	Green
18	Green	Amber	No test	No test
19	Amber	Amber	Green	Green
20	Amber	Amber	No test	No test
21	Red	Red	Amber	Amber
22	Red	Red	Amber	Green
24	Red (Test end)	Red (Test end)	Amber	Amber
25	No test	No test	Amber	Amber
26	No test	No test	Amber	Amber
27	No test	No test	Amber	Amber
28	No test	No test	Amber	Amber
29	No test	No test	Amber	Amber
31	No test	No test	Red	Red
32	No test	No test	Red	Red (Test end)
33	No test	No test	Amber	No test
34	No test	No test	Red	No test
35	No test	No test	Red	No test
36	No test	No test	Red (Test end)	No test

Key	Red	Amber	Green	No test

The same conclusions are reached when considering the deterioration scores and comparing the lines of best fit for the four cucumber conditions (Figure 5). The main comparisons are made at a deterioration score of 0.3, as discussed in Section 2.3. Full details of the line of best fit for the deterioration scores can be found in Appendix 2.

However, in the case of how fridge temperature affects the shelf life of cucumbers, there are some differences if the comparison is made at different deterioration scores. These are discussed below.

Figure 5: Deterioration scores and lines of best fit for cucumbers in four different conditions



Shrink-wrapped v loose:

- At a deterioration score of 0.3, there was minimal difference (<1 day) between the shrink-wrapped and loose cucumbers, for both temperatures tested.
- For cucumbers stored at 4°C, there are indications that the onset of deterioration (the linear fit moving above zero) for loose cucumber started earlier than for shrink-wrapped cucumbers, but then progressed more slowly. However, given the scatter in the data, more data would have been required to determine any difference with confidence.

Fridge temperature:

- For moderate levels of deterioration (deterioration score of 0.3), the lower fridge temperature (4°C) extended the shelf life by 5 days, compared to suboptimal fridge storage (9°C). This difference in shelf life was the same for both shrink-wrapped and loose cucumbers.
- However, the difference in fridge temperature varies with the deterioration score used for the comparison. For the point where the linear fit first increases above zero (the initial stages of deterioration), the difference made by fridge temperature is

minimal (0-1 days). However, if the comparison were made as the deterioration score reaches 0.6 (a high degree of deterioration), the difference is 9-10 days.

This analysis suggests that lower fridge temperatures do not delay the *initial* onset of deterioration, but that the lower fridge temperatures do slow the rate of deterioration thereafter.

- A deterioration score of 0.3 occurred at around two and a half weeks for cucumber stored at 9°C compared to three and a half weeks for cucumber stored at 4°C.

Best Before date versus earliest signs of deterioration: WRAP research shows that most citizens are highly sensitive to visual signs of deterioration on cucumber[47]. In this study, the first signs of deterioration (linear fit moves above zero) were observed 16-18 days after packing, depending on the exact conditions. The deterioration score reached 0.3 18-19 days after packing (for 9°C) and 23-24 days after packing (for 4°C). In comparison, the Best Before date was the equivalent of 17 days after packing.

In summary, shrink-wrapping had no measurable effect on the shelf life of cucumber stored at 4°C and at 9°C. The lower fridge temperatures appeared to slow the rate of deterioration of the cucumbers and was, therefore, the key variable driving deterioration in these experiments.

3.5 Potatoes

To compare the impact of packaging and different storage temperatures on the shelf life of potatoes, the following eight conditions were tested:

- Loose — Stored in ambient conditions*
- Loose — Refrigerated at 4°C
- Packaged in mostly transparent PE bags — Stored in ambient conditions
- Packaged in mostly transparent PE bags — Refrigerated at 4°C
- Packaged in 70% whitewash PE bags — Stored in ambient conditions
- Packaged in 70% whitewash PE bags — Refrigerated at 4°C
- Packaged in opaque PE bags — Stored in ambient conditions
- Packaged in opaque PE bags — Refrigerated at 4°C

*The target temperature of ambient conditions was 21°C

In all test conditions, potatoes were stored in the dark (either the fridge or a cupboard). At the time of writing, the Food Standards Agency (FSA) stated that potatoes should not be stored in the fridge.

Potatoes underwent both sensory evaluation and pressure testing: the former evaluating appearance, aroma, texture and taste, the latter measuring the amount of

[47] *Citizen insights on food disposal, packaging, and date labels. WRAP 2022.* *https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

force required to penetrate the flesh of the sample. The descriptions that were used for the sensory evaluation are provided in Appendix 2.

The average temperature and humidity were monitored over the course of the sensory evaluation. The target temperature was 4°C for refrigerated and 21°C for ambient conditions, though ambient conditions were not controlled. There were no targets for humidity, but it was monitored.

Table 14: Potatoes: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Ambient	Refrigerated	Ambient	Refrigerated
Target	21.0	4.0	N / A	N / A
Mean	20.2	4.0	51.4	79.3
Min	17.3	1.9	30.6	43.9
Max	22.1	14.6	64.5	93.4

3.5.1 Sensory evaluation

Table 15 shows the RAG ratings for each test condition in the sensory evaluation against the number of days after packing. There are some instances where there appears to be a reversal of deterioration: e.g., the overall assessment changes from Green to Amber, and then back to Green. This is because there is 'scatter' or 'noise' in the data: different potatoes deteriorated at different rates, starting at slightly different levels of deterioration, and there was a degree of subjectivity in the assessment. Having three replicates and three assessors for most test points reduced this scatter, but, nonetheless, some remained. Furthermore, analysis using deterioration scores and lines of best fit allowed comparisons between conditions despite this scatter. Section 2.3 and Appendix 1 have more details.

Table 15 demonstrates that the shelf life is highly dependent on the storage location. Potatoes in ambient (dark) conditions were first rated as Amber 24 days after packing. For refrigerated potatoes, this point was not reached until 72-79 days after packing, around 50 days later than ambient-stored potatoes.

Overall, the combined RAG rating is similar for the four different packaging conditions in each of the storage locations (Table 15). From this display of the data, the presence or absence of packaging, or the type of packaging, made little measurable difference to the shelf life of the potatoes. The exception was a combined Red rating recorded on the last test day (116 days after packaging) for loose, refrigerated potatoes; no combined RAG assessment was Red for any of the refrigerated, packaged potatoes.

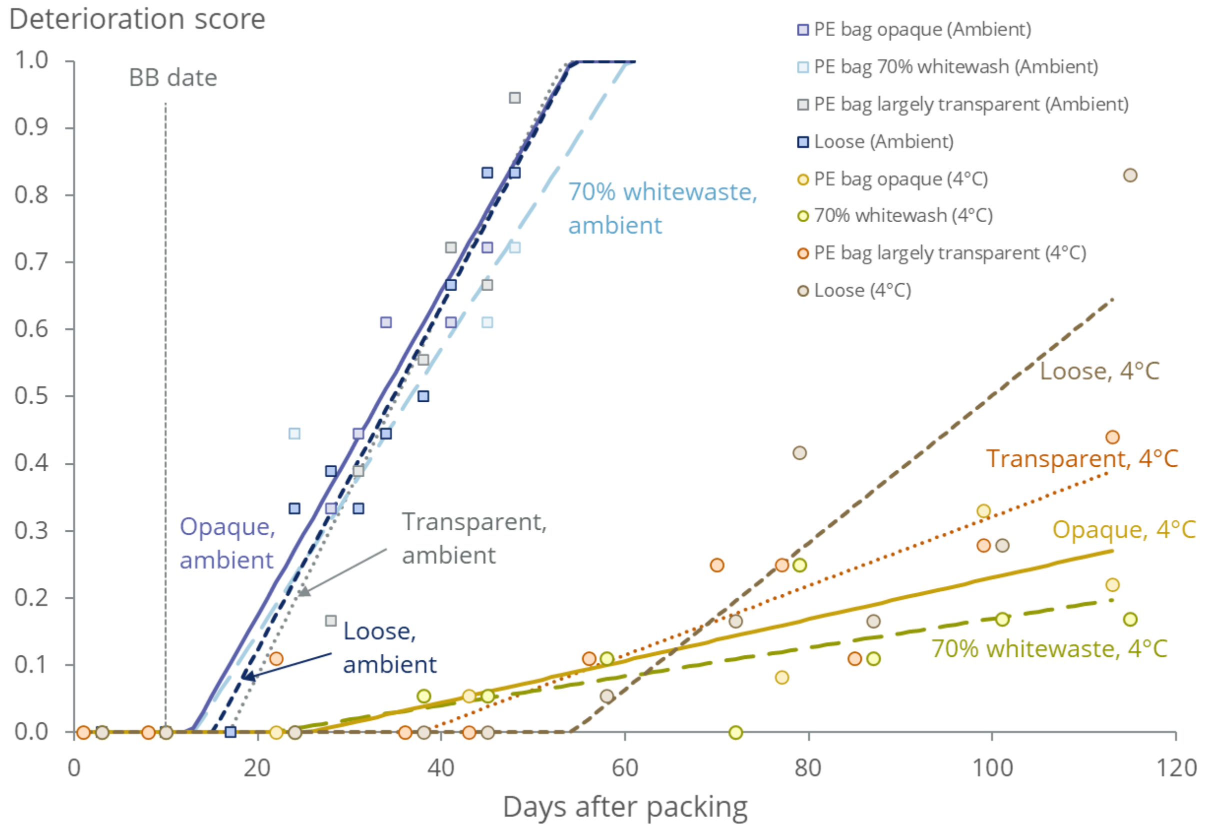
For finer analysis of the results, the 'deterioration score' was calculated for each condition on each test day. Detailed in Section 2.3, the deterioration varies from zero (all assessments were green) to one (all assessments were Red). Lines of best fit were fitted to the data points to help navigate the scatter in the data. These are shown in Figure 6, representing the same behind data in Table 15, but in a different way. Comparisons were made at the point that the lines of best fit reached 0.3, as discussed in Section 2.3. Full details of the line of best fit for the deterioration scores can be found in Appendix 2.

Table 15: Combined RAG rating for sensory evaluation of **potatoes:** BB = Best Before date

Days after packing	Ambient				Refrigerated (4°C)			
	PE bag largely transparent	PE bag 70% whitewash	PE bag opaque	Loose	PE bag largely transparent	PE bag 70% whitewash	PE bag opaque	Loose
3 (PD)	Green	Green	Green	Green	Green	Green	Green	Green
10 (BB)	Green	Green	Green	Green	Green	Green	Green	Green
17	Green	Green	Green	Green	Green	Green	Green	Green
24	Amber	Amber	Amber	Amber	Green	Green	Green	Green
28	Amber	Amber	Amber	Amber	Green	Green	Green	Green
31	Amber	Amber	Amber	Amber	Green	Green	Green	Green
34	Amber	Amber	Red	Amber	Green	Green	Green	Green
38	Amber	Amber	Amber	Amber	Green	Green	Green	Green
41	Red	Red	Red	Red	Green	Green	Green	Green
45	Red	Amber	Red	Red	Green	Green	Green	Green
48	Test end	Test end	Test end	Test end	Green	Green	Green	Green
58	No test	No test	No test	No test	Green	Green	Green	Green
72	No test	No test	No test	No test	Amber	Green	Amber	Amber
79	No test	No test	No test	No test	Amber	Amber	Green	Amber
87	No test	No test	No test	No test	Green	Green	Green	Amber
102	No test	No test	No test	No test	Amber	Amber	Amber	Amber
116	No test	No test	No test	No test	Amber	Amber	Amber	Test end

Key	Red	Amber	Green	No test

Figure 6: Deterioration scores for loose and packaged potatoes stored in ambient conditions and refrigerated at 4°C.



In the case of refrigerated potatoes, the deterioration score does not reach 1 (i.e., the point at which all samples were given a Red rating). The experiment was stopped after Day 116, before this point was reached. This is because the rate of deterioration of packaged potatoes was much slower than loose potatoes. It is estimated that the test would have been required to continue for a few weeks or even months beyond Day 116 in order for the potatoes to deteriorate past a score of 0.6. Unfortunately, this timeframe was beyond the project timeline, and insufficient potatoes had been refrigerated in the different conditions to continue the testing.

This means that, for refrigerated potatoes, there are fewer data points during the period of deterioration compared to other products. This led to a greater degree of scatter and more uncertainty in the results relating to refrigerated potatoes.

Packaged versus loose: For ambient potatoes, there is minimal difference in the speed of deterioration between packaged and loose. At a deterioration score of 0.3, the difference between loose potatoes and the average of the packaged potatoes is less than 1 day.

For refrigerated potatoes, there is considerable scatter in the data, making it difficult to distinguish differences between packaged and loose potatoes. Figure 6 indicates that loose potatoes may start to deteriorate later than packaged, but the rate of deterioration is then faster. However, more data would be required for this to be concluded with certainty. This is investigated further in Appendix 3 using a Monte Carlo simulation.

Ambient versus refrigerated at 4°C: These results demonstrate the substantial impact of fridge storage on the shelf life of potatoes. Moderate deterioration (linear fit reaches 0.3) occurred at around one month for ambient potatoes compared to 2-3 months for refrigerated potatoes.

Best Before date versus earliest signs of deterioration: WRAP research shows that most citizens say they would still eat potatoes with moderate signs of deterioration[48]. In this study, moderate signs of deterioration (linear fit reaches 0.3) were observed, on average, >116 days after packing when refrigerated at 4°C and 27 days when stored in ambient conditions. The first signs of deterioration for ambient-stored potatoes occurred 13-17 days after packing. In comparison, the Best Before date on-pack was the equivalent of just 10 days after packing.

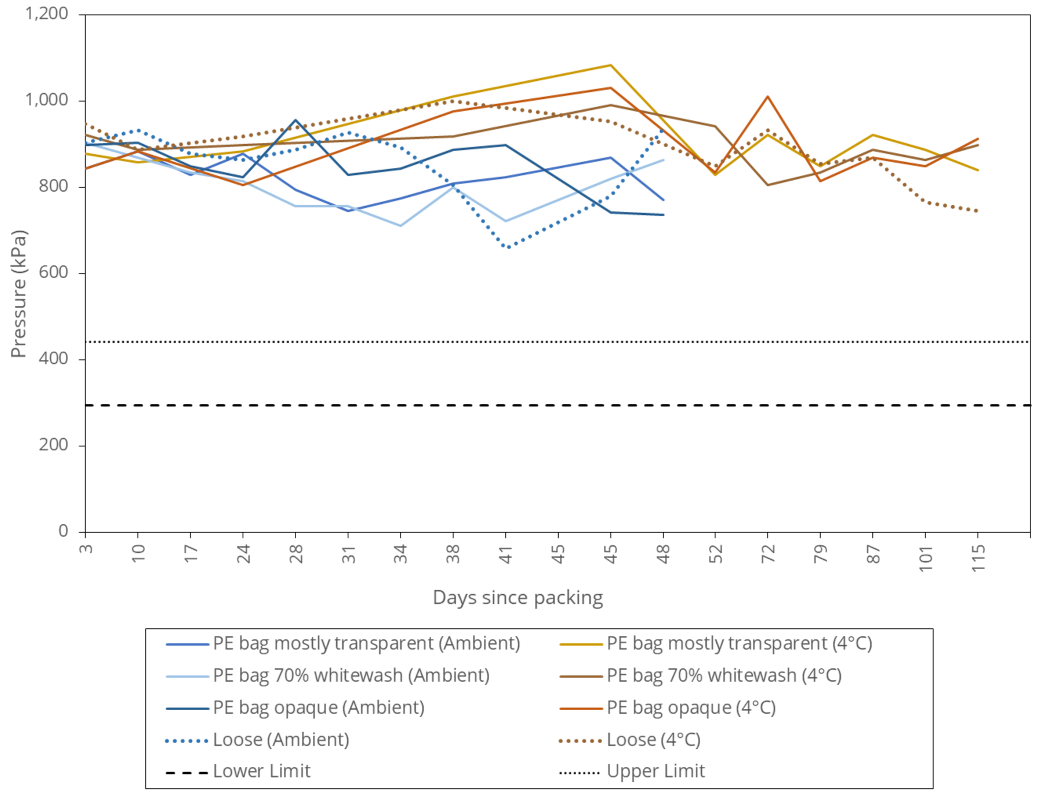
3.5.2 Pressure testing

Pressure testing was also applied to potatoes for all conditions. The results for the different packaging types and temperature conditions are shown below in Figure 7.

Although some downwards trends in pressure readings were observed, all pressure readings stayed above the threshold limits set in the research. In addition, given the scatter between readings, it would be difficult to use this data to determine the shelf life of these potatoes. Therefore, **the results from pressure testing for potatoes were not used further in this study.**

[48] *Citizen insights on food disposal, packaging, and date labels. WRAP 2022. https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

Figure 7: Pressure testing readings for potatoes in different conditions



3.6 Milk

For milk, two research questions were investigated:

- What is the difference in shelf life for milk refrigerated at sub-optimal (9°C) and optimal (4°C) fridge temperatures?
- What effect does the day of opening (relative to the Use By date) have on shelf life?

