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Assessing the environmental sustainability of consumer-centric poultry chain in the UK through life cycle approaches and the household simulation model

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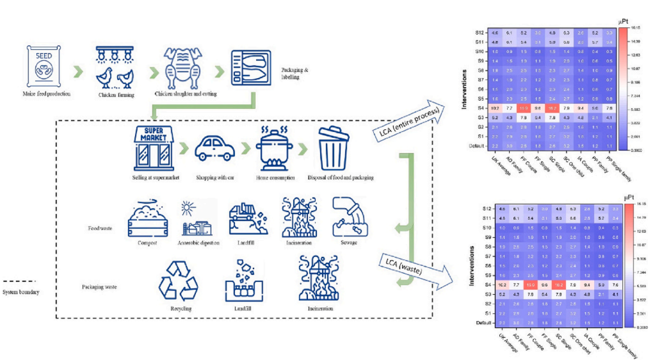
HIGHLIGHTS

- Life cycle assessment is integrated with the household simulation model.
- Environmental performance of household consumption and disposal is involved.
- Disposal phase encompasses both food and packaging waste.
- Impact of consumer behaviours driven by various interventions is discussed.
- Environmental impacts of UK households' behavioural variances are studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Chicken fillets, predominantly encased in disposable plastic packaging, represent a common perishable commodity frequently found in the shopping baskets of British consumers, with an annual slaughter exceeding 1.1 billion chickens. The associated environmental implications are of considerable significance. However, a noticeable gap exists concerning the household-level ramifications of chicken meat consumption, which remains a prominent driver (165 kg CO_{2e} yr^{-1} per capita) of environmental impacts in the United Kingdom (UK). This study's primary objective is to integrate Life Cycle Assessment (LCA) methodology with insights derived from a spectrum of interventions simulated within the Household Simulation Model (HHSM). The interventions that are simulated are influenced by various consumer behaviours related to the purchase, consumption, storage and

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disposal of chicken fillets. The overarching aim is to provide a comprehensive understanding of the environmental consequences associated with each intervention.

The research encompasses eight distinct household archetypes and the UK average, with a focus on discerning differences in their environmental influence. The introduction of shelf-life extension measures leads to a reduction in the overall environmental impacts (in μ*Pt*), with reductions ranging from 1 % to 18 %. Concurrently, waste treatment's environmental burdens can be curtailed by 9 % to 69 % for the UK average. Of the 12 interventions tested, the intervention that combines a one-day extension in the shelf life of open packs and a three-day extension for unopened packs leads to the greatest reduction in environmental impacts, at 18 % for the entire process and 69 % for the waste treatment. This intervention is estimated to yield annual reductions of 130,722 t of CO2 emissions across the entire process and 34,720 t of CO2 emissions from waste treatment, as compared to the default scenario. These findings demonstrate the importance of integrating consumer behaviour, food waste, and packaging considerations within the domain of food LCA research.

Abbreviations

FWL	Food waste and loss
GHG	Greenhouse gas emission
LCA	Life cycle assessment
HHSM	Household simulation model
NGO	Non-governmental organisation
HA	Household archetype
OPP	Oriented Polypropylene
AD	Aspirational discoverer
FF	Functional fueller
SC	Spontaneous creative
IA	Ideal advocate
PP	Pressured provider
EF	Environmental footprint
EOL	End-of-life

1. Introduction

Growing global concerns about food consumption and waste management arise from its pronounced environmental consequences intertwined with economic progress and the challenge of providing sustenance for a burgeoning population (Goucher et al., 2017; Kookana et al., 2020). A third of the global food supply is estimated to be wasted or lost, leading to about 6 % of global emissions (Sandström et al., 2018). To contextualise the magnitude of food waste and loss (FWL) impact, envisioning food waste as a separate nation would reveal it as the third-largest emitter of greenhouse gas emissions (GHGs), surpassed only by China and the United States (FAO, 2013).

