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Modelling the impact of shelf-life extension on fresh produce waste in UK homes

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ABSTRACT

This research uses the Household Simulation Model (HHSM), to assess shelf-life extension mechanisms for reducing fresh produce waste in UK homes. Removal of Best Before dates is the most effective mechanism, reducing waste by 8–28 percentage points depending on the product (e.g., for bananas, a modelled waste reduction from 24 % of purchases to 16 %, an 8 percentage-point reduction). The findings support current recommendations to remove Best Before dates on uncut fresh produce. Refrigerating apples at 4°C extends product shelf life from 31 to 108 days resulting in a modelled reduction of 2.5 percentage points from 3.1 % to 0.61 %. Storage at optimal fridge temperature (4°C compared to 9°C) shows a modelled waste reduction for cucumbers of 16 percentage points from 43 % to 27 %. However, both refrigeration mechanisms assume a major change in consumer behaviour which could be challenging to overcome. Edible bio-based coatings show a modelled reduction for oranges, satsumas, and avocados ranging from 3 to 12 percentage points, offering a high-reward, low-effort solution for reducing Household Food Waste (HHFW) with relatively low implementation costs. Plastic packaging removal varies by product with a 9-percentage point reduction for bananas, but no effect on apples and cucumber. Consumer behaviour and proportion of products sold packaged will substantially affect waste reductions. The broader impact of plastic packaging on food management practices is not fully considered in this study, so results should not inform policy decision-making. Whilst the findings are UK-specific, they offer insights for other countries, though country-specific data is recommended for policy decisions.

1. Introduction

Food waste is a global issue with significant social, political, and economic impacts (World Bank, 2020; Forbes et al., 2024). Globally around 13.2 % of food produced is lost in the supply chain from post-harvest up to and excluding retail (FAO, 2022), and 19 % of food available to consumers is wasted at the retail, food service and household levels (Forbes et al., 2024). Food loss and waste account for around 8–10 % (FAO, 2013) or more (Zhu et al., 2023) of global greenhouse gas emissions. The United Nations Sustainable Development Goal 12, target 12.3 (SDG 12.3) is a commitment to halve, per capita, global food waste at the retail and consumer levels by 2030, and to reduce food losses along production and supply chains (Goucher et al., 2019), including post-harvest losses (United Nations General Assembly, 2015). Other initiatives include the United States 2030 food loss and waste reduction goal (US EPA, 2019), the European Commission, 2019 circular economy strategy (European Commission, 2019), and various Public-Private-Partnerships worldwide such as Mexico's Pacto por la Comida, The South African Food Loss and Waste Initiative, and the UK's Courtauld Commitment 2030.

1.1. Household food waste

Globally, HHFW is the largest contributor of total food waste accounting for 61 % (Forbes et al., 2024). In the UK – the focus of this paper – 60 % of all food waste is generated in households, of which

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almost three quarters (74 %; 4.7 million tonnes; 55.3 kg per person per year) was food that could have been eaten (WRAP, 2023a). A four-person household in the UK wastes, on average £ 1000 worth of food per year (WRAP, 2023a). However, food waste from UK homes is not equally distributed between food categories: 35 % of total HHFW is fresh produce with 'fresh vegetables and salads' the category with the highest percentage at 27 % and 'fresh fruit' the sixth highest at 8 % (WRAP, 2023b). The edible parts of all fresh produce waste in UK homes equates to 1.67 million tonnes with a value of £ 4 billion annually (WRAP, 2023b).

Food is wasted in UK homes for many reasons including when too much is cooked or prepared, personal preferences, or when it is not consumed in time (WRAP, 2023b). By weight, 38 % occurs because it is not consumed in time, with the largest proportion from fresh produce (WRAP, 2023b). As fresh produce is often highly perishable, its short shelf life is one of the key reasons why it is not consumed in time (Quested et al, 2020). Therefore, ensuring that fresh produce has a long shelf life and remains at its best for as long as possible is a key strategy to increase the chance that food is eaten and not thrown away. Some of the factors that contribute to the shelf life and quality of fresh produce are outlined below.

1.2. Optimal storage conditions

Storing products in optimal conditions can help reduce the amount of fresh produce wasted in the home (Secondi et al., 2015; van Holsteijn and Kemma, 2018; Dobernig and Schanes, 2019). Keeping fresh produce in the fridge below 5 °C as opposed to in a fruit bowl, significantly extends the shelf life. For example, experiments conducted by WRAP (2022a) demonstrate that packaged apples stored at 4 °C last 108 days after purchase compared to 31 days when stored at a mean ambient temperature of 19.8°C.

1.3. Edible coatings

Edible coatings can extend shelf-life through their ability to protect against oxidation, minimise browning and reduce moisture loss (Shahbazi et al., 2021; Andriani and Handayani, 2023). The coatings are extremely thin (often a few microns in thickness) and are derived from biodegradable, edible polymers such as lipids and proteins. The most commonly applied coatings are waxes on citrus fruit, and many are made of shellac or carnauba (Devi et al., 2023). Waxes and other coatings are often applied during the processing and packing stages of the supply chain to replace the natural wax which is removed during harvesting and handling. Other examples of edible coatings include neem oil (Wijewardane and Guleria, 2013), pea starch, and guar gum (Saberi et al., 2018). Some edible coatings are enriched with antimicrobial agents such as organic acids that inhibit the growth of microorganisms (Nandane et al., 2017, Oluba et al., 2022), and many have been applied to fresh produce items to prolong their shelf life (Yuan et al., 2016; Duguma, 2022). For example, Sucharitha et al. (2018) report that chitosan-coated tomato lasted 30 days compared to the control which spoiled after 20 days and waxes on citrus fruit have been shown to reduce weight loss and shrinkage (Devi et al., 2023).

1.4. Best Before dates

Whilst Best Before dates do not affect the physical shelf life of products, they do influence when people dispose of items, thus reducing the time available to consume products (TNS European Behaviour Consortium, 2014; Roe et al., 2018; WRAP, 2022b). A recent survey of UK citizens suggests that 8–11 % of people mostly or entirely use Best Before dates on fresh produce to decide whether to eat or dispose of an item, despite Best Before dates being a marker of product quality, rather than safety (WRAP, 2022b). The same research found that Best Before dates do not support people to judge when food is good to eat, instead they drive people to dispose of food that is perfectly edible and safe to consume (WRAP, 2022b). Subsequent modelling suggested that removing date labels from apples, potatoes, bananas, cucumbers, and broccoli alone could prevent 50,000 tonnes of wasted food in UK homes, the equivalent of 240 million items (WRAP 2022c). Consequently, guidance developed by WRAP, the Department for Environment Food and Rural Affairs (Defra), and the Food Standards Agency (FSA) advocates for removal of Best Before dates on uncut fresh produce unless it can be demonstrated that dates lead to a reduction in HHFW (WRAP, 2023c).

1.5. Plastic packaging

Another important factor is plastic packaging and there are multiple ways in which plastic packaging can impact HHFW (Verghese et al., 2015; Wikström et al., 2018; Chan, 2022). These include, but are not limited to, protecting products from physical damage, providing portion sizes e.g. a split-pack or multi-pack, reducing deterioration and extending product life, and creating a barrier to oxygen and contaminants to prevent product spoilage. As well as protecting the physical properties of the product, packaging can also provide citizens with information such as fridge temperature advice, freezing and defrosting advice, leftover recipes, and date labels to support them to manage and store their food to maximise shelf life and minimise HHFW.

In recent years there have been many initiatives aimed at reducing the amount of plastic packaging placed on the market (e.g. the European Plastics Pact), but these can be at odds with food waste prevention initiatives. For example, for fresh produce, there have been many studies outside of the UK that demonstrate the positive effect of plastic packaging in reducing spoilage (Dhall et al., 2012; Fikiru et al., 2024; Hailu et al., 2014) and extending product shelf life (Nath et al., 2012). However, a review of the role of plastic packaging in extending product shelf life revealed that many studies are either based on product varieties that are not sold in the UK, test plastic packaging formats that are not used in the UK (e.g. individually wrapped apples) or use test conditions that do not closely match the temperature and storage conditions of UK homes (White and Stanmore, 2018).