In total, 10 test conditions were used to answer the research questions above:

- Refrigerated at 4°C and opened:
  - 8 days before the Use By date,
  - 4 days before the Use By date,
  - 2 days before the Use By date,
  - On the Use By date,
  - 4 days after the Use By date.
- Refrigerated at 9°C and opened
  - 8 days before the Use By date,
  - 4 days before the Use By date,
  - 2 days before the Use By date,
  - On the Use By date,
  - 4 days after the Use By date.

Milk was not tested in ambient conditions as it spoils rapidly when not refrigerated.

The average temperature and humidity were monitored over the course of the sensory evaluation (Table 16). The target temperature was 4°C for the optimal fridge temperature and 9°C for the sub-optimal fridge temperature. There were no targets for humidity.

Table 16: Milk: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Optimal	Sub-optimal	Optimal	Sub-optimal
Target	4.0	9.0	N/A	N/A
Mean	3.9	8.5	78.0	69.0
Min	3.4	7.6	43.9	51.6
Max	14.6	11.3	89.8	85.0

In each of the test conditions, milk was subjected to temperature abuse to simulate what might happen in 'real life' where products may be taken out of the fridge for a period of time (e.g., when milk is taken out of the fridge at breakfast, or between purchasing and refrigerating the item at home). For further details refer to section 2.2 in the methodology chapter.

Sensory evaluation and microbiological testing were performed on milk. In the sensory evaluation, trained assessors evaluated the appearance, aroma, texture and taste of each sample. When the sample had passed the Use By date, the assessors did not taste the product due to safety reasons. The descriptions that were used for the sensory evaluation are provided in Appendix 2. The microbiological testing measured the growth of micro-organisms and can be used alongside the sensory evaluation as indicators of product quality.

3.6.1 Sensory evaluation

Table 17 shows the RAG ratings for each test condition in the sensory evaluation against the number of days relative to the Use By date and the number of days after packing. Each column represents a different condition, with the day the milk is opened varying in addition to the two different fridge temperatures used.

It should be noted that there is some scatter in the data whereby a condition may change from Amber to Red, and then back to Amber. Unlike the fresh produce items, after a sample was opened and evaluated it remained in the test. This means that any "reversal" in the quality rating for a particular product likely reflects two things: variability in product quality/ speed of deterioration between individual samples, and variability between different assessors. For a full explanation of how the RAG ratings were derived refer to section 2.3 in the methodology.

In all test conditions where the milk was opened on or before the Use By date, the RAG rating was still Green one day after the Use By date (14 days after packing). **This suggests that the milk was still of optimal quality one day after the Use By date, irrespective of whether it was stored at 4°C or 9°C. This was the case even for milk opened 8 days before the Use By date.**

Furthermore, milk that was opened four days after the Use By date, and refrigerated at 4°C, was Green on the day of opening, but then deteriorated to Amber the next day. In contrast, milk that was opened four days after the UB date, but refrigerated at 9°C, was already Amber when it was opened.

Table 17. Combined RAG rating for sensory evaluation of **milk:** OD = Open Date, PD = Purchase Day, TE = Test End, UB = Use By.

Open date relative to the UB	Days after packing	Refrigerated at 4°C					Refrigerated at 9°C				
-8	5 (PD)	OD					OD				
-6	7										
-4	9		OD					OD			
-2	11			OD					OD		
-1	12										
0 (UB)	13 (UB)				OD					OD	
+1	14										
+3	16										
+4	17					OD					OD
+5	18										
+6	19										
+7	20										
+8	21										
+10	23						TE	TE	TE	TE	
+11	24	TE	TE								
+12	25			TE	TE						
+13	26					TE					TE

Key	Red	Amber	Green	No test

For reference, the sensory properties of milk when classed as Amber were as follows:

- **Appearance** - Crust forming at the top of the milk bottle. Some loss to glossy colour.
- **Aroma** - Some off aroma to the top of the bottle.
- **Taste** - Loss of creaminess. No off flavour, uncertainty around freshness on consumption.
- **Texture** - Texture turning similar to full fat milk.

This illustrates that, although some citizens might reject it, an Amber rating indicates only a minor loss in quality. For this reason, the analysis of the sensory-evaluation results focuses on the point where the RAG rating turns from Amber to Red.

There appears to be little difference between the results for milk stored at 4°C compared to 9°C in terms of when the test conditions moved from Green to Amber. However, there is a difference between the fridge temperatures when looking at the length of time the milk remained Amber (Table 18).

Table 18: Effect of fridge temperatures on deterioration of milk, comparing transition from 'Amber' to 'Red' in sensory evaluation

Day of opening relative to UB date	**Date of last assessment prior to first 'Red' (number of days relative to the UB date)**		
	4°C fridge	**9°C fridge**	**Difference**
-8 days	+5 days	+5 days	0 days
-4 days	+8 days	+6 days	+2 days
-2 days	+8 days	+5 days	+3 days
0 days	+6 days	+5 days	+1 days
Ave. of above conditions	**+6.8 days**	**+5.3 days**	**+1.5 days**

For the four test conditions at 4°C, milk opened on or before the Use By date was still rated 'Amber' (without any 'Red' assessments) 5 to 8 days after the Use By date (Table 18). For milk at 9°C, it lasted between 5 and 6 days. For the milk opened 4 days after the Use By date, there is considerable variation in the sensory-evaluation results over time, making a quantitative comparison difficult.

For the conditions where the milk was opened on or before the Use By date, the average difference between the two fridge temperatures was 1.5 days (Table 18). Therefore, **keeping the fridge temperature within the recommended range extends the shelf life compared to a warmer fridge**. This is consistent with previous studies of a similar nature (Section 1.2.2). These results given an indication of the magnitude of this effect: to determine the exact shelf-life extension would require more replicate experiments to reduce the scatter in the data.

The opening date appears to make negligible difference to the shelf life of milk: there is no clear trend relating to the date at which milk first becomes rated as 'Red' (Table 18). **This suggests that when milk is opened makes little difference to its shelf life.** With a greater number of replicate samples, small differences due to when milk is opened may be detectable. In addition, the sensitivity of shelf life to the open life could depend on the degree to which it is exposed to air-borne pathogens: e.g., how long it is left with the lid off each day. In these tests, it was 1 hour on test days, exposed to the air in a laboratory that may have been cleaner than the average UK home.

For milk opened on or before the Use By date, the sensory evaluation rated the milk:

- Green one day after the Use By date
- Amber between 5 to 8 days after the Use By date

Therefore, in all conditions, including a warmer fridge (9°C) and opening the milk on the day of purchase, **milk was still of acceptable quality at least 5 days after opening.**

3.6.2 Microbiological testing

For all test conditions at 4°C the results show no linear growth of the micro-organisms tested (aerobic colony count, mould, yeast and Enterobacteriaceae). Throughout the course of the experiments all micro-organisms tested remained at acceptable levels when refrigerated at 4°C. There were occasional increases in the microbial growth, but these occurred inconsistently throughout the test and remained under the threshold for sub-optimal quality. As a result, these are of low microbiological concern.

For all but one of the test conditions at 9°C, all micro-organisms tested remained at acceptable levels up to 13 days after the Use By date. For milk that was opened 4 days after the Use By date, mould, yeast and Enterobacteriaceae remained at acceptable levels 13 days after the Use By date. The aerobic colony count remained at acceptable levels for 11 days after the Use By date, but exceeded the threshold level 12 days after the Use By. It should also be noted that for milk at 9°C as the duration of storage increased, the aerobic colony count also increased - except for milk opened 8 days before the Use By, which did not show an increase in aerobic colony count over the course of the experiment. Table 19 below provides a summary of the microbiological results for milk.

Table 19. Summary of microbiological results for milk.

<table>
<tr><th>Temperature</th><th>Open date relative to the UB</th><th>Description of results</th></tr>
<tr><td rowspan="5">4°C</td><td>-8</td><td rowspan="6">• No linear growth of ACC, mould, yeast and Enterobacteriaceae
• Throughout the course of the experiment all micro-organisms tested remained at acceptable levels
• There were occasional increases in the microbial growth, but these occurred inconsistently throughout the experiments and remained under the threshold for sub-optimal quality
• Low microbiological concern.</td></tr>
<tr><td>-4</td></tr>
<tr><td>-2</td></tr>
<tr><td>0 (UB)</td></tr>
<tr><td>+4</td></tr>
<tr><td>9°C</td><td>-8</td></tr>
<tr><td rowspan="3">9°C</td><td>-4</td><td rowspan="3">• No linear growth of mould, yeast and Enterobacteriaceae.
• Linear growth in aerobic colony count, but remained at acceptable levels
• Throughout the course of the experiment, all micro-organisms tested remained at acceptable levels</td></tr>
<tr><td>-2</td></tr>
<tr><td>0 (UB)</td></tr>
<tr><td>9°C</td><td>+4</td><td>• No linear growth of mould, yeast and Enterobacteriaceae
• Linear growth in aerobic colony count, which exceeded the threshold level 12 days after the Use By date</td></tr>
</table>

Overall, only one microbiological indicator (aerobic colony count) in one test condition at 9°C exceeded the threshold for sub-optimal quality. The aerobic colony count is an indicator of quality, not safety, and cannot directly contribute towards a safety assessment. Whilst the microbiological results indicate that most milk was of acceptable quality for as long as 13 days after the Use By date, most samples did reach Red in the sensory tests until around 10 days after the Use By date. **This suggests that milk was deemed unpalatable well before it reached or surpassed any of the microbiological thresholds.**

3.7 Natural Yogurt

For natural yogurt, two research questions were investigated:

- What difference in shelf life is there between natural yogurt refrigerated at sub-optimal (9°C) and optimal (4°C) temperatures?
- What effect does the day of opening relative to the Use By date have on shelf life?

In total, eight test conditions were used to answer the research questions above:

- Refrigerated at 4°C and opened:
    - 18 days before the Use By date,
    - 8 days before the Use By date,
    - On the Use By date,
    - On the Use By date but a new sample was opened on each test day (as opposed to opening the first sample and testing the same sample each day).

- Refrigerated at 9°C and opened
    - 18 days before the Use By date,
    - 8 days before the Use By date,
    - On the Use By date,
    - A new sample opened on each of the test days on or after the Use By date (0, 9, 12, 17 and 19 days after the Use By date)

Natural yogurt was not tested in ambient conditions as it spoils rapidly when not refrigerated.

The average temperature and humidity were monitored over the course of the sensory evaluation (Table 20). The target temperature was 4°C for the optimal fridge temperature and 9°C for the sub-optimal fridge temperature. There were no targets for humidity.

In each of the test conditions, natural yogurt was subjected to temperature abuse to simulate what might happen in 'real life' where products may be taken out of the fridge for a period of time (e.g., when yogurt is taken out of the fridge at breakfast, or between purchasing and refrigerating the item at home). For further details refer to section 2.2 in the methodology chapter.

Table 20: Natural yogurt: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Optimal	Sub-optimal	Optimal	Sub-optimal
Target	4.0	9.0	N / A	N / A
Mean	3.9	8.5	78.0	69.0
Min	3.4	7.6	43.9	51.6
Max	14.6	11.3	89.8	85.0

Sensory evaluation and microbiological testing were performed on natural yogurt. In the sensory evaluation, the trained assessors evaluated the appearance, aroma, texture and taste of each sample. When the sample had passed the Use By date, the assessors did not taste the product due to safety reasons. The descriptions that were used for the sensory evaluation are provided in Appendix 2. The microbiological testing measured the growth of micro-organisms and can be used alongside the sensory evaluation as indicators of product quality.

3.7.1 Sensory evaluation

Table 21 shows the RAG ratings for each test condition in the sensory evaluation against the number of days after packing. It should be noted that there is some scatter in the data whereby a condition may change from Amber to Red, and then back to Amber. Unlike the fresh produce items, after a sample was opened and evaluated it remained in the test. This means that any “reversal” in the quality rating for a particular product likely reflects two things: variability in product quality/ speed of deterioration between individual samples, and variability between different assessors. For a full explanation of how the RAG ratings were derived refer to section 2.3 in the methodology.

For reference, the sensory properties of natural yogurt when classed as Amber were as follows:

- **Appearance** - approximately two teaspoons of whey visible. Loss of glossy sheen. One or two mould spots on less than 5% of sample.
- **Aroma** - Loss of fresh aroma, very slight taint noticed.
- **Taste** - Loss of creaminess, watery and slightly bitter.
- **Texture** - Yogurt is starting to thin. A spoon struggles to stand up in the yogurt, and when poured onto a plate the yogurt will start to flow in clumps. When a spoon is dragged through the yogurt the divide will not remain for longer than 20 seconds

This illustrates that, although some citizens might reject it, an Amber rating indicates only a minor loss in quality. For this reason, the analysis of the sensory-evaluation results focuses on the point where the RAG rating turns from Amber to Red (summarised in Table 22).

In general, for both fridge temperatures, **the later the natural yogurt was opened, the later it remained in either optimal condition (Green rating) or acceptable**

condition (Amber rating). This can be seen, despite the scatter in the data, from the diagonal trend, downward from left to right, in the colours presented in Table 21.

Table 21: Combined RAG rating for sensory evaluation of **natural yogurt:** OD = Open Date, PD = Purchase Day, TE = Test End, UB = Use By.

Days relative to the UB	Days after packing	Refrigerated at 4°C				Refrigerated at 9°C			
		Items opened and then retested			New item opened for each test	Items opened and then retested			New item opened for each test
-16	11 (PD)	OD				OD			
-12	15								
-8	19		OD				OD		
-5	22								
-4	23								
-3	24								
-1	26								
0 (UB)	27 (UB)			OD	OD			OD	OD
+2	29								
+3	30								
+4	31					TE			
+6	33	TE							
+9	36				OD				OD
+10	37								
+11	38								
+12	39				OD		TE		OD
+17	44		TE		OD				OD
+18	45								
+19	46			TE	OD/ TE			TE	OD/ TE

Key	Red	Amber	Green	No test

Furthermore, for the natural yogurts that were opened on the day of the test (fourth and eighth columns of Table 21), these were – with one exception – assessed to be in optimal condition (Green rating) during all the tests, which extended to 19 days after the Use By date. This further illustrates the impact of when the yogurts were opened: natural yogurt appears to be in optimal condition when opened and tested two and a half weeks after the Use By date (with one exception).

Due to the scatter in the sensory-assessment data, it is difficult to quantify how date of opening affects the speed at which natural yogurt deteriorates. Nevertheless, even for the items opened 16 days before the Use By date, it was still in at least acceptable condition by the Use By date (16 days later). In the case of the yogurt stored in the optimal temperature (4°C) fridge, it was still of acceptable quality four days after the Use By date (20 days after opening).

Table 22: Effect of fridge temperatures on deterioration of natural yogurt, comparing transition from 'Amber' to 'Red' in sensory evaluation

Day of opening relative to UB date	Assessment prior to first 'Red' (number of days relative to the UB date)		
	4°C fridge	**9°C fridge**	**Difference**
-16 days	+4 days	0 days	+4 days
-8 days	0 days	+10 days	-10 days
0 days	+17 days	0 days	+17 days
Ave. of above conditions	**+7.0 days**	**+3.3 days**	**+3.7 days**

Across the three different opening times, **natural yogurt stored at 4°C deteriorates more slowly than yogurt stored at 9°C** (Table 22), lasting approximately 3.7 days longer than at the lower temperature. However, there is uncertainty in this magnitude of difference due to the scatter found in the sensory-assessment results.

This pattern was also seen for the transition from Green rating to Amber, with this transition also happening later for yogurt stored at 4°C. These results are consistent with previous studies of a similar nature (Section 1.2.2). These results provide an indication of the magnitude of the effect of fridge temperature. However, to determine the exact shelf-life extension would require more replicate experiments to reduce scatter present in the data.

These same results suggest that all conditions were optimal or acceptable up to and including the Use By date. For the three test conditions at 4°C that were opened on or before the Use By date, natural yogurt was still rated 'Amber' (without any 'Red' assessments) between 0 to 17 days after the Use By date. For natural yogurt at 9°C, it lasted between 0 and 10 days. However, there is considerable variation in the sensory-evaluation results over time, making it problematic to quantify how long items are acceptable to eat after their Use By date.