According to the United Nations Environmental Programme, household is identified as one of the major contributors to FWL. Globally, it's estimated that households discard approximately 570 million tons of food each, amounting to around 530 billion US dollars. This constitutes 30–45 % of the total wastage in the entire food supply chain (UNEP, 2021). This issue is particularly pronounced in high-income countries (Ammann et al., 2021; Jribi et al., 2020).Around 40 % of food is wasted during the consumption stage in developed countries (Cederberg and Sonesson, 2011; USDA, 2017). The consumption stage has the most significant carbon footprint in terms of food waste, as the carbon intensity associated with 1 kg of food wasted downstream (e.g. retailing and household consumption) in the supply chain is higher than when it is wasted upstream (e.g. farming, cultivation and production, etc.) (WRAP, 2020).

The UK is positioned among high-income countries experiencing substantial food waste. Animal products generally demonstrate a more pronounced environmental impact in comparison to most plant-based alternatives (Poore and Nemecek, 2018). It is pertinent to mention that FAOSTAT (2023) indicates an average per capita annual consumption of poultry meat at 34.1 kg, with poultry meat being the most preferred animal protein source (Salazar et al., 2020), constituting approximately 42 % of the country's total meat consumption. Notably, chicken fillets (also called "boneless chicken breast fillets") emerge as the top-selling cut, with annual slaughter of more than 1.1 billion chickens, solidifying its status as a prominent food source (DEFRA, 2019; Statista, 2023). Data has revealed that the chicken value chain in the UK experiences losses or waste amounting to 58 %, while consumers waste 38 % of the chicken they purchase (de Gorter et al., 2021; World Bank Group, 2020), the highest among all the meat (Jeswani et al., 2021). The corresponding environmental implications are substantial, reaching 16.78 million tonnes of CO2e annually, due to the associated emissions during poultry production, provisioning of animal feed and manure management (FAO, 2013; Poore and Nemecek, 2018). The carbon footprint from land use for chicken meat production is higher compared to pork and is similar as that of beef (Poore and Nemecek, 2018). Despite the fact that the water footprint of chicken products is lower in comparison to other types of meat, it surpasses that of other agricultural products like cereals or fresh vegetables (Harris et al., 2017). Consequently, increased consumption and wastage of chicken contribute to further depletion of natural resources. The chicken waste culminating in emissions contributes to 54.4 % of the total emissions from its production (de Gorter et al., 2021; World Bank Group, 2020). However, the perishable nature of chicken meat also challenges households to store them safely and therefore minimise food waste (Yavas and Bilgin, 2010).

The majority of food items, including meat, are retailed as packaged products in the UK (Robertson, 2009), for packaging plays a pivotal role in food production and supply chains by safeguarding and maintaining the quality of food products while also serving as an enticement for end consumers (Sazdovski et al., 2021). By modifying the packaging method, it can also influence the volume of household food waste generated. As an illustration, excessively large packages can impede complete food consumption, resulting in increased food waste and subsequently higher environmental footprints (Molina-Besch et al., 2019; Boone et al., 2023). Besides, the lack of circularity in single-use packaging undermines the sustainability of packaged food, thereby contributing to elevated environmental footprints associated with food packaging. Altogether, a well-conceived eco-friendly system, encompassing both food and packaging, is expected to find a harmonious equilibrium between minimising waste, and upholding efficient preservative performance (Verghese et al., 2015).

In light of these challenges, Life Cycle Assessment (LCA) has emerged as a valuable tool for identifying sustainable food systems. LCA presents a systematic methodology that includes a product's system, considering inputs, outputs and prospective environmental impacts throughout its lifecycle (ISO, 2006). Its application can highlight problematic areas within supply chains, thus enabling interventions that mitigate environmental burdens while boosting efficiency and profitability (Skunca et al., 2018).

In the context of LCA research, significant attention has been paid to the production phase, limiting to poultry farms (cradle-to-farm gate), slaughterhouses (cradle-to-slaughterhouse gate/ farm-to-slaughterhouse gate), and the entire chicken supply chain (Costantini et al., 2021; López-Andrés et al., 2018; Usva et al., 2023). However, there is a gap concerning the household-level implications of chicken meat consumption, which stands out as a primary catalyst for the environmental impacts originating from households in Europe (Cooreman-Algoed et al., 2022), including the UK (amounting to 165 kg CO_{2e} yr^{-1} per capita) (Poore and Nemecek, 2018; Salazar et al., 2020). Specifically, limited research has been carried out on the impact of consumer and market interventions, particularly those related to packaging, storage dynamics and specific socioeconomic groups (Skunca et al., 2018) potentially promoting a disinterested attitude towards resource conservation (Rasines et al., 2023). Furthermore, indirect environmental consequences, such as those resulting from food waste related to packaging, receive insufficient attention in the context of LCA methodologies (Molina-Besch et al., 2019). This oversight in LCA research was also commented on by Cooreman-Algoed et al. (2022), who pointed out the lack of research on food waste intricacies, food-packaging systems relationship and consumer behaviours. These behaviours and relationships, largely shaped by sociodemographic aspects, would need consideration in LCA research for a more comprehensive understanding of the environmental impact of interventions.