More recent research based on UK-specific test conditions suggests that the preservation qualities of plastic packaging is small in comparison to other food waste prevention methods, and selling uncut fresh produce items unpackaged in the UK could lead to a reduction in HHFW (WRAP 2022a). By selling fresh produce items unpackaged, it enables people, in particular single-person households, to buy the right amount for their consumption needs rather than buying packages of multiple items which could lead to over purchasing. For example, a comparison of UK supermarket pack sizes, National Diet and Nutrition Survey consumption data, and citizen insights on food waste and product deterioration showed that the smallest available pack sizes often exceed what a single-person household can consume before the food spoils and is discarded (WRAP 2022a; 2022b; 2022c). Following recent research on the role of plastic packaging and fresh produce waste in UK homes, the UK government and the Fresh Produce Consortium support a target for 50 % (by sales volume) of uncut fresh produce to be sold unpackaged in supermarkets by 2030.

1.6. Measurement data from large scale food waste interventions

Whilst previous studies in several countries have shown the promising effect of different shelf-life extension mechanisms on HHFW reduction (e.g., Verghese et al., 2015; Oliveira et al., 2015; Secondi et al., 2015; WRAP 2022c), there are very few evaluations of large-scale HHFW interventions that apply a robust measurement approach (Reynolds et al., 2019; Simões et al., 2022). Indeed, both scholars and policymakers have called for more evaluations to be underpinned by empirical data (Stöckli et al., 2018; Quested, 2019).

Two primary methods for gathering empirical data on the effectiveness of HHFW reduction initiatives are direct measurement through waste composition analysis, and self-reported data via diaries and surveys. These methods should be applied both before and after the intervention. However, large-scale food waste intervention pilots are prohibitively expensive, often costing hundreds of thousands or even over £ 1 million. This is the primary reason so few have been implemented to date (Reynolds et al., 2019), especially for estimating national food waste levels.

Large-scale food waste diaries have been used to estimate HHFW in the UK, offering a more cost-effective alternative than direct measurement. However, studies indicate that diaries substantially underestimate HHFW (Delley and Brunner, 2018; van Herpen et al., 2019; Giordano et al., 2019) and are unsuitable for evaluating intervention effectiveness (Quested at al., 2020). This creates challenges for policymakers and businesses in assessing which shelf-life extension mechanisms are most impactful on a national scale.

Due to these limitations, in this research we did not conduct trials using direct measurement or self-reported data. Instead, we adopted a pragmatic approach using digital simulation modelling. Other analytical approaches, such as statistical analyses, were deemed inappropriate due to lack of reliable data.

1.7. The Household Simulation Model (HHSM)

This study uses the HHSM to investigate the relationship between the shelf life of fresh produce items and HHFW in the UK. The HHSM incorporates data from empirical studies on citizen behaviour, food purchase and consumption patterns of UK households, and other relevant data. It uses Discrete Event Simulation (DES) to understand the complex household dynamics associated with food management and disposal by simulating the journey of food from purchase to consumption/disposal. DES as a digital simulation methodology has been used to make informed decisions on the issue of food waste in UK homes and was found to be beneficial (Quested, 2013; Kandemir et al., 2020a; 2020b; WRAP, 2022c). Whilst other modelling approaches have been applied to the issue of food waste such as agent-based modelling, system dynamics, mass balance estimation, and Bayesian networks, DES is the most suitable modelling approach for the HHSM (Kandemir et al., 2020a). This is due to the stochastic nature of food shopping and consumption behaviours as people shop and eat varying amounts on different days (Kandemir et al., 2020b). Further details on the suitability of DES over other modelling approaches are described by Kandemir et al. (2020b).

1.8. Research questions

This research addresses three key questions: 1) What is the relationship between shelf-life extension of fresh produce and waste in UK homes? 2) What is the likely impact of different shelf-life extension mechanisms on fresh produce waste in UK homes? 3) Which mechanisms might be most suitable for different products, taking into consideration the barriers and challenges of implementing shelf-life extension mechanisms at scale?

2. Materials and methods

2.1. Model overview

The HHSM was developed using the Arena simulation software (version 16.2), which uses DES. The HHSM includes four modules that replicate the journey of food from purchase to consumption or disposal: shopping, storage, consumption, and wastage. The modules are based on studies by Evans (2012; 2014) and WRAP (2012) on HHFW dynamics. The model can simulate various household types, reflecting differences in food management behaviours and practices across the UK population, such as household size, presence of children, decision making, food type.

Fig. 1 summarises the main inputs, modules, and outputs of the HHSM, with further details in Kandemir, et al. (2020b). Input parameters for each product are provided in Appendices A-G, with corresponding data sources in Appendix H.

The HHSM models food waste due to products ‘not being used in time,’ including food that has reached the end of its shelf or open life, deteriorated in quality, or is considered unsafe to eat. It does not estimate food waste from other causes, such as personal preferences (e.g. fussy eating), kitchen accidents (e.g. spillage) or too much being cooked or served.

The version of the HHSM used in this study builds on Kandemir et al. (2020b) but has been modified to include ‘ripen at home’ products like avocados, which are not ready for consumption immediately after purchase. An additional ripening period was incorporated into the HHSM, during which the product remains unconsumed until ripe. For these products, the shelf life starts at ripeness rather than purchase.

2.2. Product selection and household archetypes

Seven fresh produce items were selected for this study: apples, bananas, cucumbers, oranges, satsumas, ready-to-eat (RTE) avocados and ripen-at-home (RAH) avocados. These products were chosen based on

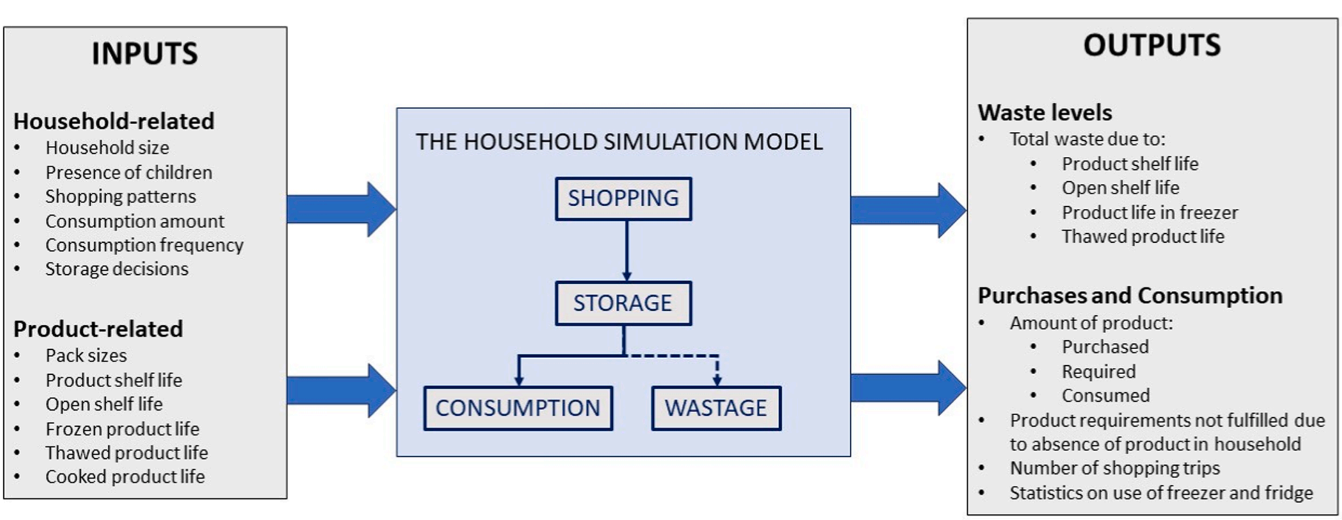

Fig. 1. Schematic of the HHSM showing the inputs, modules, and outputs. Adapted from Kandemir et al. (2020b).

four key criteria:

1) They are among the most wasted fresh produce items in UK households, with over 50,000 tonnes of waste annually (Table 1).
2) Comprehensive shelf-life data are available that meet the following standards:

a) organoleptic testing had been conducted by trained assessors in laboratory conditions,
b) availability of all raw data files,
c) testing of more than 50 items per condition.