3.7.2 Microbiological testing

Refrigerated at 4°C

For all test conditions the results show no linear growth of mould, yeast and Enterobacteriaceae, which remained at acceptable levels throughout the experiments. As a result, these are of low microbiological concern. In all but one test condition at 4°C there was a linear growth in the aerobic colony count, but this did not reach sub-optimal levels until at least 8 days after the Use By date. The specific timings that sub-optimal aerobic colony counts were reached in each test condition are as follows:

- For natural yogurt opened 16 days before the Use By date, the aerobic colony count remained at acceptable levels throughout the experiment and the final sample – which was tested 2 days after the Use By date - was also at acceptable levels.
- For natural yogurt opened 8 days before the Use By date, the aerobic colony count reached sub-optimal quality 14 days after the Use By, meaning it was at acceptable levels for three weeks after opening.
- For natural yogurt opened on the Use By date, the aerobic colony count reached sub-optimal quality 8 days after the Use By, meaning it was at acceptable levels for around a week after opening.

Refrigerated at 9°C

For all test conditions the results show no linear growth of mould, yeast and Enterobacteriaceae, which remained at acceptable levels throughout the experiments. There was one instance where mould was detected, but this occurred 12 days after the Use By date in samples that had been opened *on* the Use By date. Moreover, in the subsequent days, no mould was detected in the same samples, which likely reflects variability between assessment days. Since, mould was inconsistently detected throughout the test and remained under the threshold for sub-optimal quality, the results are of low microbiological concern.

Table 23. Summary of microbiological results for natural yogurt.

Temp.	Open date relative to the UB	Description of results
4°C	-16	• No linear growth of ACC, mould, yeast and Enterobacteriaceae • Throughout the course of the experiment all micro-organisms tested remained at acceptable levels • Low microbiological concern.
	-8	• No linear growth of mould, yeast and Enterobacteriaceae • Linear growth in aerobic colony count, which reached sub-optimal levels 14 days after the Use By date.
	0 (UB)	• No linear growth of mould, yeast and Enterobacteriaceae • Linear growth in aerobic colony count, which reached sub-optimal levels 8 days after the Use By date.
9°C	-16	• No linear growth of ACC, mould, yeast and Enterobacteriaceae • Throughout the course of the experiment all micro-organisms tested remained at acceptable levels • Low microbiological concern.
	-8	• No linear growth of mould, yeast and Enterobacteriaceae • Linear growth in aerobic colony count, which reached sub-optimal levels 6 days after the Use By date.
	0 (UB)	• No linear growth of mould, yeast and Enterobacteriaceae • Linear growth in aerobic colony count, which reached sub-optimal levels 8 days after the Use By date.

In all but one test condition at 9°C, there was a linear growth in the aerobic colony count, but this did not reach sub-optimal levels until at least 8 days after the Use By date. The specific timings that sub-optimal aerobic colony counts were reached in each test condition are summarised in Table 23.

Overall, only one microbiological indicator (aerobic colony count) exceeded the threshold for sub-optimal quality in three test conditions (at both 4°C and 9°C). The aerobic colony count is an indicator of quality, not safety, and cannot directly contribute towards a safety assessment. **Whilst the microbiological results indicate that most natural yogurt was of acceptable quality for as much as 8 days after the Use By date, most samples started to reach Amber in the sensory tests 3 - 5 days after the Use By date.**

Therefore, in the tests conducted here, natural yogurt was deemed unpalatable well before it reached or surpassed any of the microbiological thresholds.

3.8 Fruit yogurt

For fruit yogurt, two research questions were investigated:

- What is the difference in shelf life between fruit yogurt refrigerated at sub-optimal (9°C) and optimal (4°C) fridge temperatures?
- What effect does the day of opening, relative to the Use By date, have on shelf life?

In total, eight test conditions were used to answer the research questions above:

- Refrigerated at 4°C and opened:
    - 9 days before the Use By date,
    - 5 days before the Use By date,
    - On the Use By date,
    - A new sample opened on each of the test days on or after the Use By date (0, 7, 14, 21 and 28 days after the Use By date)

- Refrigerated at 9°C and opened
    - 9 days before the Use By date,
    - 5 days before the Use By date,
    - On the Use By date,
    - A new sample opened on each of the test days on or after the Use By date (0, 7, 14, 21 and 28 days after the Use By date)

Fruit yogurt was not tested in ambient conditions as it spoils rapidly when not refrigerated.

The average temperature and humidity were monitored over the course of the sensory evaluation (Table 24). The target temperature was 4°C for the optimal fridge temperature and 9°C for the sub-optimal fridge temperature. There were no targets for humidity.

Table 24: Natural yogurt: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Optimal	Sub-optimal	Optimal	Sub-optimal
Target	4.0	9.0	N / A	N / A
Mean	3.9	8.5	78.0	69.0
Min	3.4	7.6	43.9	51.6
Max	14.6	11.3	89.8	85.0

In each of the test conditions, fruit yogurt was subjected to temperature abuse to simulate what might happen in 'real life' where products may be taken out of the fridge for a period of time (e.g., when yogurt is taken out of the fridge at breakfast, or between purchasing and refrigerating the item at home). For further details refer to section 2.2 in the methodology chapter.

Sensory evaluation and microbiological testing were performed on fruit yogurt. In the sensory evaluation, the trained assessors evaluated the appearance, aroma, texture and taste of each sample. When the sample had passed the Use By date, the assessors did not taste the product due to safety reasons. The descriptions that were used for the sensory evaluation are provided in Appendix 2. The microbiological testing measured the growth of micro-organisms and can be used alongside the sensory evaluation as indicators of product quality.

3.8.1 Sensory evaluation

Table 25 shows the RAG ratings for each test condition in the sensory evaluation against the number of days after packing. It should be noted that there is some scatter in the data whereby a condition may change from Amber to Red, and then back to Amber. For three of the test conditions, after a sample was opened and evaluated it remained in the test. For one of the test conditions, samples were initially opened on the Use By date, and then a new sample was opened weekly on day 7, 14, 21 and 28. This means that any "reversal" in the quality rating for a particular product likely reflects two things: variability in speed of deterioration between individual samples, and variability between different assessors. For a full explanation of how the RAG ratings were derived refer to section 2.3 in the methodology.

For reference, the sensory properties of fruit yogurt when classed as Amber were as follows:

- **Appearance** - approximately two teaspoons of whey visible. Loss of glossy sheen. One or two mould spots on less than 5% of sample.
- **Aroma** - Loss of fresh aroma, very slight taint noticed.
- **Taste** - Loss of fruit flavour.
- **Texture** - Yogurt is starting to thin. A spoon struggles to stand up in the yogurt, and when poured onto a plate the yogurt will start to flow in clumps. When a spoon is dragged through the yogurt the divide will not remain for longer than 20 seconds.

This illustrates that, although some citizens might reject it, an Amber rating indicates only a minor loss in quality. For this reason, the analysis of the sensory-evaluation results focuses on the point where the RAG rating turns from Amber to Red (summarised in Table 26).

Table 25: Combined RAG rating for sensory evaluation of **fruit yogurt:** OD = Open date, PD = Purchase Day, TE = Test end, UB = Use By.

Days relative to the UB	Days after packing	Refrigerated at 4°C				Refrigerated at 9°C			
		Items opened and then retested			New item opened for each test	Items opened and then retested			New item opened for each test
-9	13 (PD)	OD				OD			
-5	17		OD				OD		
-1	21								
0 (UB)	22 (UB)			OD	OD			OD	OD
+2	24								
+3	25								
+4	26								
+5	27								
+6	28								
+7	29				OD				OD
+9	31					TE	TE	TE	
+10	32								
+11	33	TE	TE						
+12	34			TE					
+14	36				OD				OD
+21	43				OD				OD
+28	50				OD/TE				OD/TE

Key	Red	Amber	Green	No test

The appears to be some effect on shelf life of when fruit yogurt is opened (Table 25). Stored at 4°C, fruit yogurt tended to become Amber and Red rated later for items opened later: e.g., for the first transition to Red ratings, this occurred 5 days later for the items opened on the Use By date, compared to those opened nine or five days beforehand (Table 26). However, for items stored at 9°C, there was no clear pattern relating to when they were opened in terms of the transition from Amber rating to Red (Table 26).

Table 26: Effect of fridge temperatures on deterioration of fruit yogurt, comparing transition from 'Amber' to 'Red' in sensory evaluation

Day of opening relative to UB date	Assessment prior to first 'Red' (number of days relative to the UB date)		
	4°C fridge	9°C fridge	Difference
-9 days	+4 days	+4 days	0 days
-5 days	+4 days	+2 days	+2 days
0 days	+10 days	+3 days	+7 days
Ave. of above conditions	**+6.0 days**	**+3.0 days**	**+3.0 days**

Fruit yogurt that was opened on the day of the test (fourth and eighth columns of Table 25) tended to last longer than items opened earlier. For example, the fruit yogurt stored at 4°C and opened 7 days after the Use By date was rated Green, whereas all those opened earlier were already rated Amber. Similarly, the yogurt opened 28 days after the Use By date was rated Amber, when all other opened yogurts had been rated Red 17 days previously.

This suggests that when items are opened does affect shelf life. However, even items opened on the simulated day of purchase (nine days before the Use By date) were still in optimal or acceptable condition (Green or Amber respectively) 13 days later (four days after the Use By date, Table 25 and Table 26).

There appears to be little difference between the results for fruit yogurt stored at 4°C compared to 9°C in terms of when the test conditions moved from Green to Amber. However, there is a difference between fridge temperatures when looking at the Amber-to-Red transition (Table 26). **Fruit yogurt refrigerated at 4°C lasted, on average, 3 days longer than that stored at 9°C.**

For all the test conditions, fruit yogurt is assessed to be in either optimal or acceptable condition at least 2 days after the Use By date (Table 25 and 26). For fruit yogurt refrigerated at 4°C, this extends to 4 days after the Use By date.

3.8.2 Microbiological testing

For all test conditions for fruit yogurt the results show no linear growth of the micro-organisms tested (aerobic colony count, mould, yeast and Enterobacteriaceae). Throughout the course of the experiments all micro-organisms tested remained at acceptable levels. There were occasional increases in the microbial growth, but these occurred inconsistently throughout the test and remained under the threshold for sub-optimal quality. As a result, these are of low microbiological concern.

Therefore, in the tests conducted here, fruit yogurt was deemed unpalatable/ of unacceptable sensory condition well before it reached any of the microbiological thresholds.

3.9 Hard cheese

For cheese, four research questions were investigated:

- What is the difference in shelf life between cheese refrigerated at sub-optimal (9°C) and optimal (4°C) temperatures?
- What effect does the day of opening have on shelf life?
- What effect does wrapping cheese in its packaging, either tightly or loosely, have on shelf life?
- What effect does temperature abuse have on shelf life?

In total, nine test conditions were used to answer the research questions above:

- Refrigerated at 4°C, both loosely and tightly wrapped, and opened:
  - 62 days before the Best Before date,
  - On the Best Before date.

(The above, therefore, representing four conditions.)

- Refrigerated at 9°C, both loosely and tightly wrapped, and opened
  - 62 days before the Best Before date,
  - On the Best Before date.

(The above, therefore, representing four conditions.)

In the eight test conditions above, cheese was subjected to temperature abuse for 1 hour at approximately 22°C on 70% of the storage days i.e., 5 out of 7 days a week. This simulated what might happen in 'real life' where products may be taken out of the fridge for a period of time (e.g., when cheese is taken out of the fridge to make a sandwich, or the time between purchasing and refrigerating the item at home). For further details refer to section 2.2 in the methodology chapter.

A further test condition was used to explore the impact of a shorter period of temperature abuse. In this test cheese was:

- Refrigerated at 4°C, tightly wrapped, and opened:
  - 62 days before the Best Before date, but with only 10 minutes of temperature abuse.

Cheese was not tested in ambient conditions as it spoils rapidly when not refrigerated.

Table 27: Cheese: temperature and humidity of storage conditions

	Temperature (°C)		Humidity (%)	
	Optimal	Sub-optimal	Optimal	Sub-optimal
Target	4.0	9.0	N / A	N / A
Mean	4.3	8.5	77.4	69.0
Min	3.9	7.6	67.2	51.6
Max	6.4	11.3	91.1	85.0

The average temperature and humidity were monitored over the course of the sensory evaluation (Table 27). The target temperature was 4°C for the optimal fridge temperature and 9°C for the sub-optimal fridge temperature. There were no targets for humidity.

Only sensory evaluation was performed on cheese. Trained assessors evaluated the appearance, aroma, texture and taste of each sample. The descriptions that were used for the sensory evaluation are provided in Appendix 2.

3.9.1 Sensory evaluation

Table 28 shows the RAG ratings for each test condition in the sensory evaluation against the number of days after packing. It should be noted that there is some scatter in the data whereby a condition may change from Amber to Red, and then back to Amber. Unlike the fresh produce items, after a sample was opened and evaluated it remained in the test. This means that any "reversal" in the quality rating for a particular product likely reflects two things: variability in product quality/ speed of deterioration between individual samples, and / or variability between different assessors. For a full explanation of how the RAG ratings were derived refer to section 2.3 in the methodology.

Many more conditions were investigated for cheese compared to the other dairy items. The comparisons for each of these can be found in this section.

For reference, the sensory properties of hard cheese when classed as Amber were as follows:

- **Appearance**: Some visible moisture and / or with drying edges. Visible green or white mould on < 5% of the sample.
- **Aroma**: Some uncharacteristic aromas to small areas of the sample.
- **Taste**: Savoury and creamy notes with a slightly dry mouth feel. Less complexity to the flavour.
- **Texture:** Some dry spots and edges crumbing away. Easily removable and would not deem entire sample inedible.

This illustrates that, although some citizens might reject it, an Amber rating indicates only a minor loss in quality. For this reason, the analysis of the sensory-evaluation results focuses on the point where the RAG rating turns from Amber to Red.

Table 28: Combined RAG rating for sensory evaluation of **hard cheese:** OD = Open Date, PD = Purchase Day, TE = Test End, BB = Best Before, TA10 = Temperature Abuse for 10 minutes each day. TA60 = Temperature Abuse for 60 minutes each day.

Days relative to the BB	Days since opening	Days after purchase[49]	Refrigerated at 4°C					Refrigerated at 9°C			
			Tightly wrapped			Loosely wrapped		Tightly wrapped		Loosely wrapped	
-62	0 (OD)	0 (PD)	OD TA10	OD TA60		OD TA60		OD TA60		OD TA60	
-55	7	7									
-49	13	13									
-46	16	16									
-43	19	19									
-40	22	22									
-36	26	26									
-33	29	29									
-29	33	33						TE		TE	
-26	36	36									
-21	41	41		TE		TE					
-18	44	44									
-14	48	48	TE								
0 (BB)	0 (OD)	62 (BB)			OD		OD		OD		OD
+3	3	65									
+7	7	69									
+10	10	72									
+13	13	75									
+16	16	78									TE
+20	20	82							TE		
+23	23	85									
+28	28	90									
+31	31	93									
+35	35	97									
+38	38	100									
+42	42	104									
+45	45	107			TE		TE				

Key	Red	Amber	Green	No test

[49] *Cheese was packaged 14 days before the Purchase Date. To calculate the number of days since packing, add 14 to the number of days quoted in the "Days after purchase" column.*

For all conditions, cheese lasted longer refrigerated at 4°C compared to 9°C (Table 29). Over the four conditions where comparisons were possible, the average shelf-life difference was approximately nine days. This suggests that **the shelf life of hard cheese could be extended by more than a week if stored at 4°C compared to 9°C.**

Table 29: Effect of **fridge temperatures** on deterioration of hard cheese, comparing transition from 'Amber' to 'Red' in sensory evaluation

Conditions	**Last assessment before first 'Red' (number of days relative to the BB date)**		
	4°C fridge	**9°C fridge**	**Difference**
-62 days, tightly wrapped	-29 days	-36 days	+7 days
-62 days, loosely wrapped	-29 days	-40 days	+11 days
0 days, tightly wrapped	+23 days	+13 days	+10 days
0 days, loosely wrapped	+7 days	0 days	+7 days
Ave. of above conditions	*		**+8.8 days**

* Average not calculated, as less meaningful due to wide range of storage conditions.

Wrapping hard cheese tightly also extended its shelf life (Table 30). Across the four conditions tested, **the average shelf-life extension of wrapping cheese tightly, compared to loosely, was more than a week (8.3 days).**

Table 30: Effect of **degree of wrapping** on deterioration of hard cheese, comparing transition from 'Amber' to 'Red' in sensory evaluation

Conditions	**Last assessment before first 'Red' (number of days relative to the BB date)**		
	Tightly wrapped	**Loosely wrapped**	**Difference**
-62 days, 4°C storage	-29 days	-29 days	0 days
-62 days, 9°C storage	-36 days	-40 days	+4 days
0 days, 4°C storage	+23 days	+ 7 days	+16 days
0 days, 9°C storage	+13 days	0 days	+13 days
Ave. of above conditions	*		**+8.3 days**

* Average not calculated, as less meaningful due to wide range of storage conditions.