To build an evidence-base with which to propose consumer and market interventions to reduce food and packaging waste in the UK, and a Household Simulation Model (HHSM) was co-developed by Kandemir et al. (2022) and WRAP, a climate action non-governmental organisation (NGO) working around the globe to tackle the causes of the climate crisis. This model can accommodate intricate household dynamics and enables the exploration of challenging queries related to household food waste levels. The HHSM replicates the trajectory of different food products tracking their movement from supermarket shelves to household consumption and eventual disposal. For the purposes of this study, fresh chicken fillets have been selected as the case study. The HHSM captures household dynamics, behaviours about purchase, storage, consumption and disposal as a UK average and eight different household archetypes (HAs) based on WRAP segmentation of the UK population. Using the HHSM, different outcomes can be obtained, such as the amount of chicken waste generated by storage type and location, amount of plastic packaging waste generated, purchased amount, consumption amount and number of shopping trips carried out, among others. These findings, especially when combined with LCA, can offer insights into the environmental impact of various market and consumer interventions and facilitate decision-making in navigating the inherent trade-offs among these consequences.

The primary novelty of this paper is to combine LCA methodology with insights derived from the various interventions simulated in HHSM. Our integrated approach offers a comprehensive understanding of the environmental repercussions stemming from diverse consumer behaviour influenced by these interventions. Furthermore, the combined approach captures the complex household dynamics and provides a more sophisticated perspective that spans from retail to waste disposal. The LCA's scope extended from the retail sector through the end-of-life treatment of both the chicken and its packaging. This thorough analysis took into account both the UK average and eight different HAs.

The other novelty is that this study assesses the sustainability of household chicken consumption in the UK including cooking, storage and disposal, contributing to the discussion on key improvements needed towards sustainable consumption on a national scale. And a bottom-up approach is employed for the environmental impact assessment. The LCA utilises the average consumption patterns derived from evolution over time in the UK is used for the assessment. Furthermore, a baseline scenario is established to evaluate the potential effects of different eco-interventions.

Section 2 describes the methodology following the four steps of a LCA framework (i.e., goal and scope, life cycle inventory, life cycle impact assessment, and interpretation) as applied to domestic chicken consumption and disposal. Section 3 presents and compares the results of different interventions and implements sensitivity analysis of the built model. Section 4 summarises the effectiveness of various mitigation strategies from both retailers and consumers.

2. Materials and methods

2.1. Case description

This study utilises data from the Household Simulation Model (HHSM) to conduct LCA on the environmental impact of household consumption and domestic waste generated from fresh chicken fillets in the UK.

2.1.1. Chicken fillets details

The study considered the three main pack sizes sold in the UK market: 2-piece, 4-piece and 6-piece packs. Each piece in these packs had a weight that followed a uniform probabilistic distribution, ranging between 183 and 193 grammes (Liu et al., 2019; Pellattiero et al., 2020). The packaging of these products comprised a polypropylene tray, an Oriented Polypropylene (OPP) sealing film and a label. Packaging data was provided by Valpak (2022).

2.1.2. Household archetypes

Household profiles were obtained from WRAP's UK households segmentation research (Table A.1 in the Supplementary information) (Kandemir et al., 2022). There are eight HAs: aspirational discoverers (AD) family, functional fuellers (FF) single, FF couple, spontaneous creatives (SC) single, SC one child, ideal advocates (IA) couple, pressured providers (PP) family and PP single household. Moreover, a representative average UK household, quantified based on a weighed household composition, was considered.