3) Shelf-life data reflect UK conditions, including appropriate test temperatures and product varieties sold in the UK.
4) The product has potential for application of edible coatings in the UK market, as discussed with Apeel Sciences. For example, the shelf-life extension of potatoes and broccoli has been studied previously (WRAP 2022a) but were excluded from this research because they rarely have edible coatings applied.

To ensure UK representativeness, a range of "household archetypes," which are based on WRAP segmentation research (Kandemir et al., 2020b), were modelled. The segmentation categorises the population according to their attitudes and practices regarding food and food waste. Whilst Kandemir et al. (2020b) used seven archetypes for studying milk wastage under various interventions, for this research, an additional archetype was included to represent single-parent households in the UK. Descriptions of each household archetype are provided in Table 2.

2.3. Model inputs

2.3.1. Model setup

To account for variations in household dynamics over time, the simulation was run over a 1,500-year period to minimise variability from the probabilistic nature of input parameters. For each product, an additional run was conducted to assess model output variability, with 10 replicate runs performed for comparison. These comparisons showed low variability between model runs.

2.3.2. Data collection for model inputs

Data for the model inputs have been collected from various sources, including:

- WRAP's nationally representative surveys of UK household shopping patterns by household archetype,
- Public databases such as the National Diet and Nutrition Survey, which provides weekly consumption amounts of each product,
- WRAP's citizen insights survey on food waste management behaviours by household archetype.

Additional details on the model inputs and underlying data are provided in the following section, and Appendix H includes a complete list of data collection methods and data sources for the 88 variables in the HHSM.

2.3.3. Shopping module

This module determines when shopping events occur, the number of items purchased during each trip, and the lifespan of products.

According to a recent survey of UK citizens, 60 % of people purchase fresh fruits and vegetables weekly or less, while 40 % purchase them more frequently (WRAP, 2021). The same research also includes data by household archetype and as such, the main shop frequency was set to weekly for the FF single, FF couple, PP family, PP single parent and IA archetypes (i.e. 61.3 % of UK households). The specific day of the main shop was set as random but can be set to a specific day of the week. For the AD family, SC single, and SC one child archetypes (i.e. 38.7 % of UK households), shopping occurs randomly every 3, 4 or 5 days.

Households can buy items either during a main shop and/or a top-up shop. Top-up shops occur when food runs low, with customisable trigger levels and checking frequency. Top-up shops were switched on for commonly purchased items like apples, bananas, oranges, and satsumas but switched off for less common items like cucumber and avocados. For

Table 1
Highly wasted fruits and vegetables in the UK ranked by total food waste (in tonnes) per year. Data from WRAP (2023b). Products included in this research are those that meet all four criteria.

	Total food waste (thousand tonnes per year)	1. More than 50 thousand tonnes waste per year	2. Comprehensive shelf-life data available	3. Shelf-life test conditions relevant for UK context	4. Potential for application of an edible coating in the UK
Potato	510	X	X	X	
Banana	330	X	X	X	X
Apple	110	X	X	X	X
Carrot	100	X			
Onion	93	X			
Melon	91	X			
Orange	71	X	X	X	X
Other citrus	65	X			
Soft/berry fruit (excludes grapes)	59	X			
Tangerine/ satsuma/ clementine	57	X	X	X	X
Broccoli	59	X	X	X	
Cucumber	57	X	X	X	X
Avocado	53	X	X	X	X
Pineapple	42				
Grapes	41				
Stone fruit (excludes avocado)	37				
Other fruit	32				
Sweetcorn/corn on the cob	24				
Mushroom	22				
Pear	18				
Spring onion	8				

Table 2
Household archetypes for the UK population, based on segmentation research by WRAP.

Household archetype	Weight (%)	Number of occupants	Number and age of children	Food management behaviours	Level of risk associated with date labels*
Aspirational Discoverers (AD), Family	11.4 %	4	Two children under 7 years old	Good confidence and good planning. Moderately likely to throw away leftovers	Not willing to take risks
Functional Fuellers (FF), Single	16.6 %	1	No children	Low confidence and poor planning. Likely to throw away leftovers	Less willing to take risks
Functional Fuellers, Couple	8.0 %	2	No children	Low confidence and poor planning. Likely to throw away leftovers.	Less willing to take risks
Spontaneous Creatives (SC), Single	11.4 %	1	No children	Moderately low confidence and poor planning. Likely to discard leftovers.	Less risk-averse
Spontaneous Creatives, Couple with one child	16.0 %	3	One child under 7 years old	Moderately low confidence and poor planning. Likely to discard leftovers.	Less risk-averse
Ideal Advocates (IA), Couple	16.9 %	2	No children	High confidence and good planning. Will use leftovers.	Less risk-averse
Pressured Providers (PP), Family	9.6 %	4	Two children between 7 and 17 years old	Medium confidence and good planning. Will use leftovers	Less risk-averse
Pressured Providers, Single parent	10.2 %	2	One child between 7 and 17 years old	Medium confidence and good planning. Will use leftovers.	Less risk-averse

* This refers to the households' willingness to eat beyond the date label or eat beyond the recommended "once opened use within X days" stated on the food packaging.

apples, bananas, oranges, and satsumas, top-up shops were only switched on for the AD family, PP family, PP single parent and IA archetypes (48.1 % of UK households), aligning with WRAP's finding that 44 % of UK citizens purchase fresh fruit during top-up or smaller shops (WRAP, 2021).

The amount purchased during shopping trips is based on data from the Living Costs and Food Survey, 2015–2016 (Department for Environment, Food and Rural Affairs, 2019) and is adjusted for household size and food management practices. WRAP segmentation analysis shows that some households over-purchase due to poor planning, while others buy close to their consumption needs (Table 2). Pack sizes available in supermarkets were sourced from an online product search of six major UK supermarkets (Tesco, Sainsbury's, ASDA, Morrisons, Waitrose, Iceland) in January 2023.

Each item is assigned a shelf life (time available to consume the item) and, if relevant, an open product life (time after opening). Products from the same batch and supermarket store can last for different lengths of time, even when stored in the same conditions (WRAP 2022a). Therefore, shelf life is modelled as a distribution to account for variability in product origin and quality, following methods from Kandemir et al. (2020b) and WRAP (2022c). The open life is typically applied to meat and dairy products which have a label such as "Once open consume within x days," however, the open life function was used for avocados which, after being sliced open, last only a couple of days before becoming over-ripe. In the absence of empirical data, this was set at 2 $\pm$ 1 day, meaning that once cut in half, an avocado will last between 1 and 3 days with equal probability. Further details on the specific shelf lives used are provided in Section 2.4 and shelf-life distributions are provided in Appendices B-G for each product.

2.3.4. Storage module

The storage module simulates food storage in the home, adjusting the product's shelf life based on storage conditions. Items can be stored at ambient temperature (e.g., in a fruit bowl or on the countertop), in the fridge, or in the freezer. According to a 2023 survey, up to 90 % of UK citizens use the fridge for fresh fruits and vegetables, though usage varies by product: 89 % store cucumbers in the fridge, compared to 29 % for apples and 24 % for oranges (WRAP, 2023d). The model can simulate freezing and defrosting, but this feature was switched off, as it was assumed that very few freeze the products in this study.

2.3.5. Consumption module

The consumption module simulates when and how much food is eaten. Household food requirements (i.e., how much food the household consumes) are calculated separately for adults, children aged 7–17, and children aged 0–6. This approach assumes that household members eat food independently, rather than a shared meal (e.g. a whole roast chicken or pizza).

The probability that somebody consumes the item on a given day and the amount consumed were calculated using the National Diet and Nutrition Survey data from 2016–2019 (University of Cambridge, NatCen Social Research, 2019). Consumption amount distributions were fitted using Arena's Input Analyzer software (Rockwell Automation) and are provided in Appendix I. The model compares the amount required with what is available in the kitchen. If there is sufficient food, the household consumes the amount needed. If stock levels are low, the household can either: a) Consume what is available, b) Do a top-up shop to meet their full requirement, or c) Skip a meal or not consume the item. The likelihood of each option is user-defined. In this study, the probabilities were set to 80 % for consuming what is available, 0 % for doing a top-up shop, and 20 % for not consuming the item.