For reference, the instructions for tight and loose wrapping for the experiments were:

- **Tightly wrapped**: Open pack by cutting along one end. Once opened, fold original packaging over and wrap entire block with cling film. During temperature abuse leave open for that time.
- **Loosely wrapped**: Open pack by cutting along one end. Once opened, put the cheese back into its original position in the packaging. Do not fold packaging over or secure in any way. One end of the cheese will therefore be open to the air.

Cheese that was opened on its Best Before date did not last as long after opening than cheese opened on the day of purchase (62 days before BB date). Averaging across the four sets of conditions where a comparison is possible, cheese opened on the day of purchase was acceptable (Amber rated) for four weeks (28.5 days), whereas cheese opened on its Best Before date was acceptable for a week and a half (10.5 days, Table 31). This difference is around two and a half weeks (17.8 days).

Table 31: Effect of **day of opening** on deterioration of hard cheese, comparing transition from 'Amber' to 'Red' in sensory evaluation, **expressed relative to opening**

Conditions	Last assessment before first 'Red' (number of days relative to the opening)		
	Opened 62 days before BB	Opened 0 days before BB	Difference
Tightly wrapped, 4°C storage	+33 days	+23 days	-10 days
Loosely wrapped, 4°C storage	+33 days	+ 7 days	-26 days
Tightly wrapped, 9°C storage	+26 days	+13 days	-13 days
Loosely wrapped, 9°C storage	+ 22 days	0 days	-22 days
Ave. of above conditions	**+28.5 days**	**+10.8 days**	**-17.8 days**

In contrast, by looking at the same data but expressing it by how long the cheese lasts relative to the Best Before date, cheese opened later was of acceptable quality *until a later date* than cheese opened on the day of purchase (Table 32).

Table 32: Effect of **opening date** on deterioration of hard cheese, comparing transition from 'Amber' to 'Red' in sensory evaluation, **expressed relative to BB date**

Conditions	Last assessment before first 'Red' (number of days relative to the BB date)		
	Opened 62 days before BB	Opened 0 days before BB	Difference
Tightly wrapped, 4°C storage	-29 days	+23 days	+52 days
Loosely wrapped, 4°C storage	-29 days	+ 7 days	+36 days
Tightly wrapped, 9°C storage	-36 days	+13 days	+49 days
Loosely wrapped, 9°C storage	-40 days	0 days	+40 days
Ave. of above conditions	**-33.5 days**	**+10.8 days**	**+44.3 days**

The effect of 'temperature abuse' was also investigated. For one set of products, the cheese was left out of the fridge for 10 minutes on all test days; another set of products were left out of the fridge for 60 minutes on all test days. The difference between the two condition was 11 days (Table 33). Therefore, **lower levels of temperature abuse increase the shelf life**, in this case by around one and a half weeks.

Table 33: Effect of **'temperature abuse'** on deterioration of hard cheese, comparing transition from 'Amber' to 'Red' in sensory evaluation

Conditions	Last assessment before first 'Red' (number of days relative to the BB date)		
	10 minutes	60 minutes	Difference
Tightly wrapped, 4°C storage, opened 62 days before BB date	**-18 days**	**-29 days**	**+ 11 days**

In addition to the above, one set of conditions was designed to simulate the shelf life of hard cheese stored in optimal conditions: refrigerated at 4°C, tightly wrapped and only left out of the fridge for 10 minutes for each test day. For this condition, the cheese was opened on the day of purchase. **For these conditions, the cheese was still in optimal condition 36 days after opening, and acceptable quality 44 days after opening.**

This can be compared to the 'worst' stored cheese (loosely wrapped, 9°C and 60 minutes of temperature abuse on test days), which was in optimal condition until 16 days after opening and acceptable quality 22 days after opening. Therefore, **storing cheese in optimal conditions can double its shelf life after opening, in comparison to the least favourable storage conditions tested.**

4.0 Overview of Results and Discussion

This section summarises the key results found in the previous sections, discussing the implications of the results for each area investigated. The limitations of the research are discussed alongside future research that would be beneficial to this topic.

4.1 Summary results and discussion

This section summarises the results and discusses the implications under the following headings:

- Presence / absence of packaging (Section 4.1.1)
- Fridge storage vs. ambient storage (Section 4.1.2)
- Fridge temperature (Section 4.1.3)
- When items are opened (Section 4.1.4)
- Length of time items last relative to their Best Before or Use By dates (Section 4.1.5).

The results quoted in this section for fresh-produce items describe the time taken to reach a deterioration score[50] of 0.3. This level of deterioration score represents a mix of Green (optimal) and Amber (acceptable) assessments, with the Combined RAG rating most likely to be Amber. Few / none of the assessments were 'Red' (unacceptable) at this point in time. Generally, the trends presented in this section also hold for other relevant deteriorations scores: those between 0 to 0.6. In other words, the conclusions are not dependent on the choice of deterioration score presented.

4.1.1 Packaged vs. loose

The primary motivation for this research was to understand how packaging influences product shelf life in the home. The following section presents a summary of these results. This information supported further research to understand the impact of packaging on household food waste (HHFW)[51].

As discussed in Section 2.2, with the exception of potatoes, the loose items were obtained by removing the packaging from items that were previously packaged. This ensured that loose and packaged items came from the same supply chain (e.g., same provenance, same length of time in transit and in storage). The only difference between the items was the presence or absence of packaging in the home. It is important to note that all these items travelled through the supply chain in packaging. For potatoes, the packer provided samples from the same batch of potatoes in three different packaging formats, and loose.

[50] The deterioration score summarises the sensory-assessment scores into a single number: zero represents all three assessors scoring the three replicates 'green'; a score of one represents all three assessors scoring the three replicates 'red'. Section 2.3 has more details.

[51] *Modelling the impact of selling products loose or in packaging, WRAP, 2022: https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

Figure 8 and Table 34 contain a summary of the results comparing shelf life for loose and packaged fresh-produce items. Some products having multiple conditions assessed, such as apples stored in ambient conditions and refrigerated at 4°C.

Figure 8: Comparison of packaged and loose shelf lives, for different product / condition combinations. % difference shown for those where results are substantial.

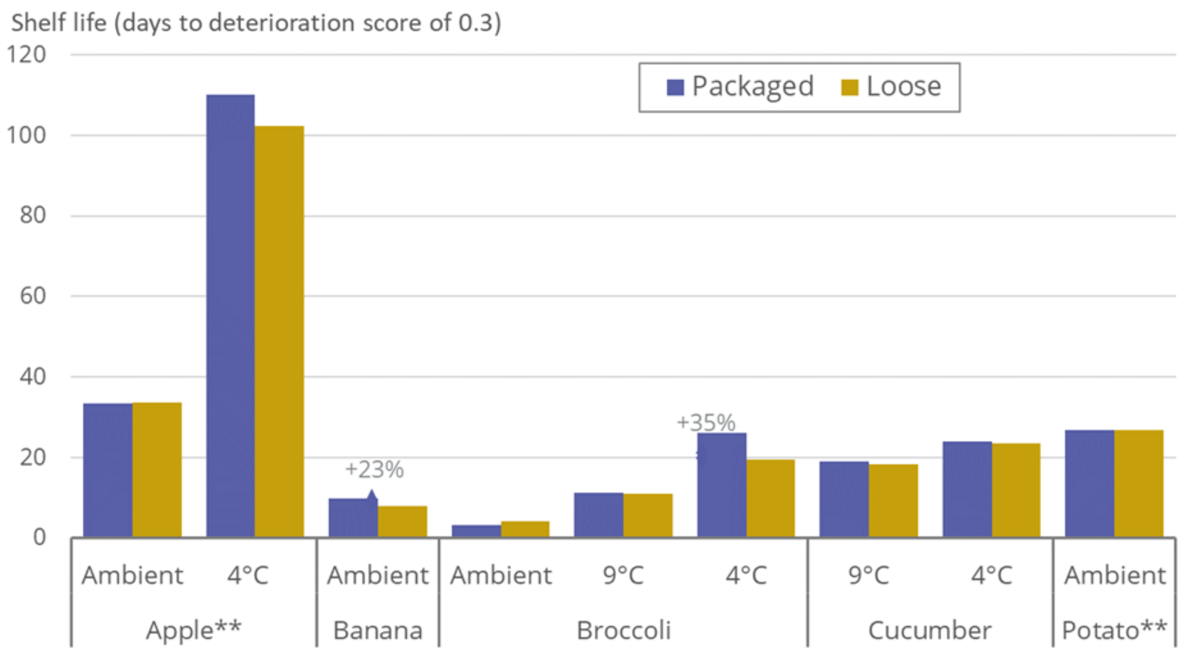


Table 34: Comparison of shelf life for packaged and loose items at a deterioration score of 0.3

Product	Condition	Impact of packaging on shelf life
Apple	Ambient	No impact detectable
	4°C fridge	No impact detectable**
Banana	Ambient	Increase of 1.8 days (+23%)
Broccoli	Ambient	No impact detectable
	9°C fridge	No impact detectable
	4°C fridge	Increase of 7 days (+35%)
Cucumber	9°C fridge	No impact detectable
	4°C fridge	No impact detectable
Potato	Ambient	No impact detectable
	4°C fridge	No impact detectable **

**For refrigerated apples and potatoes, there was considerable scatter in the sensory assessment data. Further investigation demonstrated that differences seen between packaged and loose conditions could have been due to this scatter, rather than being a real affect. More data would be required to determine any difference relating to the presence of packaging (Appendix 3 contains further analysis on this point).

In reality, any modest differences in the shelf life of refrigerated apples and potatoes (e.g., between packaged and loose) will have limited impact on HHFW: if they last months in these conditions, then there is plenty of opportunity for households to use them before they start to deteriorate.

Of the ten combinations of products and conditions assessed, the packaging led to longer shelf life for just two (Table 34):

- Bananas in ambient conditions
- Broccoli refrigerated at 4°C

For a further two combinations of products and storage conditions (refrigerated apples and refrigerated potatoes), packaging may have affected the shelf life, but the scatter in the sensory-evaluation data was too great to confirm this with any certainty. For the other six product / conditions, there was no detectable difference in shelf life between the packaged and loose variants.

For apples and potatoes, most UK citizens store these in ambient conditions, either in the fruit bowl (apples) or cupboard (potatoes)[52]. Therefore, under the most typical conditions, the shelf life is not extended for these products by the presence of packaging.

Furthermore, for apples and bananas, around 60% of UK citizens remove the packaging on their return from the shops[53]. This means that any increases in shelf life from the packaging are not realised by those households. This is especially relevant for bananas, where there was a shelf-life extension measured in these experiments. The degree of depackaging of the other three items is not well understood in the UK.

Overall, the results highlighted in this report challenge the existing narrative that packaging extends the shelf life of fresh fruit and vegetable products, reducing HHFW. Under certain circumstances, packaging can extend the shelf life. However, for the majority of conditions / products tested here, it did not

The above conclusions differ from some of the previously published literature (Section 1.2.1). In the literature, packaging was associated with shelf-life extensions for apples (ambient and refrigerated), bananas, refrigerated broccoli and cucumber (refrigerated and ambient). No information was found for potatoes. The previous research cited is in broad agreement with the current research for bananas and broccoli stored at 4°C, whereas there are substantial differences between previous and current research for apples, broccoli at 9°C and refrigerated cucumbers. The potential reasons for these discrepancies include:

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[52] *Helping Consumers Reduce Fruit and Vegetable Waste: Final Report, WRAP, 2008:* *https://wrap.org.uk/sites/default/files/2020-10/WRAP-RTL044-001%20Final%20report.pdf*

[53] *Consumer Attitudes to Food Waste and Food Packaging, WRAP (2013): https://wrap.org.uk/sites/default/files/2020-12/Consumer-attitudes-to-food-waste-and-packaging.pdf*

- **Different varieties**: e.g., the variety of cucumber differed between this study and the literature studies.
- **Different packaging**, e.g., the apples in the previous study were individually shrink-wrapped; the current research involved polyethylene bags containing multiple apples
- **Different conditions:** e.g., the temperature of the fridge used for cucumbers in the literature was 12°C, compared to 4°C and 9°C in the current study. The dominant mechanism of deterioration could vary with conditions, with packaging having differing effects.
- **Different metrics assessing deterioration:** a range of metrics have been used in the literature to assess the deterioration of a product. These include weight loss (often due to moisture loss), colour change and build-up of gases in packaging. The current study, like a small number of the literature studies, focuses on sensory evaluation, supported by pressure testing. It was felt that this best assesses the key parameters relating to HHFW – how likely householders would be to eat or reject the item in that state of deterioration. Other metrics may or may not relate to this key point of rejection.
- **Reporting bias**: it is likely that not all research on this topic has been published. There is the potential that studies that did not find a difference between packaged and loose varieties were less likely to be published in comparison to those that found a difference, leading to a bias in the reported results.

It is not possible to determine the degree to which each of the above reasons contributes to the differences between prior studies and the current research. It is suggested that the results of this research are communicated in a manner consistent with these discrepancies with previous research.

The implications of these results on food waste in the home are modelled and discussed in *The Modelling Report*[54]. The research described above indicated that packaging had only a modest impact on shelf life and, therefore, on HHFW. Other impacts relating to whether food was packaged or not – specifically the presence of date labels and the sizes of packs – had a much larger impact on HHFW. The modelling predicted that levels of HHFW would be lower for products sold loose for four of the five products investigated.

4.1.2 Fridge storage (4°C) vs. ambient

The temperature at which products are stored can influence their shelf life. This can have an impact on HHFW, as well as impacting food safety. This section looks at comparisons between products kept in refrigerated conditions (4°C) and ambient conditions (target temperature 21°C).

Experiments were carried out for products that met the following two conditions:

- A large proportion of the UK population stores the product in ambient conditions;

[54] *Modelling the impact of selling products loose or in packaging, WRAP, 2022:* https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste

- There is no prior research suggesting that the product deteriorates in the fridge (e.g., bananas were not included, as previous research suggested that they go black quickly in the fridge).

Figure 9: Comparison of shelf life for optimal fridge (4°C) and ambient conditions for different product / condition combinations

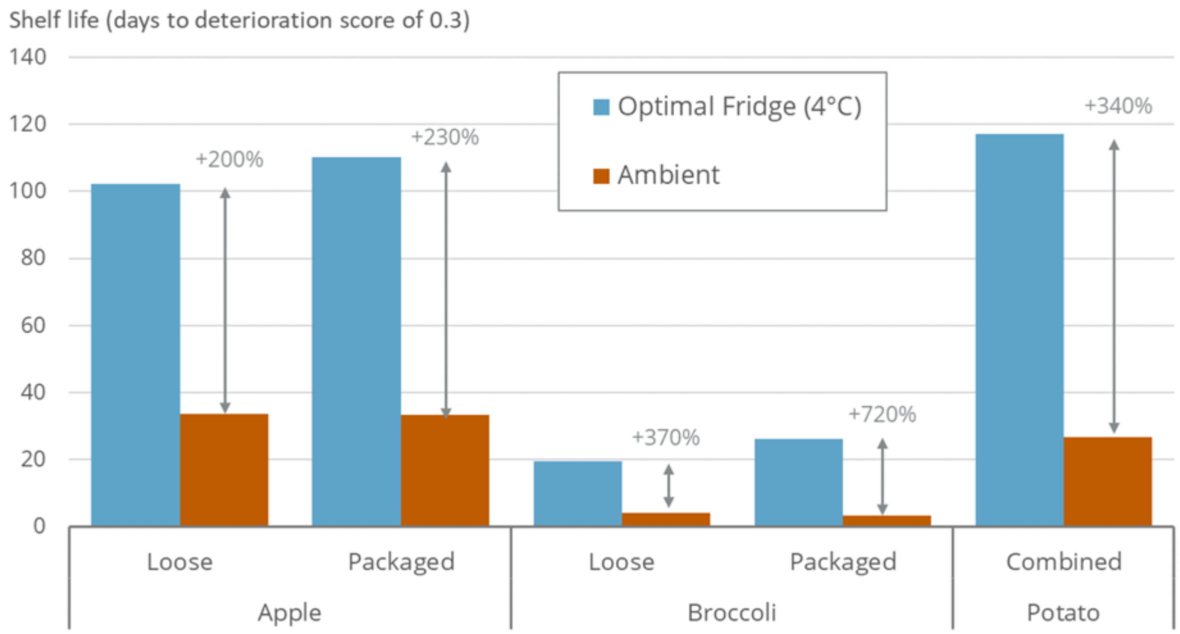

Table 35: Comparison for fridge (4°C) and ambient storage on shelf life, measured at a deterioration score of 0.3

Product	Condition	Impact of fridge storage on shelf life*
Apple	Loose	Increase of 69 days (+200%)
	Packaged	Increase of 77 days (+230%)
Broccoli	Loose	Increase of 15 days (+370%)
	Packaged	Increase of 23 days (+720%)
Potato	Average of all packaged and loose conditions	Increase of 90 days (+340%)**

**Considerable scatter in shelf-life results for potatoes stored in fridge. For this reason, an average of all four conditions (three packaged and one loose) was made. Values provided are approximate, but still demonstrate a clear shelf-life extension from storing potatoes in the fridge.