2.1.3. System boundaries

The system boundaries spanned from retail chicken sales to the end-of-life treatment of chicken and its packaging (gate-to-grave), as shown in Fig. 1. Chicken production and warehouse distribution were not considered in this study. The exclusion is a deliberate choice, aligning with the study's consumer-centric focus, as the primary goal is to investigate and provide insights into the environmental impacts of consumers' behaviours concerning food waste and consumption patterns. Additionally, the upstream environmental impacts have been comprehensively explored and documented in previous research (Costantini et al., 2021).

2.1.4. Data from the HHSM

Given the challenge of tracking real data on consumers' domestic activities and capturing the complexity of their behaviour, accurately calculating the associated environmental footprint becomes difficult. In response, the HHSM offers proxy data to depict domestic activities of various HAs, facilitating a thorough investigation into how alterations in consumer behaviour can mitigate environmental impact and how the diversity among HAs influences environmental footprint.

The HHSM, built using the Arena simulation software, simulates the behaviour of each HA for 80 years and 30 replications using default parameters (Kandemir et al., 2022). The model comprises six interconnected modules, namely (1) model setup, (2) market, (3) shopping, (4) storing, (5) consumption, and (6) expiry. These modules collectively simulate the trajectory of chicken fillet packs, spanning from their initial display on supermarket shelves to their eventual utilization and disposal within households. Each module offers customizable features through input variables, as elucidated in Kandemir et al. (2022), facilitating the replication of diverse product attributes (e.g., shelf life), market dynamics (e.g., positioning strategies in supermarkets), and household practices (e.g., shopping behaviours, leftover consumption). (Kandemir et al., 2022).