Although the model can simulate cooking and managing leftovers, it was assumed that all products were consumed raw, so the cooking function was switched off.

2.4. Shelf life

For each product, multiple shelf-life scenarios were modelled to assess the impact of different shelf-life extension mechanisms. Nine scenarios were modelled in total (Table 3), with differences between scenarios showing the effects of various mechanisms.

Several studies have identified food waste prevention mechanisms at the consumption stage (Quested et al., 2013; Reynolds at al., 2019; Schanes et al., 2018), but many cannot be modelled in the HHSM due to data limitations or irrelevance to household settings. The mechanisms selected for modelling were based on comprehensive UK-relevant shelf-life data (criteria 2 and 3 from Section 2.2) and include: a) Refrigeration instead fruit bowl storage, b) Optimal fridge temperature, c) Adding an edible coating, d) Edible coating instead of wax coating, e) Removal of Best Before dates, and f) Removal of plastic packaging. While these mechanisms could theoretically apply to all products, specific examples and shelf-life data were only available for some mechanisms and products, as shown in Table 3.

For each product and scenario, the average shelf life was determined as follows:

- Scenario A: Shelf life is the mean of the "minimum guaranteed freshness" provided by retailers, indicating the number of days that the product is guaranteed to last.

Table 3
Shelf-life scenarios, data sources and corresponding products that were modelled. Note that each scenario is labelled alphabetically and corresponds to specific data points in Fig. 1. The impact of a shelf-life extension mechanism is obtained from the difference between two scenarios. RTE = Ready to Eat, RAH = Ripen at Home.

Label	Shelf-life scenario	Description	Shelf-life data source	Modelled products
A	Minimum guaranteed freshness by retailer	The minimum number of days that the product is guaranteed by a retailer to last. This can be displayed on the product label or on the retailer website. It is different from a Best Before date (usually shorter). In this scenario, it is assumed that households dispose of the product once the guaranteed freshness date is reached.	Tesco and Morrisons websites accessed on 05/02/2023.	Apples, Bananas, Cucumbers, Satsumas, Oranges, Avocado (RTE), Avocado (RAH)
B	Dispose on Best Before date	The average number of days after purchase until a product's Best Before date, also known as the "available life." In this scenario, it was assumed that households dispose of products on the Best Before date. The "average guaranteed freshness" was used as a proxy for the available life.	Tesco and Morrisons websites accessed on 05/02/2023.	Apples, Bananas, Cucumbers, Satsumas, Oranges, Avocado (RTE)
C	Unpackaged at ambient temperature	Products sold unpackaged and stored at a mean ambient temperature of 19.8C in the home, for example, in a fruit bowl or on the kitchen countertop. In this scenario (and scenarios D-I below), it is assumed that householders dispose of products when they reach a moderate level of deterioration.	WRAP (2022a) for Apples and Bananas Apeel Sciences for Avocados	Apples, Bananas, Avocado (RTE), Avocado (RAH)
D	Packaged, at ambient temperature, no Best Before date	Products sold packaged and stored at a mean ambient temperature of 19.8C in the home, for example, in a fruit bowl or on the kitchen countertop. No Best Before date applied and so consumers use their own judgement to decide when to eat or throw away the product.	WRAP (2022a)	Apples, Bananas
E	Wax coating, ambient temperature	Wax coatings are typically applied to citrus products to reduce moisture loss and protect from postharvest decay. Wax coatings create a water repellent surface which is non-conducive to bacterial growth and establishment of pathogens. Ambient temperature of 20C.	Apeel Sciences	Satsumas, Oranges
F	Edible bio-based coating, ambient temperature	Edible bio-based coatings can preserve the appearance of food products by minimising browning and moisture loss through their ability to protect against oxidation and microbial spoilage. The coatings are extremely thin (often <1 mm in thickness) and are derived from biodegradable, edible polymers such as lipids and proteins. For Satsumas and oranges, the ambient temperature is 20C whereas for avocado ambient temperature is 21.3C	Apeel Sciences	Satsumas, Oranges, Avocado (RTE), Avocado (RAH)
G	Unpackaged or packaged refrigerated at 9°C	Products sold packaged or unpackaged and refrigerated at sub-optimal temperature at 9°C. Some domestic refrigerators in the UK operate above 4°C.	WRAP (2022a)	Cucumbers
H	Unpackaged or packaged refrigerated at 4°C	Products sold packaged or unpackaged and refrigerated at optimal temperature at 4°C.	WRAP (2022a)	Cucumbers
I	Packaged, refrigerated at 4°C, no Best Before date	Products sold packaged and refrigerated at optimal temperature at 4°C. No Best Before	WRAP (2022a)	Apples

(continued on next page)

Table 3 (*continued*)

Label	Shelf-life scenario	Description	Shelf-life data source	Modelled products
		date applied and so consumers use their own judgement to decide when to eat or throw away the product.		

- Scenario B: Shelf life is the mean of the "average guaranteed freshness" from retailers, broadly aligning with the average number of days from purchase to the Best Before date. In both scenarios A and B, it is assumed that disposal occurs based on these dates, regardless of the product's condition.
- Scenarios C, D, G, H, and I: Shelf life was derived from WRAP (2022a) experiments, which assessed the sensory attributes (appearance, aroma, texture, and taste) of produce under various conditions. A deterioration score of 0 indicated perfect condition, 0.3 moderate deterioration, and 0.6 advanced deterioration. Based on WRAP (2022b) findings that consumers typically discard produce at moderate deterioration, the shelf life for apples, bananas, and cucumbers was set to the 0.3 deterioration score. For RAH and RTE avocados, the shelf life for scenario C was derived from confidential data from Apeel Sciences, which includes sensory evaluation of oranges, satsumas, and avocados. Consistent with other products, the disposal point was set at a 70 % saleability threshold, indicating moderate deterioration.
- Scenarios E and F: Shelf life was set to the same 70 % saleability threshold and so households discard the item at moderate deterioration.

2.4.1. Standard deviations

For each product, there were differences in the number of data points available across different scenarios. Some scenarios had fewer than five data points (A, B), while others had more (C-I). For each product, the scenario with the most data points for each product was used to calculate the mean shelf life ± two standard deviations. The data sources with the most data points typically came from WRAP (2022a) and confidential data from Apeel Sciences. The shelf-life range of two standard deviations was converted into a percentage of the mean shelf life. For example, if an avocado had a shelf life of 2 ± 0.5 days, the ± 25 % variability was applied to estimate the range for other shelf-lives. For oranges and satsumas, shelf-life data from Apeel Sciences showed higher variability than other products. Using two standard deviations would have resulted in negative shelf lives, so a more conservative range of 1.5 standard deviations was applied. Consequently, the results for these citrus fruits should be interpreted with more caution compared to other products.

2.5. Model outputs

The model outputs include the total purchases, total wasted (and reasons for waste), number of shopping trips and, if relevant, the number of items stored in different locations, averaged across household archetypes for the UK (Kandemir et al. 2020b). The model also tracks any 'unfulfilled requirement' which occurs when a householder would like to consume a food item that is not available. A daily log records purchases, consumption, storage, and waste throughout each day of the simulation run.

The wastage module records the total amount of food wasted, with reasons for waste categorised by shelf-life expiration and, for avocados, open life expiration. In this study, the model does not account for waste due to thawed or cooked product life, as these functions were switched off.

2.6. Model verification and validation

The HHSM provides an approximate estimate of the impact of each mechanism, allowing users to compare their effectiveness. Verification was based on Kandemir et al. (2020b) and involved:

- Reporting results to two significant figures to avoid overinterpretation,
- Scrutinising daily logs for each product and shelf-life scenario to ensure the HHSM performed consistently with model specifications and inputs.
- Checking model outputs (waste amounts, total purchases, shopping trips) for consistency between the daily log and UK totals.
- Ensuring all food entering the home was accounted for (consumed, wasted or in storage).