For all combinations of products and packaging conditions, storing the item in the fridge extended the shelf life. These results are not particularly surprising: shelf-life extension is, after all, the primary function of the fridge. However, the magnitude of the shelf-life extension was particularly marked. In all cases, the shelf life at least tripled when items were stored in the fridge compared to ambient conditions (+200% shelf life):

- For broccoli, the increased shelf life was approximately two to three weeks, depending on the presence of packaging.
- For potatoes, the increase in shelf life was almost two months for loose potatoes and over three months for packaged potatoes
- For apples, the increases were over two months. Therefore, apples stored in the fridge lasted more than three months. This has potentially important implications for HHFW: a shelf life of this magnitude, if realised, could reduce waste relating to apples not used in time to close to zero: essentially, just leaving waste relating to the few apples bought with pre-existing defects. However, there are important potential barriers to achieving this.

Increasing the proportion of the population storing apples in the fridge is not straightforward. Despite storage advice for apples present on most packaged apples (88% in November 2020[55]) and campaigns to this effect going back more than a decade, the proportion of the UK population storing their apples in the fridge remains around one-quarter.

Part of the issue may be a knowledge gap: around half the population are unaware that storing apples in the fridge extends their life[56]. Part may be related to habit, with storage location being determined by long-standing associations built up in childhood. In addition, fridge storage may not be necessary to achieve low levels of waste for some groups of the population (for example, those buying 'little and often' and who manage the 'stocks' of apples in their home well). Many people may have limited storage space in their fridge and prioritise other items for refrigeration over apples. Finally, storage location of apples may be down to personal preference: many people like the aesthetics of a fruit bowl and their fruit to be visible to encourage consumption. In addition, some people prefer to eat apples at ambient temperatures. Storing apples in the fridge can stop people achieving these goals.

Therefore, the challenge with apples is how to reduce food waste in a way that helps people meet these preferences and works for people in their own context. For many, storing apples in the fridge and using this 'reservoir' of apples to replenish their fruit bowl is one such solution. This allows the long shelf life of refrigerated apples to help cut food waste, whilst having apples on hand for ease of consumption.

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[55] *Consumer Attitudes to Food Waste and Food Packaging*, WRAP (2013): https://wrap.org.uk/sites/default/files/2020-12/Consumer-attitudes-to-food-waste-and-packaging.pdf

[56] *Life under Covid-19: Food waste attitudes and behaviours in 2020,* WRAP (2021): https://wrap.org.uk/sites/default/files/2021-02/WRAP-Life-under-Covid-19-Food-waste-attitudes-and-behaviours-in-2020.pdf

4.1.3 Fridge temperature, 4°C vs. 9°C

The previous section explored one aspect of temperature and shelf life. This next section investigates the impact on shelf life of two different fridge temperatures:

- 4°C – within the recommended range for fridge temperatures in the UK
- 9°C – a 'sub-optimal' fridge, above the recommended temperature range

Data on the actual temperatures achieved for the fridges for the duration of the experiments can be found in the sections for individual products within Chapter 3.0. The comparison of fridge temperatures was only carried out for products typically stored in the fridge. Results are presented separately for fresh-produce and dairy items due to differences in the analysis method stemming from different levels of scatter in the data

Figure 10: Comparison of shelf life for fridge temperatures (4°C vs 9°C) for different combinations of product and condition

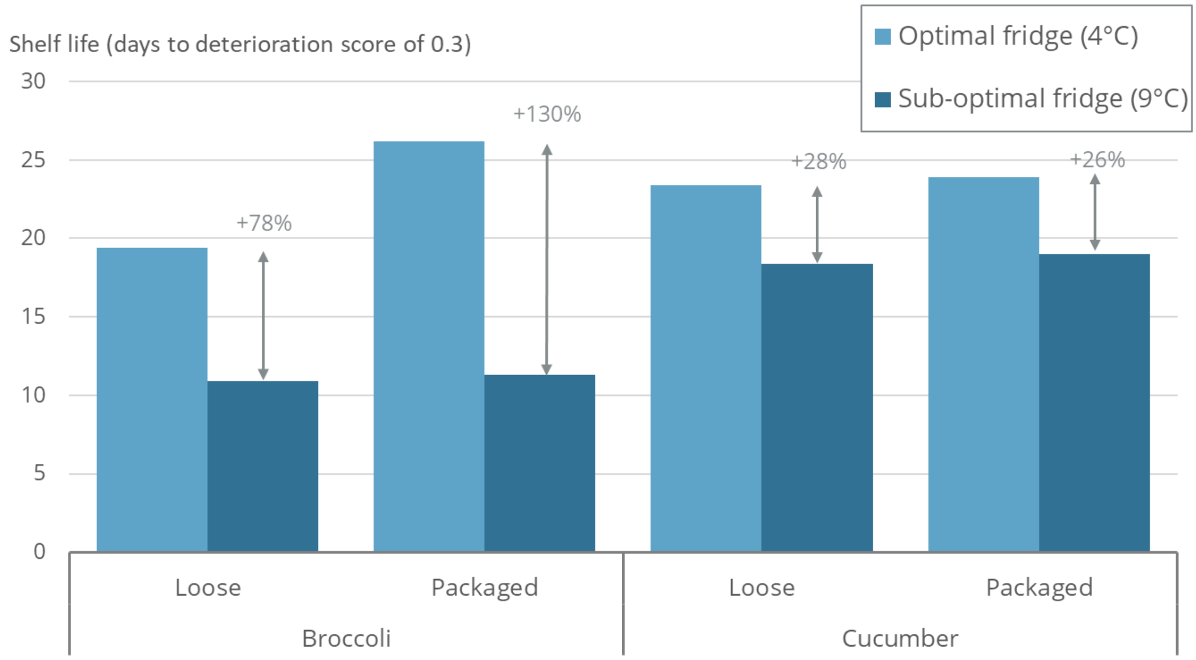


Table 36: Comparison of fridge temperatures (4°C vs 9°C) on shelf life for fresh produce items (comparison at deterioration score = 0.3)

Product	Condition	Impact of fridge temperature on shelf life
Broccoli	Loose	Increase of 8.5 days (+78%)
	Packaged	Increase of 15 days (+130%)
Cucumber	Loose	Increase of 5 days (+28%)
	Packaged	Increase of 5 days (+26%)

For the two vegetables tested, optimal refrigeration increases lifespan by a significant amount compared to the warmer, sub-optimal fridge (Table 36). For cucumber, it extends the shelf life by 5 days, adding approximately one-quarter to its life. For broccoli, it adds 8-15 days, depending on whether the broccoli is packaged. For packaged broccoli, it therefore more than doubles the shelf life.

Table 37: Comparison of fridge temperatures (4°C vs 9°C) on shelf life for dairy items, comparing transition from combined RAG rating of Amber to Red

Product	Notes	Impact of fridge temperature on shelf life (days, % change since bottling / packing)
Milk	Average over four different opening times	+1.5 days shelf life (+8%)
Natural yogurt	Average over three different opening times	+3.7 days shelf life (+12%)
Fruit yogurt	Average over three different opening times	+3.0 days shelf life (+12%)
Hard cheese	Average over four different conditions	+8.8 days shelf life (+19%)

For the dairy products tested, all four showed a marked increase in shelf life when stored in the optimal fridge (target temperature 4°C) compared to the sub-optimal fridge (target temperature of 9°C, Table 37). This is consistent with previous research findings, discussed in Section 1.2.2, and likely reflects slower growth of spoilage bacteria at lower temperatures.

For natural yogurt, there was considerable scatter in the results between the three conditions tested. For the other three products, there was modest scatter. This suggests that the averages presented in Table 37 are approximate. More data would have been needed to determine the exact shelf-life extension, or to allow for comparison between products.

4.1.4 Effects on product shelf life of when they are opened

The experiments conducted for dairy products allowed the shelf life to be compared for products that were opened on different dates but were otherwise stored in the same conditions. This section summarises these results.

For most of the dairy products, scater present in the data means it is only possible to provide qualitative observations concerning the effect of when items were opened. Quantitative differences due to the opening date are only possible for cheese due to lower levels of scatter observed in the results for this product.

For **milk**, there was little indication that the date of opening had a substantial impact on how long the milk lasted. Instead, the important factor in determining deterioration was the length of time since bottling. For example, for most conditions tested, milk went from Green to Amber ratings between the tests one and three days after the Use By date, irrespective of when it was opened.

This means that, for the conditions tested, the effective 'open life' of milk (the time between when it was opened and when it starts to deteriorate in quality) varied substantially. Milk opened on the day of purchase lasted much longer (around two weeks) after opening than milk opened close to the Use By date, which lasted around one week after opening. This variability potentially calls into question the use of statements on milk packaging such as 'once opened use within X days': when the milk was opened does not appear to be an important factor.

However, it should be noted that these results could be dependent on the exact conditions with regards to milk being left open. In this research, milk was subjected to 'temperature abuse' – left out of the fridge at 21°C and open for an hour on all test days.

In contrast to milk, results for both **natural and fruit yogurt** exhibited a trend in which items opened later lasted until a later date. It is difficult to quantify this trend exactly due to the scatter in the data. However, items opened on their Best Before date usually lasted several days longer than those opened on the day of purchase (16 days before the Best Before date for natural yogurt, nine days for fruit yogurt).

For cheese, the time of opening strongly influenced how long it lasted. A comparison was made between cheese opened: i) on the day of purchase and ii) the Best Before date, a gap of 62 days in these tests. For cheese opened on the Best Before date, it lasted until 73 days after purchase. In comparison, cheese opened on the day of purchase lasted 29 days after purchase. This represents a difference of 44 days: around a month and a half.

However, when assessed on how long cheese lasts after opening, cheese opened on its Best Before date lasted a further 11 days, compared to the cheese opened on its purchase date (29 days).

This difference between the results for milk and those for yogurt and cheese could be due to contamination. For yogurt, when samples were taken, the pots were opened and stirred with a clean (but not sterilised) spoon to simulate realistic conditions for large pots of yogurt that may be eaten over multiple days. Similarly, for cheese, each time a test was performed, there was an opportunity for air-borne microbes (e.g., mould spores) to land on the cheese. Furthermore, a clean (but non-sterile) knife was used to cut the cheese to obtain the test samples. In both cases, delaying the opening of the product also postponed deterioration of the product. The testing protocols for yogurt and cheese could have introduced more microbes than the protocol for milk, explaining these differences. It should also be noted that the laboratories in which the experiments were run could be cleaner than the average UK home, leading to lower levels of contamination.

4.1.5 Deterioration relative to BB date

The data collected in this study also allowed comparison of when items started to deteriorate relative to their Best Before (BB) date. This comparison used the sensory evaluation as described in Chapter 3.0.

The results in this section are specific to the products tested and the process used to set the date of the BB date. Different producers and retailers may set their date labels in different ways (or not have BB dates for some of these fresh-produce items), so these results cannot be taken as representative of the whole market.

For fresh produce items, the point in time when the linear fit to the data first deviated above zero was compared to the BB date on that particular product (Table 38).

Table 38: Comparison between the Best Before date and the first signs of deterioration for **fresh produce**. All dates are relative to the number of days after packing.

Product	Condition	BB date	Date of 1st sign of deterioration	Difference between BB date and 1st sign of deterioration
Apple	Ambient	14	17	3 days after the date (+21%)
	4°C		88	74 days after the date (+529%)
Banana	Ambient	6	7	1 day after the date (+17%)
Broccoli	Ambient	6	2	4 days before the date (-67%)
	9°C		7	1 day after the date (+17%)
	4°C		21	15 days after the date (+250%)
Cucumber*	9°C	17	17	0 days – no difference
	4°C		18	1 day after the date (+6%)
Potato**	Ambient	10	14	4 days after the date (+40%)
	4°C		30	20 days after the date (+200%)

**For Cucumber, there was no Best Before date on the product. Instead, the retailer had a 'product life', which has been used in the same way as the BB date in this table.*

***Results for packaged potatoes uses an average of the results for the three types of plastic packaging.*

Table 38 indicates that the first signs of deterioration were generally after the Best Before date for packaged fresh produce. There were two exceptions: broccoli stored in ambient conditions, which showed deterioration four days before the BB date, and cucumber refrigerated at 9°C, which started deteriorating on the BB date.

In all other cases, no deterioration was found until after the Best Before date. For items stored in sub-optimal conditions, this was often soon after the BB date (e.g., broccoli at 9°C, apples in ambient conditions). However, for some of the items stored in optimal conditions in the home, no signs of deterioration were seen until well after the BB date: 15 days afterwards for broccoli at 4°C and 74 days afterwards for apples when stored refrigerated at 4°C.

These results illustrate that deterioration is greatly affected by storage conditions in the home. Therefore, when stored in optimal conditions, the Best Before date could be much shorter than the actual quality life of the item. Although it is only a minority of the UK population whose disposal decisions are influenced by a date label for fresh-produce items, recent modelling indicates that this can be a substantial contributor to food waste for these items[57]. Given that there can be a substantial gap between the BB date and the first signs of deterioration, the presence of a BB date on fresh produce could be contributing greatly to HHFW in the UK.

4.2 Limitations and future research

This report has made a significant contribution to understanding how the shelf lives of fresh fruit, vegetable and dairy products are influenced by packaging, storage location and temperature, and when items were opened. However, the research has its limitations.

Firstly, the research only studies particular types of product: not all types of fresh produce and dairy products were studied. The reasoning behind these products' inclusion can be found in Section 2.1. However, this means that little can be said from this study of the influence of, for example, packaging on the shelf life of onions.

For three of the five fruit and vegetables (bananas, broccoli and cucumber), the UK market is dominated by one variety. However, for apples and potatoes, the market is made up of many varieties. There was only budget to study one variety of each within this project. Royal Gala and Estima, respectively, were chosen. Section 2.1 contains the rationale for these choices. Therefore, the above results relate to these varieties specifically. The shelf life of other apple and potato varieties may differ from these varieties, as could the influence of packaging and temperature on the shelf life. Future research would benefit from studies of this nature investigating other types of fruit and vegetables, as well as a wider range of varieties.

The study also looked at products from one particular time of year. Items were sourced in January and February 2021. In addition to the varieties on sale, supply chains vary throughout the year: produce comes from different countries, is stored in different ways and for different lengths of time. These results apply to the particular supply chains they come from. However, the studies were designed so that comparisons between conditions were valid. For example, all the apples sourced in this experiment had the same supply-chain characteristics, so any differences seen in shelf life were due to conditions they were subjected to during the experiments: the presence / absence of packaging and the storage location / temperature. Further studies would benefit from investigating whether the results found in this study are similar throughout the year for different supply-chain characteristics.

For the comparison of packaged and loose products, the decision had to be made of either using products *as sold* (i.e., loose and packaged items from UK supermarkets) or creating the loose variant by depackaging packaged items. The latter option was chosen, as discussed in Section 2.2. This allowed any differences in shelf life to be attributed to the packaging. However, there are differences between loose and packaged products: differences in specification and supply-chain characteristics. This research, therefore, cannot say anything about how these differences (in specification and supply-chain

[57] *See other two reports at: https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste*

characteristics) impact shelf life. Future studies could take a different approach, investigate these factors.

Occasionally, a lack of samples meant that on some occasions the frequency of testing and the number of samples tested had to be reduced. This led to fewer assessments on a given test day, increasing the scatter in the data, and reducing the ability of the results to identify differences between conditions. These occurrences were kept to a minimum and the analysis methods used were designed to overcome the scatter in the data (Section 2.3).

All results were subject to scatter, which, in some cases, did not allow conclusions to be drawn from differences between products. To check which differences between conditions were robust despite this scatter, Monte Carlo simulation was undertaken for key products / conditions (Appendix 3).

For dairy items, the number of replicates in the sensory evaluation and microbiological tests was low. This meant that the scatter in the data was high, and it was not possible to make firm conclusions. Future research can use this data to calculate the number of replicates required to measure differences between conditions and make stronger conclusions.

The temperature and humidity of the fridges and ambient conditions varied over time. In general, the temperatures of the fridges were acceptably close to the target temperature. For ambient conditions, we did not set a target temperature or humidity. Instead, the temperature and humidity of ambient conditions was logged. The results are a function of these ambient conditions: higher ambient temperatures would probably have led to shorter shelf lives and lower temperatures longer shelf lives. Future projects with larger budgets could control the ambient temperature and humidity and investigate a range of ambient conditions.

This area of research would also benefit from an updated comparison of the impacts of the increased energy requirements of running a fridge at the recommended temperature (rather than a higher temperature) with the impacts of less food waste resulting from these longer shelf lives.