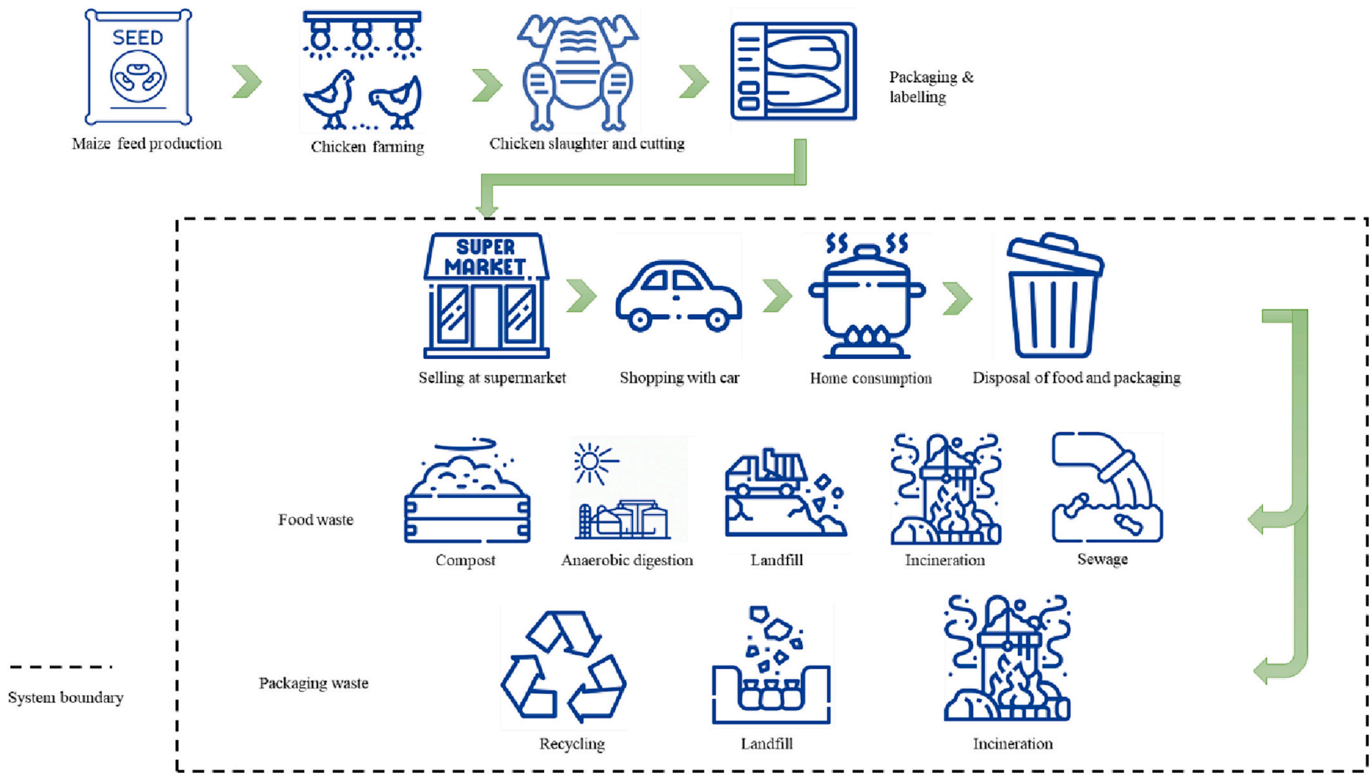

Fig. 1. The system boundary of chicken fillet products.

The model captures the weekly average and standard deviation of various outputs. The results from the HHSM provided quantities of chicken and associated packaging waste generated in UK households for different market and consumer interventions, along with purchased, consumed and storage amounts (Table A.2). This study specifically utilised data from a generated default scenario and the interventions shown in Table 1. Three interventions were devised to assess the impact of various combinations of pack sizes, extended shelf-life and portioning chicken for storage. Within each intervention, multiple scenarios were considered, resulting in a total of 12 envisioned scenarios, including a default scenario which served as a comparison point between the different scenarios. In the default scenario chicken remained unportioned and stored in its original packaging to mimic the behaviour of most UK citizens (Pickering, 2023). The shelf-life of unopened packs conforms to a triangular distribution denoted as TRIA (2, 5.2, 9), while that of opened packs remains constant as 3 days.

Table 1
The pack size, shelf-life extension and portioning interventions investigated in 12 scenarios.

Intervention	Scenario
Pack size availability for purchase	Availability of packs with 2 and 4 pieces (S1) Availability of packs with 2 and 6 pieces (S2) Availability of packs with 4 and 6 pieces (S3) Availability of packs with 6 pieces only (S4)
Shelf-life extension	
Unopened pack	1-Day extension (S5) 3-Day extension (S6) 5-Day extension (S7)
Opened pack	1-Day extension (S8)
Integration of unopened and opened pack	1 day extension for both unopened and opened packs (S9) 3-Day extension for unopened packs and 1-day extension for opened packs (S10)
Portioning	No portioning, but the chicken is stored in a household container (S11) The chicken is divided into two portions and stored in household containers (S12)

2.2. Material flow analysis

Material flow analysis (MFA) is a tool that examines the movement and quantities of materials within a system. It elucidates the links between sources, pathways and initial and final destinations of materials (Brunner and Rechberger, 2004). In this study, MFA were performed to trace the domestic waste flow from chicken fillets and its packaging, complying with the system boundaries defined in Section 2.1.3.

2.3. Life cycle assessment

2.3.1. Goal and scope

This study aimed to determine and compare the environmental impact of various market and consumer interventions scenarios for fresh chicken fillets sold in supermarkets and consumed by households in the UK depicting the influence of consumer behaviour. The details of interventions and the system boundary for LCA have been described in Section 2.1.

The functional unit corresponds to the average UK household's weekly consumption of a packed chicken fillet. This quantity was determined based on the output from the HHSM (weighted averages from Table A.2).

2.3.2. Inventory analysis

The analysis adhered to the ISO 14040 international standard. Data was mainly derived from the HHSM simulation results and secondary data from relevant literature. Ecoinvent V3.8 (cut-off allocation and unit processes) was adopted for the background processes. This study does not account for infrastructure or appliances.

2.3.2.1. Retail. Fresh chicken fillet packs were displayed on the open cold counters at the retail shops. Key data, including energy, water, and refrigerant gas consumption, were sourced from Cooreman-Algoed et al.

(2022). According to Heard (2020), the retail loss was assumed at 4 %. This study did not consider the destination of surplus food at the retail level due to lack of available data.

2.3.2.2. Household behaviours and dynamics. The consumption stage included household dynamics related to storage, food preparation and disposal. This data was derived from the HHSM simulations, including retail purchase quantities, the average chicken amount cooked and stored and the amount of food and packaging discarded (Table A.2). Further specifics, such as the percentage of chicken stored in the fridge and the freezer and the storage duration, were also derived from the simulation results as shown in Fig. 2. All the data provided from the HHSM included an UK average and figures across the eight HAs.