To validate the model outputs the following steps were taken as outlined by (Sargent, 2013):

- Face validity was achieved by animating purchasing, storage, consumption, and wastage events to observe their behaviours. This step had been undertaken in the initial development of the HHSM as described by Kandemir et al. (2020b) and was replicated in this research when refining the new "ripen-at-home" functionality.
- Subject matter experts (authors RD and SK) conducted expert review. Both daily logs and model outputs were scrutinised to ensure that shopping trips and waste amounts aligned with household behaviours. This often led to refinement of model input data.
- Comparison Scenarios (Table 4) were used to assess model outputs against empirical data of average UK HHFW levels (WRAP, 2023b). Adjustments were made to model inputs to better match observed waste levels while remaining realistic.

2.7. Research limitations

A key limitation of this research is the lack of empirical data to directly validate the changes in food waste between scenarios. Ideally, this would involve measuring the impact of each shelf-life extension mechanisms on food waste reduction across a representative sample of UK households or specific household archetypes. However, conducting such studies requires significant time and resources, which exceeded the budget and scope of this project.

Whilst a limitation, the results still offer valuable approximate insights into the relative impact of different shelf-life extension mechanisms. This limitation also highlights an important opportunity for future research, where direct measurement could provide more accurate and robust estimates of the effectiveness of various interventions.

3. Results

3.1. Overview

Results are presented as the average shelf life (in modelled days) plotted against product waste (expressed as a percentage of purchases). The comparisons between different shelf-life scenarios highlight the relationship between shelf-life extension mechanisms and food waste reduction.

To assess the relative impact of each mechanism, comparisons are made against a reference point representing the most common scenario for UK households. Table 4 explains the justification for each comparison point. For example, for apples, most UK citizens store them in a fruit bowl at ambient temperature (mean 19.8°C), which results in an average shelf life of 31 days. Therefore, waste levels for apples are compared across scenarios relative to this 31-day benchmark (represented by point

Table 4
Most likely shelf-life for each product and justification for each product. The most likely shelf-life is used as a comparison point to assess the impact of different shelf-life extension mechanisms. RTE = ready to eat. RAH = ripen at home.

Product	Comparison scenario	Shelf-life comparison point	Justification
Apples	Scenario C: Unpackaged apples stored at ambient temperate	31 days	Most UK citizens store apples at ambient temperature. A recent survey of UK citizens also suggests that 71 % store apples in a fruit bowl (WRAP, 2023d). A survey of large-format supermarkets in 2021/22 suggests that around 23 % of apple lines that are sold in the UK are sold unpackaged with the remaining sold in plastic packaging (WRAP 2022c). However, most (58 %) UK citizens remove their apples from the packaging before storing at home (WRAP, 2013) **Therefore, the shelf life of unpackaged apples stored at ambient temperature, specifically, a mean ambient temperature of 19.8C is assumed to be the UK average.**
Bananas	Scenario C: Unpackaged bananas stored at ambient temperature	5 days	Citizens are most likely to store bananas at ambient temperature. A survey of UK fridges suggests that only 6 % of people store them in the fridge. A survey of large-format supermarkets in 2021/22 suggests that around 20 % of banana lines that are sold in the UK are sold in packaging (WRAP 2022c). As most are sold unpackaged, **the shelf life of unpackaged bananas stored at ambient temperature, specifically, a mean ambient temperature of 19.8C, is assumed to be the UK average.**
Avocado RTE	Scenario C: Unpackaged ready to eat avocado stored at ambient temperature	5 days	It was assumed that most UK households store avocados **unpackaged at an ambient temperature of 21.3C** in a fruit bowl or on the kitchen countertop.
Avocado RAH	Scenario C: Unpackaged ripen at home avocado stored at ambient temperature	9 days	It was assumed that most UK households store avocados **unpackaged at an ambient temperature of 21.3**C in a fruit bowl or on the kitchen countertop.
Cucumber	Scenario H: Unpackaged or packaged cucumber stored in a refrigerator at 4 °C	11 days	Shelf-life data for a 4 °C fridge was used as it is close to empirical data on domestic fridge temperatures in the UK. Bigila et al. found average temperature of fridges in England were 5.3 °C and Evans et al. (2014) found the average temperature in fridges in the UK were 4.4 °C. A survey of 228 domestic fridges suggests that 64 % of people store cucumbers in the fridge. WRAP research suggests that there is no significant difference in the shelf life of cucumbers sold unpackaged versus packaged. Therefore, the **shelf life of cucumbers at 4C is assumed to be the UK average.**
Oranges	Scenario E: stored at ambient temperature with a wax coating	15 days	Citizens are most likely to store oranges at ambient temperature. A survey of 228 domestic fridges suggests that only 4 % of people store them in the fridge. It was assumed that **oranges would have a wax coating, and most UK households store them** at an ambient temperature **of 20C.**
Satsumas	Scenario E: stored at ambient temperature with a wax coating	13 days	Citizens are most likely to store Satsumas at ambient temperature. A survey of 228 domestic UK fridges found that only 7 % of participants stored 'Easy peels' in the fridge. It was assumed that Satsumas would have a **wax coating, and most UK households store them at an ambient temperature of 20C.**

C in Fig. 2).

In the figures provided (Figs. 2–5), the shelf-life scenario that is most representative of typical UK households is highlighted in blue. The difference in food waste levels across various shelf-life scenarios provides an approximate estimate of the impact of each shelf-life extension mechanisms. This comparison allows for insights into how different approaches to prolonging shelf life can potentially reduce food waste. Fig. 6

3.2. Shelf life versus food waste

For all products studied, the results indicate a clear inverse relationship between shelf life and food waste: as the shelf life of a product increases, the amount of waste decreases. The largest reductions in food waste occur early in shelf-life extension, represented by the steep gradient in the early days of each curve. However, as shelf life continues to increase, the rate of waste reduction slows down, eventually leading to a flatter curve.

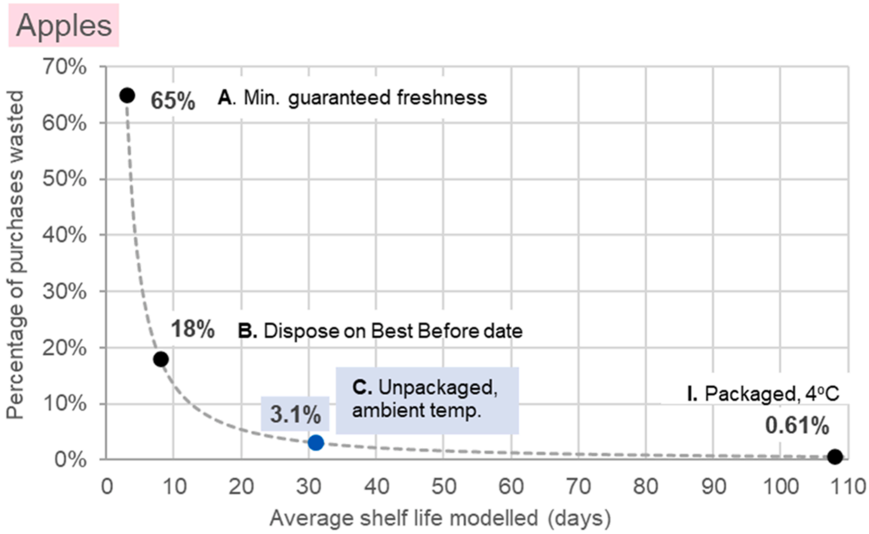

Fig. 2. Percentage of apple purchases wasted against the average modelled shelf life in days. Scenario C is the most representative of UK households.