Appendix 1: Analysis of sensory-evaluation data

The sensory-evaluation tests provided a large amount of data on the shelf life of products. This data required processing to make meaningful comparisons between conditions. This appendix provides details about this process. Due to the nature of the data, these processes were different for the dairy and the fresh-produce items.

In this Appendix, the following are covered:

- How the sensory evaluation results were converted to a deterioration score.
- How the line of best fit was constructed, including the different forms of line tested.

Calculation of a deterioration score: The sensory-evaluation data from a given test day for a product in a given condition consists of a number of Red, Amber and Green ratings: up to nine, for the case of three assessors each making an assessment on three replicates. These assessments may differ due to different conditions of the three replicate samples, and differences in how each assessor grades a given sample. It is therefore useful to calculate an 'average' assessment to allow further analysis and comparison between conditions. This is the 'deterioration score'.

The 'scores' given to each assessment are:

- Green = 0
- Amber = 0.5
- Red = 1

The average score is then calculated for all assessments on that day:

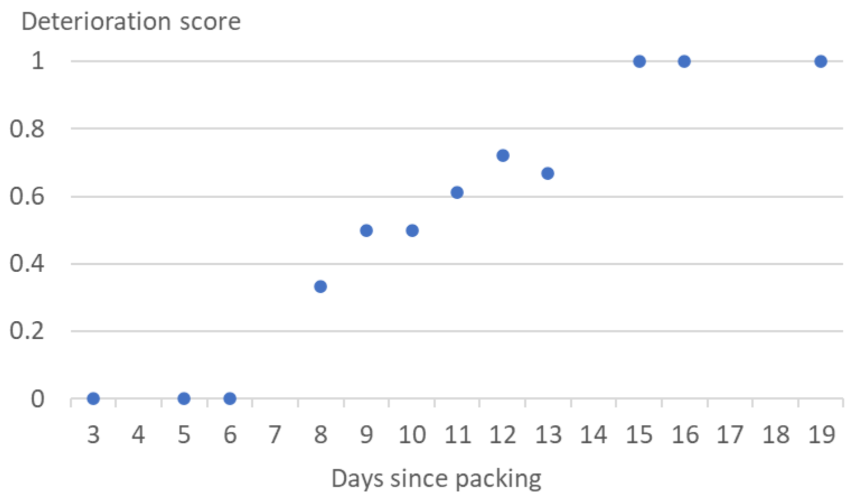
$$\text{Deterioration score} = \frac{\text{No. of greens} \times 0 + \text{No. of ambers} \times 0.5 + \text{No. of reds} \times 1}{\text{Total number of assessments}}$$

For example, if on a given day of testing, nine sensory assessments were made – one green, five amber and three red – this would give a deterioration score of 0.61 (to two significant figures):

$$\text{Deterioration score} = \frac{(1 \times 0) + (5 \times 0.5) + (3 \times 1)}{(1 + 5 + 3)} = \frac{5.5}{9} \cong 0.61$$

Scores are calculated for each product in each condition for each test day. These scores are then plotted over time. As can be seen in the example in Figure A1, there is some scatter in this data. For instance, between days 12 and 13, the deterioration score decreases, against the general trend.

Figure A1: Example of deterioration scores for loose bananas in ambient conditions

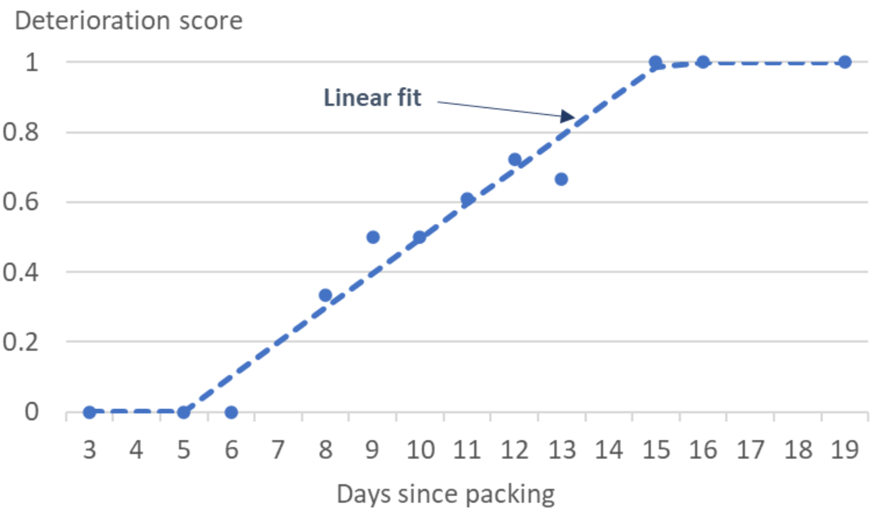


Calculating a line of best fit: To overcome this problem, a line of best fit can be calculated for sensory-evaluation data. This helps to understand the general trend in deterioration, despite the 'noise' in the data. Three different types of best fit line were tried to see which best fitted the deterioration-score data.

These are:

A linear fit: the line is horizontal up to the on onset of deterioration, then increases linearly until it reaches 1, at which point it becomes horizontal again (Figure A2).

Figure A2: Example of a linear fit using the deterioration scores from loose bananas kept at ambient (21°C) temperature.



Line

Linear fit equation:

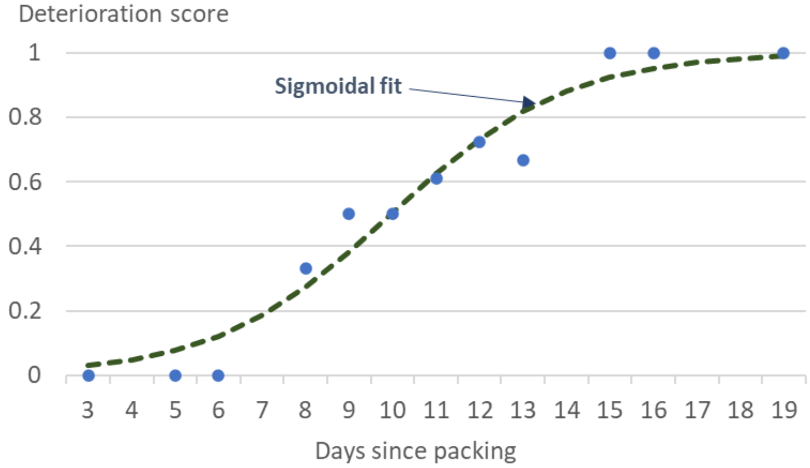
=IF(test.date<estimated.deterioration.start.date,0),IF(test.date > estimated.deterioration.end.date,1,(test.date - estimated.deterioration.start.date)/(estimated.deterioration.end.date - estimated.deterioration.start.date))

Test.date is the test day. In addition, there are two adjustable parameters, adjusted to maximise the fit between the fitted line and the data:

- estimated.deterioration.start.date being the estimated point at which deterioration is first observed, and
- estimated.deterioration.end.date being the estimated point at which the deterioration score is 1

The second curve to be fitted was the **sigmoidal curve** (Figure A3).

Figure A3: Example of a sigmoidal curve using the deterioration scores from loose bananas kept at ambient (21°C) temperature.



Sigmoidal curve equation:

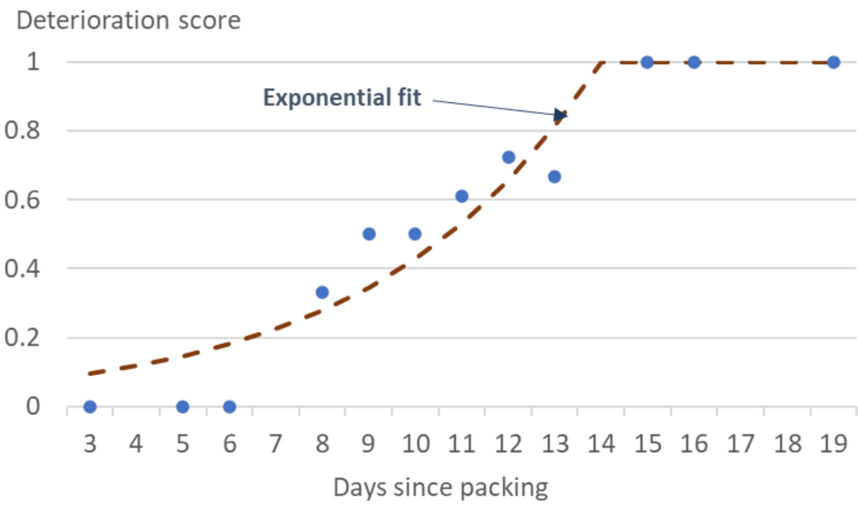
=1/(1+EXP(-gradient*(test.date – estimated.deterioration.mid.point)))

This also has two adjustable parameters:

- 'gradient' being related to the gradient of the line at the mid-point, and
- estimated.deterioration.mid.point being the estaimted point at which the deterioration score is 0.5

The final curve to be fitted was the **exponential curve** (Figure A4):

Figure A4: Example of an exponential curve using the deterioration scores from loose bananas kept at ambient (21°C) temperature.



The equation for the exponential fit is:

=IF(EXP((test.date- estimated.deterioration.end.date)/ scaling factor)<1,EXP((test.date-estimated.deterioration.end.date)/ scaling.factor),1)

Which, like the other two lines / curves, has two adjustable parameters:

- scaling.factor being inversely related to the gradient of the function, and
- estimated.deterioration.end.date being the point at which the deterioration score reaches one

The dates were converted into numerical values for the purposes of the calculations. To fit each of the curves to the data points, the square of differences between the fitted deterioration score and measured deterioration score was calculated for each test day. The sum of these differences was then minimized by varying the adjustable parameters using the 'solver' function within Microsoft Excel.

The accuracy of the fit was determined by the value of the deviation, which was calculated using the square of differences method in the previous paragraph. Through testing it was decided that the linear fit would be used as the line of best fit to estimate the deterioration score. The linear fit was chosen because in testing for bananas and cucumbers it was found that all three had similar accuracy. The linear fit was chosen for simplicity and because, in the researchers view, it would be more adaptable to a wider range of data. The linear fit was then used for all products, to keep consistency in the type of analysis applied to the deterioration scores for each of the products.

A further advantage of creating a deterioration score and having a best-fit line is the point at which a product hits a given level of deterioration can be determined, without the scatter in the data near this point unduly affecting the results. Key comparisons were made at a deterioration score of 0.3, midway between the point where the line of best fit first deviates from zero to a value of 0.6. This value of 0.6 is the point where the combined RAG rating (Section 2.3) goes from Amber to Red, or from acceptable to unacceptable. Therefore, a value of 0.3 represents a mid-point for those using their senses to determine when to when to dispose of items: halfway between the first signs of deterioration and the point when the majority of people would reject the item.

For fresh-produce items, this is preferable to using the Combined RAG ratings (Section 2.3), as there are situations when the Combined RAG ratings move 'backwards', i.e., from Amber back to Green, or from Red back to Amber. This is the result of the scatter within the data, and the deterioration score / best-fit line method overcomes this. This is why deterioration scores are used for fresh-produce items. This data is shown in Tables A1 to A5 for the five fresh-produce items tested.

Table A1: Number of days since *packing** taken to reach specific stages of deterioration for **apples** in different conditions

Deterioration stage	Loose Ambient	Packaged Ambient	Loose 4°C	Packaged 4°C
Linear fit moves above 0	21	17	67	88
Linear fit reaches 0.3	34	33	102	110
Linear fit reaches 0.6	46	50	137	132
Overall rating first moves to Amber	33	28	84	126
Overall rating first moves to Red	49	42	106	106

*Packing for these apples occurred two days before they would have been available for purchase in stores

Table A2: Number of days *since packing** taken to reach specific stages of deterioration for **bananas** in ambient conditions

Deterioration stage	Loose Ambient	Packaged Ambient
Linear fit moves above 0	5.0	6.8
Linear fit reaches 0.3	8.0	9.9
Linear fit reaches 0.6	11.1	12.9
Overall rating first moves to Amber	7	7
Overall rating first moves to Red	11	14

*Packing for these bananas occurred two days before they would have been available for purchase in stores

Table A3: Number of days *since packing** taken to reach specific stages of deterioration for **broccoli** stored in a range of conditions

Deterioration stage	Loose Ambient	Shrink-wrapped Ambient	Loose 9°C	Shrink-wrapped 9°C	Loose 4°C	Shrink-wrapped 4°C
Linear fit moves above 0	2.0	2.0	5.2	7.3	13.9	21.3
Linear fit reaches 0.3	4.1	3.2	10.9	11.3	19.4	26.2
Linear fit reaches 0.6	6.2	4.4	16.6	15.3	24.9	31.0
Overall rating first moves to Amber	n/a	n/a	7	11	9	27
Overall rating first moves to Red	6	6	20	18	27	31

*Packing for this broccoli occurred approximately two days before they would have been available for purchase in stores

Table A4: Number of days *since packing** taken to reach specific stages of deterioration for **cucumber** stored in a range of conditions

Deterioration stage	Loose 9°C	Shrink-wrapped 9°C	Loose 4°C	Shrink-wrapped 4°C
Linear fit moves above 0	16.3	17.1	16.3	18.3
Linear fit reaches 0.3	18.4	19.0	23.4	23.9
Linear fit reaches 0.6	20.5	20.9	30.5	29.5
Overall rating first moves to Amber	17	18	21	21
Overall rating first moves to Red	21	21	31	31

*Packing for these cucumbers occurred approximately 11 days before they would have been available for purchase in stores

Table A5: Number of days *since packing** taken to reach specific stages of deterioration for **potatoes** stored in **ambient** conditions. PE = polyethylene.

Deterioration stage	PE bag largely transparent	PE bag 70% whitewash	PE bag opaque	Packaged (average)	Loose
Linear fit moves above 0	16.9	13.0	12.7	**14.2**	**15.1**
Linear fit reaches 0.3	27.8	27.2	25.2	**26.7**	**26.9**
Linear fit reaches 0.6	38.8	41.3	37.6	**39.3**	**38.6**
Overall rating first moves to Amber	24	24	24	**24.0**	**24**
Overall rating first moves to Red	41	41	34	**38.7**	**41**

Table A6: Number of days *since packing** taken to reach specific stages of deterioration for **potatoes** stored in **refrigerated** conditions. PE = polyethylene.

Deterioration stage	PE bag largely transparent	PE bag 70% whitewash	PE bag opaque	Packaged (average)	Loose
Linear fit moves above 0	39.6	23.0	27.5	**30.0**	**56.2**
Linear fit reaches 0.3	97.8	163.0	124.4	**128.4**	**83.6**
Linear fit reaches 0.6	156.0	303.0	221.4	**226.8**	**111.0**
Overall rating first moves to Amber	72	79	72	**74**	**72**
Overall rating first moves to Red	NA	NA	NA	NA	**116**

*Packing for these potatoes occurred approximately 2 days before they would have been available for purchase in stores

Analysis of dairy sensory-evaluation data

The scatter in the dairy results was more pronounced than for fresh-produce items. This was due to fewer replicates being assessed on each test day. The consequence of this was that the fitting of a straight line to the data – as described above for fresh produce – did not work well for dairy products. In particular, the parameters for the lines of best fit were highly susceptible to small changes in the results, as investigated via Monte Carlo simulations. For this reason, a different approach to analysing the data was required.

The main method was to use the 'Combined RAG' rating of a product on a given test day (Section 2.3). Comparison is made where the rating goes from Amber to Red, as this reflects where the product changes from being 'acceptable to most of the population' (Amber) to 'unacceptable to most' (Red). In particular, the comparison focuses on the last test day before the first overall 'Red' assessment: after this point, there was at least one test day when the product was assessed as unacceptable (i.e., Red).

In all cases, checks were carried out to ensure that the scatter in the data did not affect the conclusions drawn. For instance, for some combinations of product and test condition, there were overall 'Red' assessments that appeared spuriously early (e.g., subsequent test days were rated Green or Amber immediately after a Red). These instances are few but are noted in the text.

Appendix 2: Quality matrices and testing frequency

A quality matrix was used to classify each sample as either Red, Amber or Green (RAG) for each of its sensory properties: appearance, aroma, texture, and taste. The proportion of RAG samples in each batch was then converted into a deterioration score.

- Green = Optimal Product Quality with minimal defect
- Amber = Sub-Optimal Quality, 'The majority of consumers would still consume'
- Red = Failed Product Quality - 'Deemed inedible by the majority of consumers'

In the main body of this report the deterioration scores – and the line of best fit – are presented for each product (Chapter 3) and an example quality matrix is provided in the methodology chapter for apples (Chapter 2). However, each product was evaluated using a slightly different quality descriptors that were tailored to the specific properties of that product. These are provided in the following pages.