Information about energy usage (electricity and water) for cooking and storage was retrieved from the Ecoinvent database and the literature of Schmidt Rivera et al. (2014) and Castellani and Cardamone (2022) (Table A.1). The assessment of interventions did not encompass an evaluation of the environmental footprint arising from different cooking methods and kitchen appliances Nevertheless, to gauge the robustness of the model, diverse cooking methods will be adopted, with elaborations provided in Section 3.3 (Frankowska et al., 2020), only energy consumption metrics were factored into the cooking and storage processes.

2.3.2.3. Packaging. The focus was on primary packaging materials, specifically the polypropylene tray and not including the OPP sealing film (Valpak, 2022). According to Valpak's EPIC database (Valpak, 2022), the average package weight for small and medium sizes was 13.5 grammes and 17 grammes, respectively the weight for large packages was 22.2 grammes (Cooreman-Algoed et al., 2022). The designation of small, medium and large sizes for chicken fillets packs corresponds packs containing 2, 4 and 6 pieces, respectively, as indicated by the available pack sizes in retailers throughout the UK (Valpak, 2022). It is assumed each chicken piece within these packs weighs 188 grammes. Once the packaging was finished with, i.e. discarded, the plastic packaging was recorded as household waste.

Intervention 3 introduced the option of using reusable household containers for storing portioned chicken. The study assumed that households cleaned these containers before use, with an equal distribution between dishwashing and handwashing. Data on water and electricity consumption for this process was sourced from Greenwood et al. (2021). The usage of the household container and original package is not calculated in the storage process, only electricity and water usage are considered.

2.3.2.4. Transport. This stage encompasses consumer transport to retail outlets for households' food purchasing and food and packaging waste transport to processing facilities. Based on the data from the Department for Transport shown in Table A.8 (Department for Transport, 2023), the distances for shopping in retail vary across HAs. The consumer transport was assumed to be carried out on a middle-size passenger car with Euro engine class 4. The waste transport was assumed to be 21 metric ton lorry with an average distance of 25 km.

2.3.2.5. End-of-life waste. Based on the literature of Khoo et al. (2010) and the data from WRAP (WRAP, 2014), the distribution of food waste treatment was as follows: 45.45 % incineration, 8.3 % composting, 11.82 % anaerobic digestion and 12.12 % landfill, with the remainder being sewed. Regarding packaging waste, 59.2 % was recycled, 4.9 % incinerated, and 35.9 % landfilled, in line with existing practices (DEFRA, 2016). The environmental impact of food waste treatment was based on the data from Slorach et al. (2019a) and Slorach et al. (2019b). The data for packaging waste was acquired from the Ecoinvent database.

2.3.3. *Impact assessment methods and categories*

The environmental impacts were calculated using SimaPro 9.5.0.0 software. The impact assessment method was the Environmental Footprint (EF) 3.1 (the latest version), launched by the European Commission (European Commission, 2021). The EF method is used by Product Environmental Footprint Category Rules (PEFCRs) and Organisation Environmental Footprint Sector Rules (OEFSRs), as well as Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) studies (Knigawka and Ganczewski, 2023). The EF method contains 16 midpoint impact categories next to an aggregated single score based on the former. The single score is a dimensionless single indicator computed by weighting and normalising the endpoint values obtained from aggregating midpoint impact categories. The normalization factors used are articulated per capita, referencing a global standard (European Commission, 2022). Subsequently, in the weighting stage, the normalised results are multiplied by a series of weighting factors (expressed as percentages as shown in Table A.9), representing the relative importance of the considered life-cycle impact categories. The process of determining EF 3.1 weighting factors is elaborated on in (Sala et al., 2018). In essence, they incorporate evaluations from both the public and LCA experts across various aspects and criteria for each environmental impact category. Additionally, they assess the robustness of the underlying models for these categories, along with the normalization factors derived from global emissions data. The obtained single point is used to make the LCA results more accessible and understandable to communicate the environmental performance. Cut-off method is