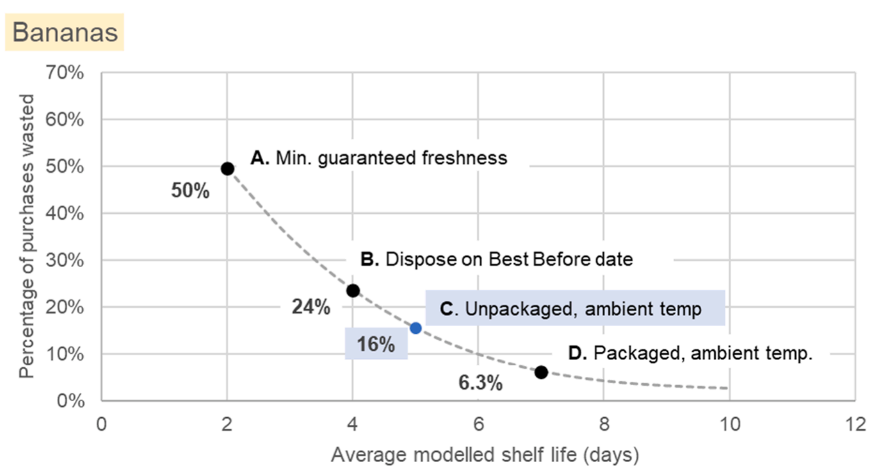

Fig. 3. Percentage of banana purchases wasted against the average modelled shelf life in days. Scenario C is the most representative of UK households.

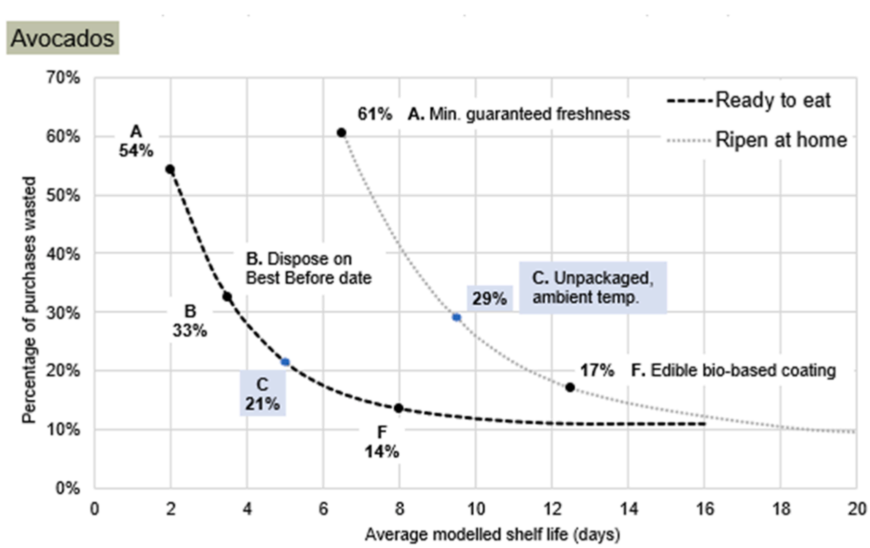

Fig. 4. Percentage of ready to eat and ripen at home avocado purchases wasted against the average modelled shelf life in days. Scenario C is the most representative of UK households. The shelf-life curve for ripen at home avocados begins at the moment it becomes ripe. i.e. the average number of days the product takes to ripen is 6.5 days.

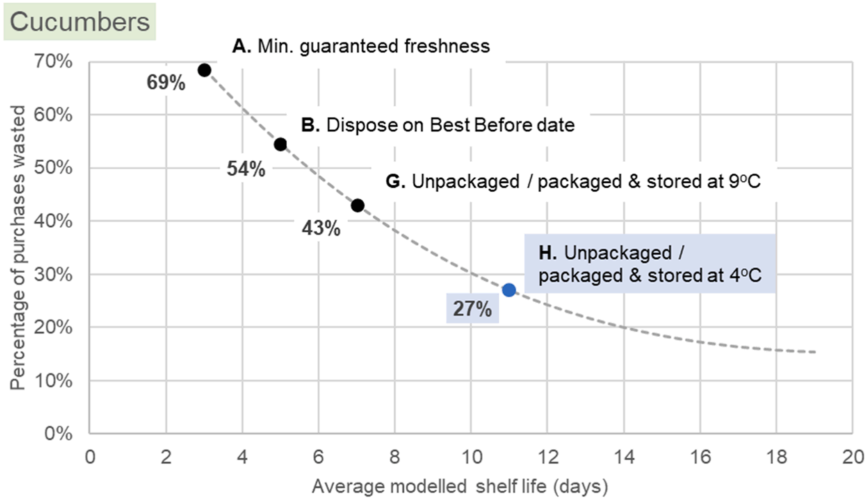

Fig. 5. Percentage of cucumber purchases wasted against the average modelled shelf life in days. Scenario H is the most representative of UK households.

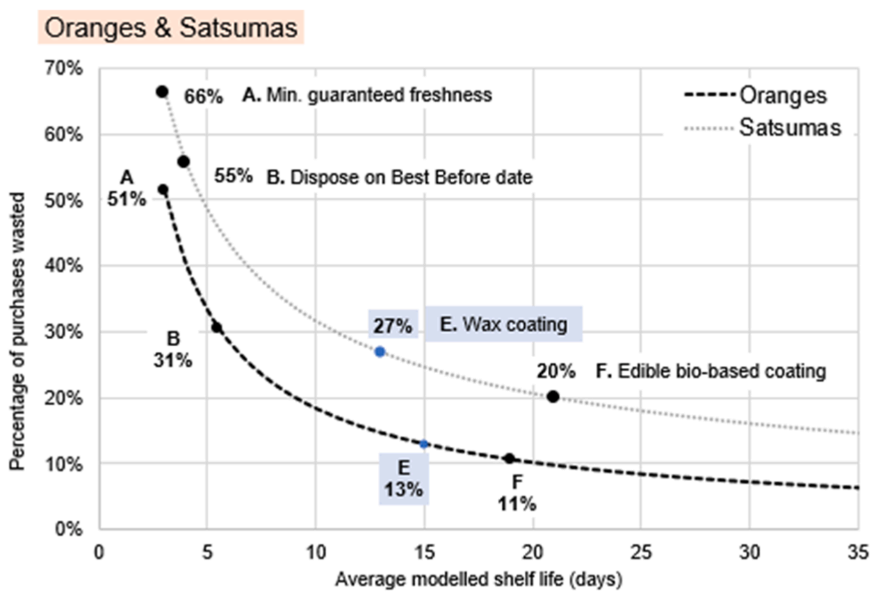

Fig. 6. Percentage of oranges and satsuma purchases wasted against the average modelled shelf life in days. Scenario E is the most representative of UK households.

Table 5
Percentage point change in food waste for each product and shelf-life extension mechanisms. The shelf lives that are compared to make the comparison are shown in brackets.

Product	Refrigeration instead of fruit bowl	Optimal versus sub-optimal fridge temperature	Add edible coating	Edible coating instead of wax coating	Remove Best Before date	Remove plastic packaging*
Apples	−2.5pp (108–31 days)	-	-	-	−16pp (8–31 days)	No change (31–31 days)
Bananas	-	-	-	-	−8pp (4–5 days)	+ 9pp (5–7 days)
Cucumbers	-	−16pp (11–7 days)	-	-	−27pp (5–11 days)	No change (11–11 days)
Satsumas	-	-	-	−7pp (21–17 days)	−28pp (4–13 days)	-
Oranges	-	-	-	−2.4pp (19–15 days)	−18pp (5.5–15 days)	-
Avocado RTE	-	-	−8pp (8–5 days)	-	−12pp (3.5–5 days)	-
Avocado RAH	-	-	−12pp (12.5–9.5 days)	-		-

* This only considers the physical shelf-life extension properties of the plastic packaging. It does not consider other properties of the packaging such as the Best Before date, on-pack storage instructions, and number of items purchased per pack which can affect the length of time available to consume the item and provisioning rates.

The point at which each food waste reduction curve begins to flatten indicates that further extending shelf life beyond this threshold offers diminishing returns of food waste reduction. These thresholds are approximately 30 days for apples, 9 days for bananas, 17 days for cucumbers, 30 days for satsumas, 25 days for oranges, 9 days for RTE avocados, 17 days for RAH avocados. These findings suggest that extending shelf life beyond these points provides limited additional benefits in reducing food waste.