As well as the quality matrix, the frequency of product testing is also provided. Throughout the sensory evaluation, samples were tested at a set frequency - usually about every 2 or 3 days - until most samples had started to show signs of deterioration. Once most samples in the batch had started to deteriorate, the sample testing frequency was increased - usually to every day.

Apples: In total, 193 samples of Gala apples were tested.

Table A7: Quality matrix used in the sensory evaluation of apples.

Sensory property	Green	Amber	Red
Appearance	Acceptable fruit colour and shape. Acceptable russeting. Punctures are healed where present. No shrivel.	Partial shrivelling to the apple skin which could be removed before consumption. Some minor browning or bruising to the exterior. Some slight external discolouration. Some internal discolouration <10%.	Significant discoloration or misshape. Fresh wounds, significant bruising. Red rot spots greater >5%. Significantly pale colour. Significant and severe shrivelling to skin, beyond salvage.
Aroma	Fresh produce aroma, sweet and acidic aroma on consumption	Loss of acidic and sweet aroma. No rotting aroma.	Any off taints or rotting aroma.
Texture	Firm, with minimal bruising when handled. Crisp texture with slight resistance to bite. Some foam-like texture is acceptable on consumption.	Soft exterior. Minimal crisp on consumption. Foamy mouthfeel but not completely dry. Slight resistance to bite. Holds shape and structure.	Soft and easily bruised. Little to no resistance to bite on consumption. Dry mouth feel. Wrinkled skin becomes easily broken and soggy.
Taste	Sweet and acidic. Typical of a fresh produce.	Loss of some sweetness and acidity, not completely absent. Some bitter or tasteless areas are acceptable where it does not represent the entire sample.	Off flavours, no sweetness or complete lack of acidity.

Bananas - In total, 193 samples of banana were tested.

Table A8: Quality matrix used in the sensory evaluation of bananas.

Sensory property	Green	Amber	Red
Appearance	Green or Yellow at colour stages 1-4. Bruising and browning to exterior is on appx. 30% of the sample or less. Pulp ideally has no browning or bruising. <10% of bruising or browning in pulp is still acceptable for optimal product quality.	Colour stage 5-6. Yellow with significant browning to the banana's peel. >30% browning, bruising or scarring present. Pulp starting to brown and bruise in >10% of the sample.	Colour stage 7 or worse. Significant browning, bruising or scarring to >40% of the peel & pulp.
Aroma	Natural starchy & earthy smell to greener bananas. On ripening, banana should have a sweeter aroma which increases in intensity on peeling. Banana should be free from off taints. Strong smelling esters like 'isoamyl acetate' suggest the banana is at a ripe & would still be considered optimal product quality.	Ester aroma is very strong and fills air surrounding the sampling arena. Some difficulty in distinguishing rot vs strong sweet aroma.	Fermented or mouldy aroma. Mildew aroma from pulp.
Texture	Firm and rigid texture to the exterior, softening slightly through ripening stages. Free from soft spots >10% in size. Dry flesh, free from excessive moisture. Soft & tender pulp.	Softening to stalk, peel & pulp. 10-30% soft / mushiness to peel & pulp. Dry flesh, free from excessive moisture.	Overly soft and tender peel & pulp with wet spots to peel or flesh. Overly dry stalk. Pulp does not hold shape when removed from peel.
Taste	Pulp is slightly bitter & astringent in underripe bananas. On ripening, taste should be sweet with a likeness to honey, cloves, rum, syrup or all of the above.	Strong sweetness with notes of vanilla & rum becoming more prominent. Some areas of banana starting to have off mouldy or rotten taste = <10% of sample.	Rotten or mouldy taste

Broccoli - In total, 210 samples of calabrese broccoli were tested.

Table A9: Quality matrix used in the sensory evaluation of broccoli.

Sensory property	Green	Amber	Red
Appearance	< 5% of heads per outer with slight limpness & butts with minor discolouration. Free from rots & mould growth	< 10% of heads with slight limpness & butts with some discolouration	> 10% of heads with limpness & butts discoloured. Rots & mould growth present
Aroma	Fresh, typical broccoli & earthy odour	Very slight off odour, anticipation that this would disappear if cooked.	Stale or off odours, foreign taints
Texture	Heads textured & not mushy, stems slightly crisp	Slight mushiness in the head & slight toughness in the stalk. Slight wilting of the head or stock	Soft & mushy or stems tough & woody. Significantly wet or mushy on >10% of the sample.
Taste	N / A	N / A	N / A

Cucumber - In total, 193 samples of slicing cucumber were tested.

Table A10: Quality matrix used in the sensory evaluation of cucumber.

Sensory property	Green	Amber	Red
Appearance	<2% affected by rots. Ideally all free from rot. Greenish-white flesh.	<5% affected by rots. Ideally all free from rot. Customer could easily remove rot.	>5% affected by rots. Ideally all free from rot. Significant darkening browning or yellowing seeds. Visible mould
Aroma	Natural, fresh.	Parts of cucumber with a musty or stale aroma, easily removable.	Musty, stale aroma over entire cucumber.
Texture	Crisp and juicy. When fresh, cucumbers should feel firm.	Slightly soft, skin easily punctured. Soft spots dotted around the sample. <10-15% of the entire sample. Drying around open end of cucumber over life.	Excessively Soft or dry. Soggy
Taste	Clean, cool & fresh with a slight sweetness.	Reduced sweet & fresh flavour, free from sour or bitter notes.	Musty, earthy, sour, astringent. Bitter or off flavours / taints detected.

Potatoes - In total, 352 samples of Estima potatoes were tested.

Table A11: Quality matrix used in the sensory evaluation of potatoes.

Sensory property	Green	Amber	Red
Appearance	Uniform in colour, typical of variety with no major defects. Minor skin blemish, minor bruising removed in 3 peels. Minor mis-shapes present. Typical in size for baking potatoes.	Some minor defects (rot, greening or sprouting). Defects would not greatly impact post-cook quality if the product was peeled & cooked before being consume.	Excessive major defects (Rots, Major Greens, Major Damage) Poor shape with secondary growth evident. Excessive Sprouting or greening to the potato. Definitely would not cook and consume.
Aroma	Earthy	Slight pungent or sour smell.	Pungent, 'Fish or Vinegar' like aroma. mouldy or rotten aroma.
Texture	The surface of the tuber should be firm but may have a slight give	The surface of the tuber is soft and spongy.	The surface of the tuber is extremely soft and spongy and collapses under any pressure.
Taste	N / A	N / A	N / A

Cheese - In total, 120 samples of 400g mild cheddar cheese were tested.

Table A12: Quality matrix used in the sensory evaluation of cheddar cheese.

Sensory property	Green	Amber	Red
Appearance	Very pale yellow in colour. Slightly open texture and fractures will be visible.	Some visible moisture and or with drying edges. Visible green or white mould on < 5% of the sample.	Excessive moisture. Open or crumbly. Loss of pale yellow colour, darker yellow or brown colour. Visible green or white mould on >5% of the sample.
Aroma	Subtle, Sweet, Lactic Aroma, Clean	Some uncharacteristic aromas to small areas of the sample.	Uncharacteristic aromas, sour, cowy notes, off aroma.
Taste	Clean, Milky, Slight Sweet with low level acid notes.	Savoury and creamy notes with a slightly dry mouth feel. Less complexity to the flavour.	The cheese should not exhibit sour, sulphide, fermented, metallic unclean or any other offensive or harsh flavours or taints.

Texture	Smooth firm bodied. Closed texture, Melts in the mouth, doesn't fragment, slightly elastic, chewable.	Some dry spots and edges crumbing away. Easily removable and would not deem entire sample inedible.	Dry, crumbly or overly weak and pasty.

Milk - In total, 120 samples of 2-pint semi-skimmed milk were tested.

Table A13: Quality matrix used in the sensory evaluation of milk.

Sensory property	Green	Amber	Red
Appearance	Off white in colour. Uniform colour. Glossy sheen, white in appearance. Shiny and opaque.	Crust forming at the top of the milk bottle. Some loss to glossy colour.	Not uniform white free flowing liquid. Any separation or discolouration. Overly waterly in appearance. Any visible lumps or foreign body present.
Aroma	Fresh, clean, milky aroma. Free from stale or off odours and taints. During latter part of shelf life product may lose some degree of freshness.	Some off aroma to the top of the bottle	Rancid off notes evident. Any foreign aroma.
Taste	Sweet and creamy flavour. Slightly creamier than skimmed milk. Typical of fresh semi-skimmed milk. Free from taints. No rancid or off flavours present.	Loss of creaminess. No off flavour, Uncertainty around freshness on consumption.	Rancid and off flavours present. Taints present. Rancid off notes evident. Any foreign flavour. No creaminess evident.
Texture	Free flowing liquid with texture slightly creamy texture but not as thick as whole milk. Free from separation.	Texture turning similar to full fat milk.	Any lumps or curdling

Fruit yogurt - In total, 120 samples of 500g strawberry yogurt were tested.

Table A14: Quality matrix used in the sensory evaluation of fruit yogurt.

Sensory property	Green	Amber	Red
Appearance	Smooth, slightly mottled, glossy pale white yogurt with absence of inclusions or particles. Approximately ½ teaspoon of whey on yogurt surface is acceptable up to 1 week into life, thereafter up to 2 teaspoons of whey could be present. Glossy with strawberry fibres present	appx. 2 tsps of whey visible. Loss of glossy sheen. 1-2 mould spots on less than 5% of sample.	Texture looks curdled or open & is not smooth. The appearance is matt, and no longer glossy. Greater than 2-3 tsps. of whey present during life. Visible mould spots on greater than 5% of the surface.
Aroma	Slight dairy, lactic, creamy aroma. This is stronger when the lid is first removed. Mild lactic acidity. Sweet & Fruity aroma from strawberry.	Loss of fresh aroma, very slight taint noticed.	Confirmed taint. Off dairy notes. Aromas not representative of natural yogurt. Rotten fruit aroma.
Taste	The yogurt is fresh, clean creamy with a slightly sharp acidic back flavour. There are some mild and creamy cheese / dairy notes present. It is very slightly drying in the mouth. Sweet, creamy, fresh strawberry.	Loss of fruit flavour.	Off dairy. Flavours not Representative of natural yogurt. Overly drying. Off or rotten flavour to fruit.
Texture	It is smooth in consistency with no particles (other than strawberry pieces). It has a slightly creamy texture and dissolves quickly in the mouth, but does not leave a coating. It has a thick but pourable texture. A spoon will stand upright in the pot. When spooned onto a plate, some shape will remain and when a spoon is dragged through the yogurt there will be a clear divide.	Yogurt is starting to thin. A spoon struggles to stand up in the yogurt, and when poured onto a plate the yogurt will start to flow in clumps. When a spoon is dragged through the yogurt the divide will not remain for longer than 20 seconds	Yogurt is thin, or granulated (sandy like). Foreign body present. A spoon does not stand up in the yogurt, and when poured onto a plate the yogurt will flow and when a spoon is dragged through the yogurt the divide will not remain for longer than 10 seconds

Natural yogurt - In total, 120 samples of 500g natural yogurt were tested.

Table A15: Quality matrix used in the sensory evaluation of natural yogurt.

Sensory property	Green	Amber	Red
Appearance	Smooth, slightly mottled, glossy pale white yogurt with absence of inclusions or particles. Approximately ½ teaspoon of whey on yogurt surface is acceptable up to 1 week into life, thereafter up to 2 teaspoons of whey could be present.	appx. 2 tsps of whey visible. Loss of glossy sheen. 1-2 mould spots on less than 5% of sample.	Texture looks curdled or open & is not smooth. The appearance is matt, and no longer glossy. Greater than 2-3 tsps. of whey present during life. Visible mould spots on greater than 5% of the surface.
Aroma	Slight dairy, lactic, creamy aroma. This is stronger when the lid is first removed. Mild lactic acidity.	Loss of fresh aroma, very slight taint noticed.	Confirmed taint. Off dairy notes. Aromas not representative of natural yogurt.
Taste	The yogurt is fresh, clean creamy with a slightly sharp acidic back flavour. There are some mild and creamy cheese / dairy notes present. It is very slightly drying in the mouth.	Loss of creaminess, watery and slightly bitter.	Off dairy. Flavours not Representative of natural yogurt. Overly drying.
Texture	It is smooth in consistency with no particles. It has a slightly creamy texture and dissolves quickly in the mouth, but does not leave a coating. It has a thick but pourable texture. A spoon will stand upright in the pot. When spooned onto a plate, some shape will remain and when a spoon is dragged through the yogurt there will be a clear divide.	Yogurt is starting to thin. A spoon struggles to stand up in the yogurt, and when poured onto a plate the yogurt will start to flow in clumps. When a spoon is dragged through the yogurt the divide will not remain for longer than 20 seconds	Yogurt is thin, or granulated (sandy like). Foreign body present. A spoon does not stand up in the yogurt, and when poured onto a plate the yogurt will flow and when a spoon I dragged through the yogurt the divide will not remain for longer than 10 seconds

Appendix 3: Understanding uncertainty using a Monte Carlo simulation

The purpose of the Monte Carlo analysis reported in this section is to understand the uncertainty in the results given the scatter in the sensory-evaluation results. In particular, this analysis investigates the sensitivity of the calculated shelf life, at a deterioration score of 0.3, to this scatter.

For each set of conditions / products investigated, the following steps were undertaken:

1. Determine the approximate scatter likely for individual data-points. This is calculated from the average deviation between the data points and the line of best fit (Figure A3.1).
2. Create a distribution around each data-point of the likely results that could have been obtained had the measurement been repeated, using the average deviation calculated in stage 1 (Figure A3.2)
3. For an individual run of the Monte Carlo simulation, create a set of data by sampling from these distributions.
4. For each of these sets of data, determine the line of best fit according to the method in Appendix 1.
5. Determine the time at which the line of best fit reached the key deterioration score of 0.3 (as outlined in Section 2.3).
6. Repeat 100 times to determine the uncertainty in the results emanating from the scatter in the data.

Figure A3.1: Illustration of the deviation (black lines) from the line of best fit (dashed blue line), for the sample of loose bananas

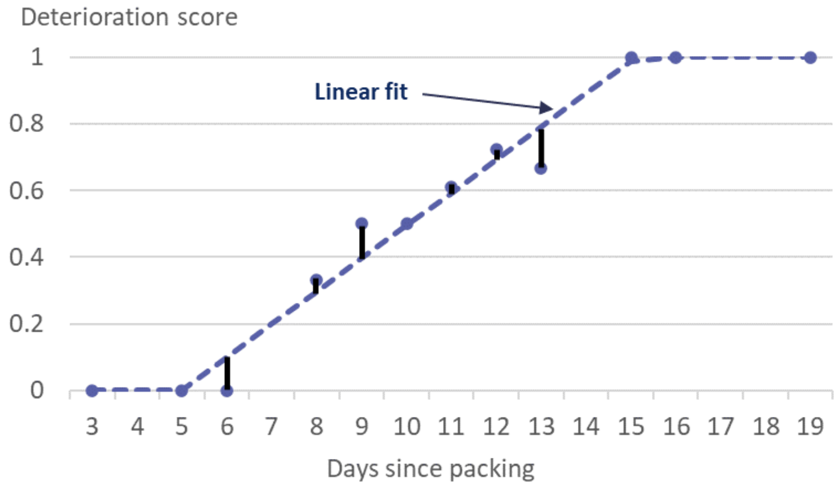
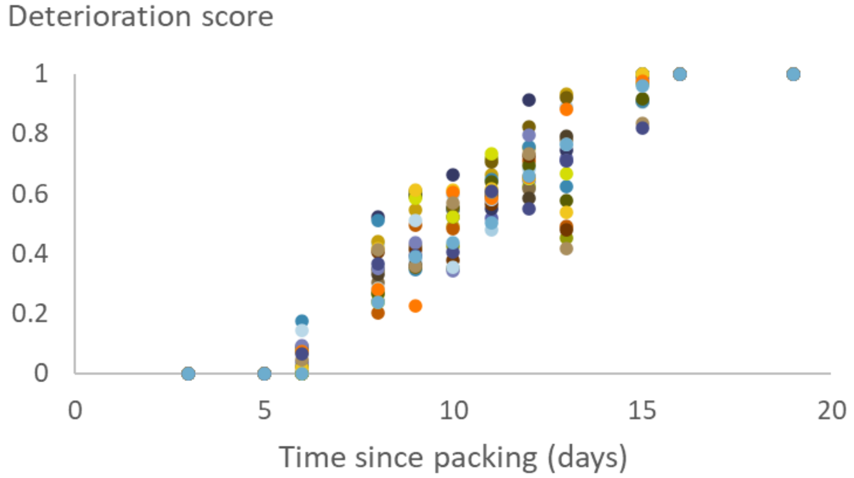


Figure A3.2: Illustration of the distributions around each data point, from which the Monte Carlo method samples for each run (for loose bananas)