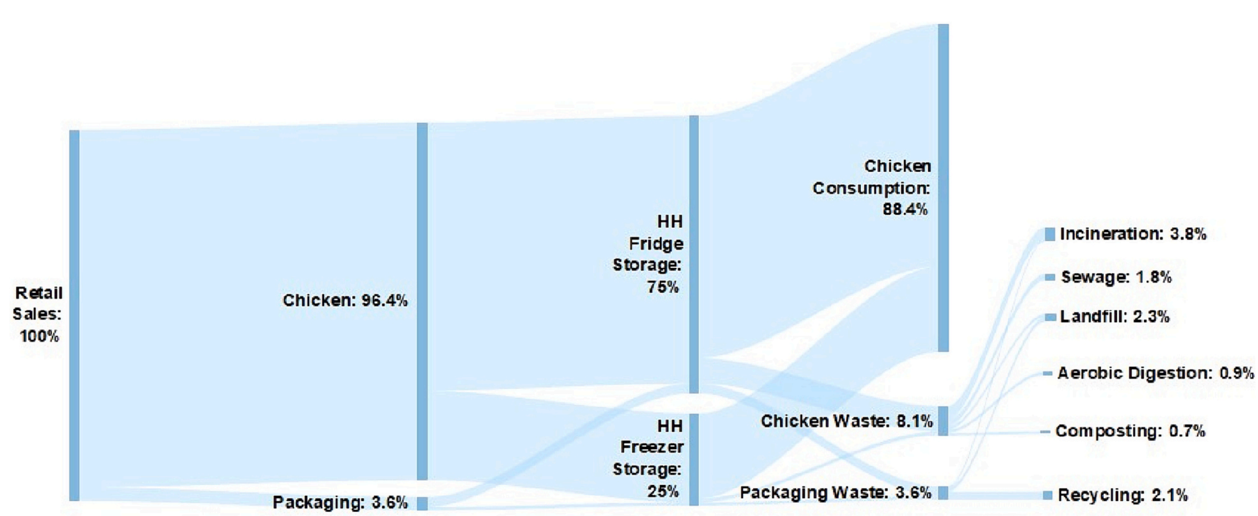

Fig. 2. Material flow analysis from retailers to end-of-life treatment.

adopted. The single score is demonstrated in the main article. Further detail of the 16 midpoint impact categories is provided in the Supplementary information section B.

3. Results

3.1. Default scenario

The default scenario modelled using the HHSM generated a weekly amount of chicken waste and a weekly chicken wasted-to-purchased ratio which resulted in 60.8 grammes and 8.3 %, respectively. Tables A.3–A.8 show all the default input parameters used for the simulation of this default scenario and Table A.2 shows the output values from the HHSM used as input for the LCA. In accordance, Fig. 2 demonstrates the material flow (expressed as a percentage) from the retailer to waste treatment facilities for the default scenario, forming the basis upon which the environmental emissions are computed.

3.1.1. The environmental impact for all the household archetypes

In the default scenario across all the interventions, the single scores for all the HAs are demonstrated in Fig. 3. A deeper red hue indicates greater environmental burdens, whereas a more pronounced purple shade suggests reduced environmental burdens. PP Family exhibits the highest score, with the AD Family and SC One Child following closely behind. In contrast, SC Single has the lowest environmental emission contribution. The second-lowest contribution is from FF Single. The performance of the remaining HAs - FF Couple, IA Couple, and PP Single Family - is comparable to that of average UK households. The end-of-life (EOL) stage has more impact from FF Single and SC Single, despite the emissions from waste not being the highest. However, the emissions from EOL have a comparatively milder impact from the PP Family, marked by the second-lowest value.

The single scores are juxtaposed with midpoint indicators frequently disclosed in food LCA studies, encompassing climate change, acidification, eutrophication, and terrestrial ecotoxicity (Vidergar et al., 2021). These indicators demonstrate comparable relative consequences across the 8 HAs and UK average (refer to Supplementary information Tables B1–B18).

Fig. 3 illustrates that in the default scenarios for the UK average, cooking stands out as the leading factor contributing to the environmental impact, accounting for approximately 24–76 μPt, which represents 42.1 %–58 % of the entire process. Among the various impact categories, home cooking emerges as the largest contributor, except in the case of ozone depletion, where the primary contributor is retail sales. This may be attributed to the refrigerant gases utilised in retails for fresh chicken storage. The next main contributor is travelling to retail for chicken purchase. However, for specific HAs, the situation complies only with FF Couple and IA Couple as shown in Fig. 3. For other HAs, retail sales contribute more. It can be attributed to less chicken purchased per trip and more shopping frequency or longer trips to retailers for the couple families. In contrast, other HAs are inclined to purchase larger quantities per trip or visit nearby supermarkets.