3.3. Shelf-life extension mechanisms and food waste

To assess the relative impact of each shelf-life extension mechanisms, comparisons were made against the most representative scenario for UK households. Table 5 shows the effects of mechanisms such as refrigeration instead of using a fruit bowl, optimal versus sub-optimal fridge temperature, adding an edible coating, switching from a wax to an edible coating, removing the Best Before date, and removing plastic packaging.

Findings for each mechanism are summarised below:

- Storing apples in the fridge instead of a fruit bowl extends product shelf life from 31 to 108 days resulting in a modelled reduction of 2.5 percentage points from 3.1 % to 0.61 %.
- Storing cucumbers at an optimal temperature of 4 °C as opposed to a sub-optimal temperature of 9 °C extends product shelf life from 7 to 11 days resulting in a modelled reduction of 16 percentage points from 43 % to 27 %.
- The application of edible bio-based coatings on both RTE and RAH avocados extends product shelf life. For RTE avocados, edible coatings extend product shelf life from 5 to 8 days resulting in a modelled reduction of 8 percentage points from 21.5 % to 13.6 %. For RAH avocados, edible coatings extend product shelf life from 9.5 to 12.5 days resulting in a modelled waste reduction of 12 percentage points from 29 % to 17 %.
- Application of an edible coating instead of a wax coating on both oranges and satsumas extends product shelf life. For satsumas, the average shelf life was extended from 17 to 21 days resulting in a waste reduction of 7 percentage points from 27 % to 20 %. For oranges, the average shelf life was extended from 15 to 19 days resulting in a waste reduction of 2.4 percentage points from 12.9 % to 10.5 %.
- Removal of Best Before dates extends product shelf-life for all products with shelf-life reductions ranging from 8 percentage points for bananas to 28 percentage points for satsumas.
- Removal of plastic packaging has no impact on shelf-life extension for apples and cucumbers but reduces product shelf life for bananas from 7 days to 5 days resulting in a waste increase of 9 percentage points from 6.3 % to 16 %.

The next section compares the findings for each shelf-life extension mechanisms with the results from other studies and discusses the implications.

4. Discussion

4.1. Refrigeration instead of a fruit bowl

Storing apples in the fridge instead of a fruit bowl has a modest impact on waste levels, as apples last 31 days at mean ambient temperature (19.8 °C) giving consumers enough time to eat most before they spoil. While refrigerating at 4 °C extends their shelf life to 108 days, the modelled reduction in apple waste relies on a major shift in consumer behaviour. Currently, only 24 % of UK citizens refrigerate apples (WRAP, 2023d), as most store them in a fruit bowl due to engrained habitual behaviours (Quested et al., 2013). A key way in which retailers can encourage their customers to store fresh produce in optimal conditions is by providing clear instructions on packaging (Brook Lyndhurst, 2011), yet only 20 % of fresh produce products recently surveyed in 2021 (carrots, apples, berries, and bagged salad) contain the correct numerical fridge temperature advice, and only 15 % have a fridge icon (WRAP, 2022d).

Another way to encourage optimal storage of fresh produce is via consumer education campaigns (e.g. Love Food Hate Waste), but robust empirical data on their efficacy is limited (Simões et al., 2022).

While optimal storage, such as refrigeration instead of a fruit bowl, could reduce waste for other products and is considered a key factor in minimising HHFW (Butler et al., 2012; Chan et al., 2022), the lack of clear storage instructions on fresh produce in UK supermarkets, along with the difficulty in changing consumers' engrained storage habits, means that significant effort is required for this approach to effectively reduce food waste.

4.2. Optimal fridge temperature

Storing cucumbers at optimal temperature has a moderate impact on the modelled waste reduction, but also has the potential to reduce waste for all other items within the household's fridge. However, this mechanism firstly requires households to know what temperature their fridge should be set at. A national survey by the FSA (n = 5991) found that just 62 % had knowledge of the correct temperature. Not only do citizens need to know what temperature their fridge should be set at, they also need to check the fridge temperature, and then if required, adjust the temperature. Whilst the average fridge temperature in the UK is around 5.3 °C (Evans et al., 2014), 63 % of UK citizens rate their ability as weak when it comes to "*checking the fridge temperature on a regular basis*" (WRAP, 2023e). Therefore, whilst optimal fridge temperature has the potential to reduce food waste, it relies on a substantial shift in citizen behaviour, which could be challenging to overcome.

There have been several behaviour-change interventions and citizen education campaigns in the UK to encourage people to store their fresh produce in the correct location (e.g. WRAP, 2023 f; Vegemates and Frenemies, Sainsbury's, 2016), and to check and adjust their fridge temperature (e.g. Chill the Fridge Out, WRAP), however, knowledge and competency of these behaviours remains low in the UK. One solution to circumvent the behaviour-change challenge would be for fridge manufacturers to provide fridge temperature in Celsius or Fahrenheit on the temperature dial, as opposed to a numbering system, which is the case for most UK domestic fridges.

4.3. Edible coatings

The findings suggest that edible coatings are an effective mechanism to reduce HHFW, with modelled reductions ranging from 2.4 percentage points for satsumas to 12 percentage points for RAH avocados. While other studies show greater potential for shelf-life extension with edible coatings (Adjouman et al., 2018), other studies are not based on test conditions that are directly applicable to the UK, and overall, there remains a gap in the literature of suitable comparative studies.

The modelled results in this study also assume widespread consumer acceptance of edible coatings on avocados, satsumas, and oranges, though research by Mauricio et al. (2022) shows that detailed product labelling on vacuum-packaged lamb meat with an edible coating negatively impacted consumer purchase decisions. The authors also conclude that, in addition to product labelling, marketing strategies are necessary to increase salience, improve consumer confidence, and drive sales.

Edible coatings may require upfront costs for research, piloting and supply chain coordination which may need to be funded by the retailer. The process will also involve time and therefore cost from retailers to liaise with their suppliers, distributors, pack houses, and/or manufacturers. However, there are several companies that sell edible bio-based coatings and offer implementation support, and so many of these challenges can be overcome. From a consumer behaviour-change perspective, additional marketing and consumer messaging may also be required to ensure products are culturally accepted by customers, however, this is likely to cost considerably less than the technology itself. Overall, edible coatings offer a low input-high reward option for reducing HHFW.

4.4. Removing best before date labels

Evidence from a recent review of packaging-related HHFW interventions from across Europe, North America and Australia indicates that Best Before dates are the most reported driver of fresh produce waste (Chan et al., 2022). The results of this study, also suggest that removing Best Before dates is the most impactful mechanism of those modelled, with reductions ranging from 8 percentage points for bananas to 28 percentage points for satsumas. However, these results assume a shift from all households using Best Before dates, to no households using them, and current estimates suggest that only 8–11 % of UK households use Best Before dates for disposal (WRAP, 2022b). Therefore, the actual impact may be smaller than the results reported in this study.

The results of this research also support current best practice guidance in the UK developed by WRAP, DEFRA and the FSA which advocates for removal of Best Before dates on fresh produce items unless it can be demonstrated that Best Before dates lead to a reduction in HHFW (WRAP, 2023c). By removing date labels and supporting households to use their own judgement to decide when to throw products away, the time available to consume the item could be extended by around 23 days for apples, 1 day for bananas, 6 days for cucumbers, 9 days for satsumas, 9.5 days for oranges, and 1.5 days for RTE avocados. Despite only a small proportion of the population using Best Before dates for disposal (WRAP, 2022b), their removal could significantly reduce food waste in absolute terms, given the overall volume of fresh produce wasted in UK homes.

Whilst removal of Best Before dates has the potential to reduce HHFW, consideration must also be given to their role in stock management within the supply chain. To overcome this challenge, several retailers in the UK have adopted best practice guidance (WRAP, 2023c) and replaced Best Before dates with Julien codes which avoid the need for a customer-facing code (WRAP, 2022d).