Monte Carlo simulation was timing consuming. Therefore, it was only applied to fresh-produce items. In addition, it was used for situations where it was not clear whether the difference between conditions was the result of scatter or a real difference. These conditions are listed below, with the results presented in this appendix:

- **Apples:** the two refrigerated conditions, comparing packaged and loose
- **Bananas:** both conditions, comparing packaged and loose
- **Broccoli:** all four refrigerated conditions, comparing the two fridge temperatures, as well the effects of packaging
- **Cucumbers:** all four conditions, comparing the two fridge temperatures, as well the effects of packaging
- **Potatoes:** the four refrigerated conditions, to understand the effect of packaging and its transparency / opacity

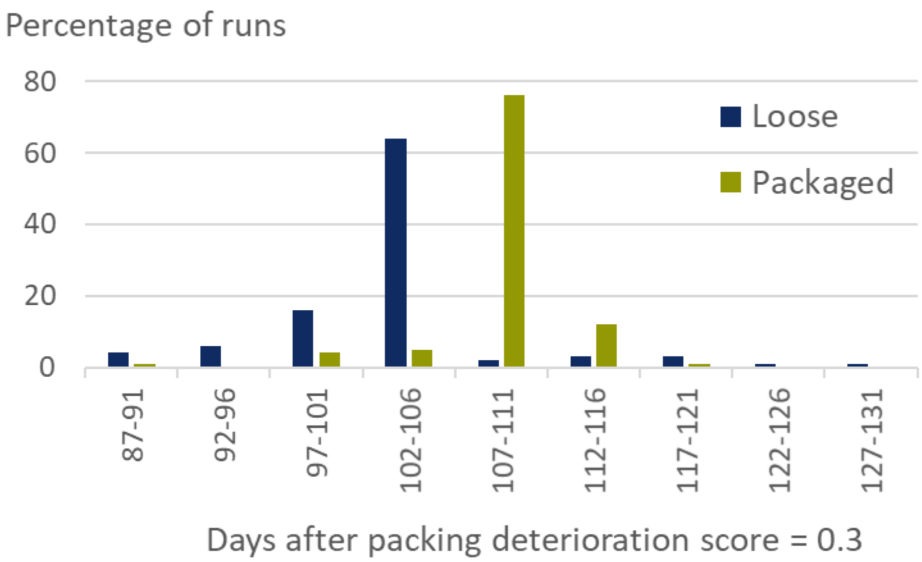
Apples: For the sensory-evaluation results for apples (Section 3.1), some of the results were clear-cut:

- For apples stored in ambient conditions, no measurable difference in the shelf life of packaged versus loose apples
- Refrigerating apples, rather than storing them in ambient conditions, has a clear and pronounced shelf-life extension.

However, the difference between packaged and loose apples stored in the fridge was relatively small: a difference of 8 days or around 8%. Figure A3.3 shows the results of the Monte Carlo simulation for these two conditions.

The results show relatively broad distributions (given that each bar represents data for 5 days). There is a reasonable degree of overlap between these two distributions. The 100 runs for each condition were paired up and comparing to see which had the longest shelf life. In 89 of the comparisons, the packaged condition had the longest shelf life; in the other 11 comparisons, the loose variant had the longest shelf life. This approximately equates to a *p*-value of 0.11.

Figure A3.3: Results of Monte Carlo simulation for **refrigerated apples**: distribution of when the line of best fit reached deterioration score of 0.3 for 100 separate runs



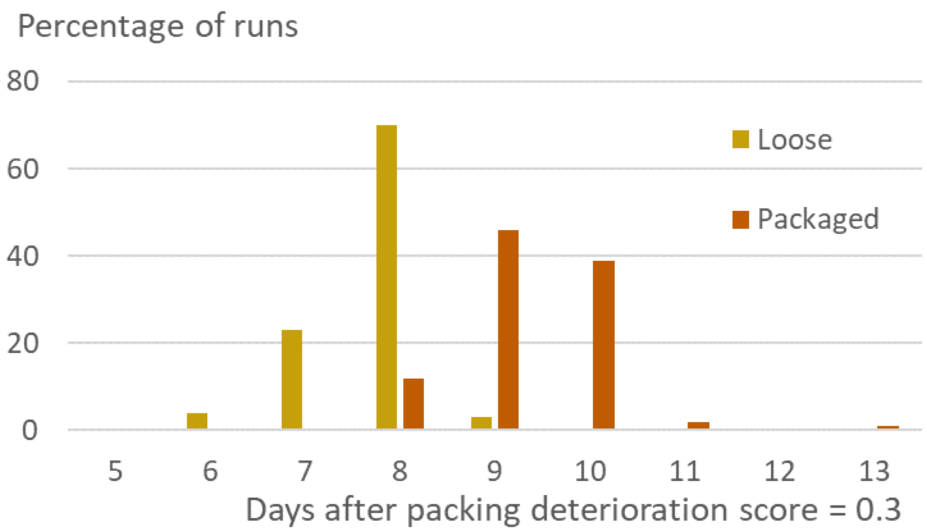
In addition, the lines of best fit for these two conditions cross one another (Figure 1), suggesting that the result of this analysis is highly dependent on the deterioration score at which the comparison is made.

For these two reasons, the evidence is inconclusive as to whether loose or packaged apples last longest in refrigerated conditions. Therefore, it is recommended not to present the measured difference as a real difference due to this lack of certainty emanating from scatter in the data. More data would be required to determine any difference between these two conditions.

Bananas: For bananas, the key result appears to be that packaged bananas last longer than loose bananas in ambient conditions (Section 3.2). This section explores whether this conclusion can be made with confidence.

Figure A3.4 illustrates the results of the Monte Carlo simulation for bananas. Two distributions are shown, each illustrating when, for 100 different runs of simulation, the line of best fit passes 0.3. The means of the two distributions are separated by 1.8 days, with only a minor degree of overlap between the distributions.

Figure A3.4: Results of Monte Carlo simulation for **bananas**: distribution of when the line of best fit reached deterioration score of 0.3 for 100 separate runs



To determine whether there is sufficient evidence from this data to conclude that these packaged bananas last longer than the loose equivalent, a pairwise comparison was made between the 100 runs for each condition. In all 100 comparisons, the packaged bananas lasted longer. 95 of these runs were within 1.6 days of the mean. Therefore, the approximate 95% confidence interval around the average difference in shelf life could be given as 1.8 days ± 1.6 days.

This suggests that, from this evidence, it is highly likely that the packaged bananas tested had a longer shelf life than loose bananas. However, the magnitude of the difference is much less certain, with the 95% confidence interval ranging from approximately 0.2 days to 3.4 days.

Broccoli: Monte Carlo simulations were run for all refrigerated broccoli conditions. This is to check the main findings found for this product (Section 3.3), which were that:

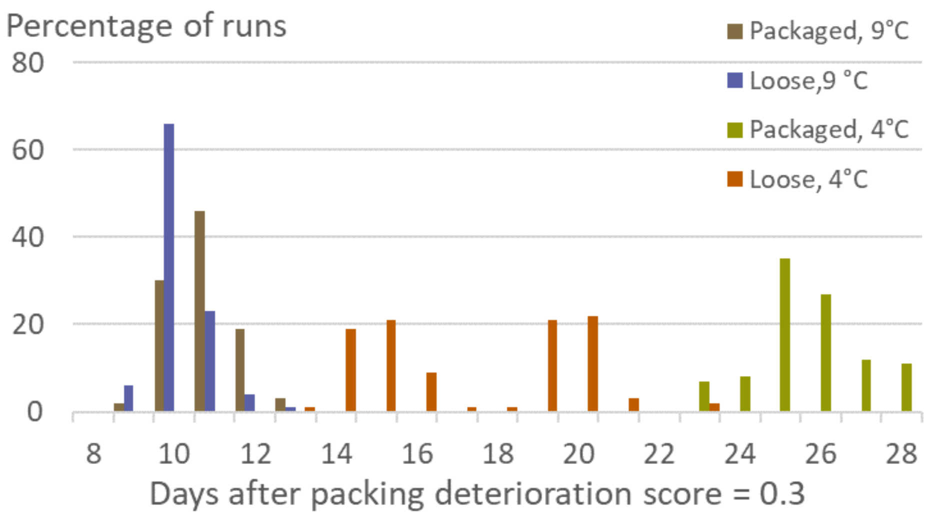
- There was no difference in shelf life for packaged and loose broccoli at 9°C
- Broccoli refrigerated at 4°C lasted longer than broccoli refrigerated at 9°C, for both packaged and loose conditions
- For broccoli refrigerated at 4°C, packaged broccoli lasted longer than loose.

Figure A3.5 suggests that all of these findings are supported by the evidence, taking into account the scatter in the data:

- The distributions for packaged and loose broccoli at 9°C overlap to a considerable extent, indicating no measurable difference in shelf life.
- In contrast, these two distributions for 9°C have no overlap with the two distributions for broccoli at 4°C, suggesting that broccoli stored at the colder of these two temperatures lasts longer.

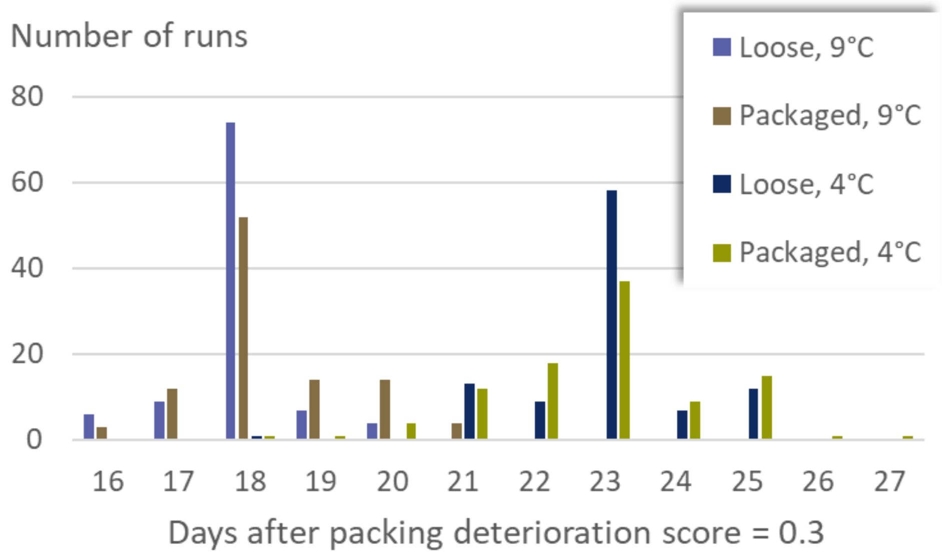
- There is also minimal overlap between the packaged and loose broccoli at 4°C, suggesting two distinct distributions: clear evidence that packaged broccoli at 4°C lasts longer than loose broccoli at this temperature.

Figure A3.5: Results of Monte Carlo simulation for **broccoli**: distribution of when the line of best fit reached deterioration score of 0.3 for 100 separate runs



Cucumber: The results for cucumber appeared clear cut from the results in Section 3.4. However, as there were apparent differences with previous research, these uncertainty around these results were checked using Monte Carlo simulation (Figure A3.6).

Figure A3.6: Results of Monte Carlo simulation for **cucumber**: distribution of when the line of best fit reached deterioration score of 0.3 for 100 separate runs



This additional analysis confirms the key results:

- There is no evidence of any shelf life relating to packaging, at either of the two fridge temperatures, as demonstrated by the overlapping distributions. This was confirmed by pairwise comparison of the 100 runs. Packaged cucumbers lasted longer in 62 out of the 100 simulation runs for 4°C and 64 out of 100 runs for 9°C: insufficient numbers to draw any conclusions.

- At a deterioration score of 0.3, the cucumbers in the colder fridge lasted longer, for both packaged and loose cucumbers. This can be seen by the low degree of overlap between the corresponding distributions, and was confirmed by pairwise comparison: for loose cucumbers, all 100 runs had a longer shelf life at 4°C compared to 9°C; for packaged cucumbers, the result was 97 out of 100 runs, sufficient evidence of a difference with a reasonable degree of certainty.

However, as noted in the main report, the effect on shelf life of fridge temperature appears to depend on the level of deterioration where the comparison is made. At a deterioration score of zero, there would be minimal difference between the shelf lives of the four variants. At a score of 0.6, the difference between different fridge temperatures would be more pronounced.

Potatoes: there appeared to be a clear difference in shelf life between refrigerated potatoes and those stored in a cupboard (Section 3.5). Furthermore, for those stored in a cupboard, there was no measurable difference between packaged and loose potatoes, nor was there a difference between different forms of packaging. These findings appear so clear-cut that they are *not* explored further using Monte Carlo simulations.

However, the difference between loose and packaged potatoes stored in the fridge is less clear-cut. Loose refrigerated potatoes appear to reach a deterioration score of 0.3 well before their packaged counterparts, but there is considerable scatter in the data. This section explores potatoes in refrigerated conditions to see what can be said about these differences.

Figure A3.7: Results of Monte Carlo simulation for **refrigerated potatoes**: distribution of when the line of best fit reached deterioration score of 0.3 for 100 separate runs

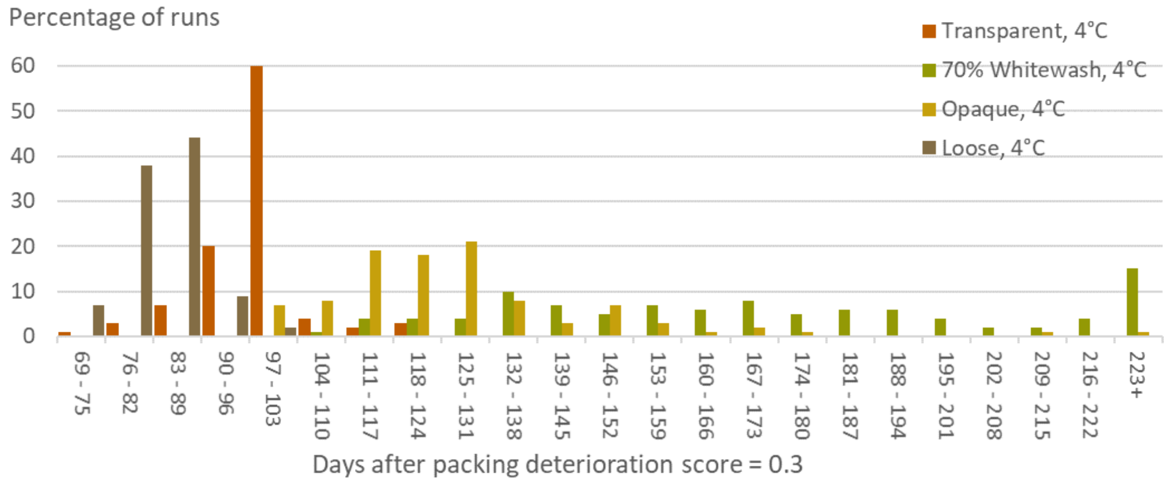


Figure A3.7 shows the results of the Monte Carlo simulation for refrigerated potatoes. For loose potatoes, the distribution is relatively tight, with a deterioration score of 0.3 being reached 75-95 days after packaging for most of the potatoes. Similarly, for potatoes in transparent packaging, there is a relatively tight distribution centred around 90-105 days.

In contrast, the other two conditions (70% whitewash and opaque packaging) have very wide distributions. In particular, the distribution for 70% whitewash extends from 110 days to over 250 days. This suggests that, for these two conditions, there is considerable uncertainty in the results. This is due to the small number of test days where the deterioration score was above zero, meaning that the best-fit line is highly sensitive to any changes in these scores.

Where there are overlaps between distributions, it instructive to undertake pairwise comparisons, similar to that conducted for bananas:

- **Refrigerated potatoes in transparent packaging versus loose**: in 94 of the 100 comparisons, the transparent condition had the longer shelf life; for six comparisons, the loose condition had the longer shelf life. This suggests that it is borderline as to whether there is a difference between the transparent and loose conditions.
- **Refrigerated potatoes: opaque versus transparent packaging**: in 98 of the 100 comparisons, potatoes in opaque packaging had a longer shelf life.

Considering only the comparison at a deterioration score of 0.3, the evidence is some evidence to suggest that loose potatoes have the shortest shelf life, followed by potatoes in transparent packaging, with opaque and 70% whitewash having jointly the longest shelf life. However, due to the difference in gradient of the lines in Figure 6, the conclusion reached would be different if the comparison was made at a different deterioration score. For example, if assessed at the first signs of deterioration (the line of best fit first moving above a deterioration score of zero), then loose potatoes would be assessed as having the longest shelf life, rather than the shortest.

For these reasons, we do not believe there is sufficient evidence from this study to differentiate the shelf life of the four different refrigerated potato conditions.

https://wrap.org.uk/resources/report/helping-people-reduce-fresh-produce-waste