4.5. Removing plastic packaging

This study indicates that removing plastic packaging is the only scenario that could either have no effect or reduce product shelf life, potentially increasing food waste depending on the product. For apples and cucumbers, shelf-life extension experiments suggest that plastic packaging does not extend their shelf life (WRAP, 2022a), and so the modelled results in this research suggest no impact on HHFW. For bananas, plastic packaging extends shelf life, and so the modelled results suggest an increase in HHFW. However, removing plastic packaging also removes Best Before dates which could lead to reductions in HHFW by encouraging citizens to use their judgement to decide when to eat or discard a product (Van Boxstael et al., 2014). In addition, storage instructions on packaging, which may outline optimal storage conditions, would also be lost if sold unpackaged, and research suggests that storage instructions play an important role in HHFW prevention (Brook Lyndhurst, 2011; Butler, 2012). Purchasing unpackaged would also allow precise quantities to be purchased based on consumption requirements (WRAP, 2022c).

WRAP have previously modelled the additional dynamics associated with plastic packaging using the HHSM to understand the impact on HHFW for apples, bananas, broccoli, cucumber, and potatoes (WRAP, 2022c). The findings show minimal shelf-life extension benefits from plastic packaging but highlight that its removal can reduce HHFW by allowing consumers to only buy what they need and removing Best Before dates (WRAP 2022c). However, simply selling more fresh produce unpackaged may not reduce HHFW due to barriers such as difficulty comparing costs between unpackaged and packaged options, low awareness of unpackaged options, and perceptions of lower quality (WRAP, 2024). Therefore, plastic packaging removal should be paired with retailer actions and campaigns to help consumers buy less, use better judgment on freshness, and store items optimally.

4.6. Differences between this study and other WRAP studies

It is important to delineate the unique contribution of this research in relation to recently published studies by WRAP (e.g. WRAP 2022a; 2022c), as this research and the WRAP studies apply the HHSM to similar products and shelf-life extension mechanisms. This research incorporates shelf-life data for apples, bananas, and cucumber for storage at different fridge temperatures, storage locations, and removal of plastic packaging (WRAP 2022a), as outlined in Table 3. However, there are important distinctions between the shelf-life data used in this study compared to the shelf-lives used in the WRAP (2022c) HHSM modelling paper. For this research, we assume that each modelled scenario is adopted by all the UK population. In comparison, the WRAP (2022c) study uses adjusted shelf-life data from the WRAP (2022a) study by attempting to quantify the proportion of the UK population that would be impacted by each scenario. Therefore, the average shelf-lives for each scenario and product used in this research differ to the shelf lives used by WRAP (2022c) in the HHSM study. Furthermore, as the focus of this research is to compare the relative impact of different shelf-life extension mechanisms, we only include the shelf life extending properties of plastic packaging within our modelling. We do not include other factors that could impact the length of time available to consume an item which are also inherently related to plastic packaging. For example, Best Before dates and storage instructions that are present on packaging would be removed when items are sold unpackaged, or if citizens de-package their food items upon return from the supermarket. These additional nuances were not included in this research, but they are included in the WRAP (2022c) HHSM study and as such, the modelled shelf lives used in this research differ to those used by WRAP (2022c). As a result, it is important to reemphasize that the findings of this study provide approximate estimates of the impact of each mechanism.

5. Conclusions

This research provides modelled estimates of the impact of different shelf-life extension mechanisms on household fresh produce waste in the UK and discusses the challenges of large-scale implementation. Table 6 summarises the key findings of this study.

Storing apples in the fridge has minimal impact on waste levels due to their longer natural shelf life, while refrigerating cucumbers at optimal temperature can substantially reduce waste but requires a considerable shift in household behaviour. The potential reduction in cucumber waste relies on citizens' knowledge and willingness to adopt optimal storage practices and fridge temperature management, as well as citizens having access to fridge storage within their household.

Edible bio-based coatings, with a modelled reduction from 3 to 12 percentage points, offer a high-reward, low-effort solution for reducing HHFW. They require minimal behaviour change messaging and are relatively inexpensive to implement. Coatings, therefore, have the potential to be effective in reducing HHFW and could also help reduce waste at various stages of the post-harvest supply chain, depending on where they are applied.

For households currently using Best Before dates as disposal dates, removing these labels is the most effective mechanism to reduce HHFW. The findings support current best practice guidance advocating for the removal of Best Before dates on uncut fresh produce.

The impact of plastic packaging removal on HHFW varies; for bananas modelled results show a potential 9 percentage point reduction, whereas for apples and cucumber there is no change. Consumer behaviour, such as de-packaging at home, and the proportion of

Table 6
Summary of shelf-life extension mechanisms, modelled impacts for selected food items, and the barriers and considerations for implementation at scale.

Type of mechanism	Modelled impact on food waste	Barriers and other considerations
Optimal fridge temperature	Reduction of 16 percentage points.	• Requires consumers to know the optimal fridge temperature required then test their own fridge temperature, and then adjust their own fridge temperature. These actions can be difficult to influence due to lack of awareness and lack of ease. • Correct fridge temperature must be present and clear on product packaging. • To overcome engrained consumer behaviours, fridge manufacturers could instead ensure that refrigerators cannot operate warmer than 5 °C as default.
Refrigeration vs ambient	Reduction of 2 percentage points.	• Change in storage decisions required for households for this impact to be realised; these decisions can be difficult to influence due to engrained habits. • Correct storage instructions must be present and clear on product packaging
Edible coatings	Reduction of between 3 and 12 percentage points.	• Requires technology to be safe, fully commercialised, and available. • Requires financial and time investment from retailers to apply to products and liaise with others in their supply chain. • Since edible coatings are applied at the pre-consumer stage of the supply chain, and they are undetected by the consumer, they require minimal input or behaviour change intervention to be impactful.
Remove Best Before date	Reduction of between 8 and 28 percentage points. Higher reductions observed with high base levels of waste.	• Retailers may need to adopt another way to manage stock such as Julien codes which avoid the need for a customer-facing date code. • Customers must use their own judgement to decide when to throw away or consume food. • Provides more time to consume the item compared to the Best Before date which is not a good indication of a products' shelf life.
Remove plastic packaging	No change or increase of 9 percentage points	• Findings do not consider broader impacts of removing plastic packaging and should not be used in isolation to inform policy or decision-making in industry. • The full functional properties of plastic packaging must be considered on a product-by-product basis alongside consumer behaviour.

products sold packaged may substantially affect the actual waste reduction achieved. However, the broader impact of plastic packaging on food management and storage practices is not fully considered in this study, and findings should not inform policy or industry decision-making.

In comparison to previous applications of the HHSM, this research includes a broader range of products such as oranges, satsumas, and both RAH and RTE avocados, which until now have not been modelled. This research also provides modelled estimates on the role of edible coatings in reducing fresh produce waste, which to date, has not been quantified for UK households, nor compared with other shelf-life extension mechanisms to contextualise any potential reductions that edible coatings could achieve. Overall, a combination of strategies, including the removal of Best Before dates, optimal refrigeration practices, the use of edible coatings, and thoughtful consideration of the role of plastic packaging, could collectively contribute to substantial reductions in HHFW. Implementation should be product and context-specific and consider the potential impact against both consumer behaviour and supply chain logistics. The findings can be used to support industry, policymakers, and other stakeholders with prioritisation of interventions to reduce HHFW.

Whilst the input data and results of this research are UK-specific, the research offers insights that can be adapted to other countries facing similar challenges. For example, if Best Before dates are prevalent within a given country, and fridge temperatures are comparable, this study's findings could provide a quick qualitative assessment for other countries. However, using country-specific data in the HHSM is recommended to inform policy decisions within government or businesses.

To the best of the author's knowledge, there are no published research articles that apply the HHSM outside of the UK. This provides an opportunity for further research, and any future studies would benefit from external validation by testing the model outputs against empirical data.

CRediT authorship contribution statement

SC Lenny Koh: Writing – review & editing, Supervision, Software, Resources, Methodology. **Penny Huckle:** Supervision, Project administration. **Sarah Key:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Rachel Devine:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cansu Kandemir:** Writing – review & editing, Methodology. **Ellie Trotman:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Christian Reynolds:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Tom Quested:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2025.100210.

Data availability

All accompanying data are supplied in the appendices unless otherwise stated. Shelf life data provided by Apeel Sciences are confidential.

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