The emission from transport to retail scoring at around 9.7–24 (ranging from 14.6 %–20.1 %) is the third contributor except FF Single, FF Couple and IA Couple. For FF Single, it is domestic storage with 10 single points (17.4 %). It indicates that FF Single stores food for a longer time and does not engage in cooking significantly. To be notified, the transport has more impact coming to IA couple and FF couple at 20 % compared to other HAs (the reason has been explained above), while PP Single family (14.6 %) is more environmentally efficient for the transport. Concerning domestic storage, the environmental impacts are significantly lower than retail storage, particularly in the case of PP Family. This suggests that increased consumer purchasing and reduced retail storage tend to be more environmentally friendly. Despite the waste amount per week is not minimal, burdens from waste are the least in the entire process. Concerning chicken waste, the most substantial proportion of environmental challenges is associated with FF Single and SC Single, in comparison to other HAs. Furthermore, the environmental footprint resulting from the packaging waste of SC Single is the most significant, although it is relatively less substantial for FF Single. This reflects the preference of SC Single to buy smaller chicken packs compared to FF Single. And reducing the amount of food and packaging waste from Single archetypes can be most effective to release household environmental burdens among all the HAs.

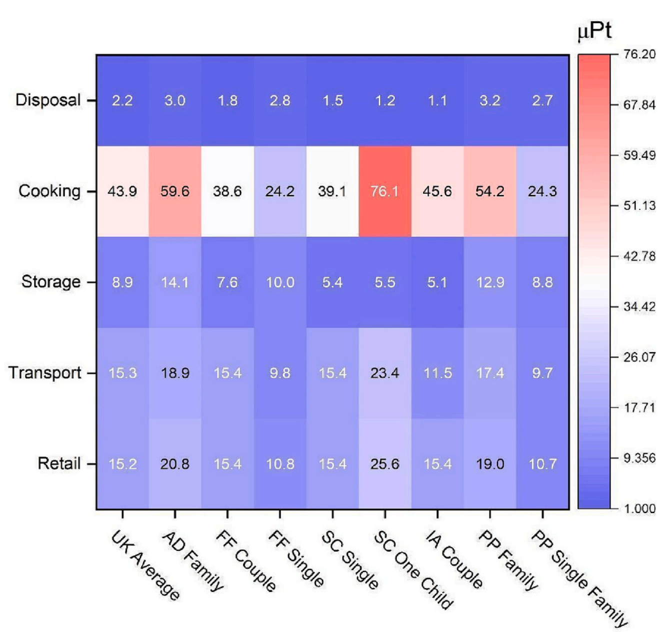

Fig. 3. Environmental impact for the default scenario.

3.1.2. Damage category details

The specifics of the damage category are presented for the UK average as a representation of the eight HAs, as shown in Fig. 4. It's evident that the majority of activities have a more pronounced effect on climate change compared to other categories. Nevertheless, domestic storage and home cooking have a greater impact on the resource category. This could be attributed to the fact that these two activities don't emit significant amounts of greenhouse gases, but they do involve substantial use of refrigerants and cooking gas/fuel. When taking into account the quantity of chicken involved in each activity, it becomes apparent that domestic storage has the most significant impact on climate change, followed by home cooking and chicken waste, in that order. Looking at the broader picture of both chicken and packaging, the climate change impact is greater than that of home cooking but still lower than that of domestic storage, reflecting the importance of choosing an environmentally friendly package. Further, the global warming potential for retail sales is higher than that of travelling to retail, and similarly for resource use-fossil and water consumption. This implies retail sales may lead to more potential abiotic fossil fuel depletion. Similarly, in the resource category, domestic storage has the most environmental impact, followed by home cooking. And the resource impact of the domestic chicken waste is higher than that of retail storage for sale. Further, the ozone depletion impact of chicken waste is the highest among all the activities per gramme, while the ionising radiation impact of home cooking is the highest. In this case, a policy decision regarding this trade-off may be needed in the future, to protect the environment. To alleviate the ozone depletion, chicken waste should be reduced or prevented, for example.

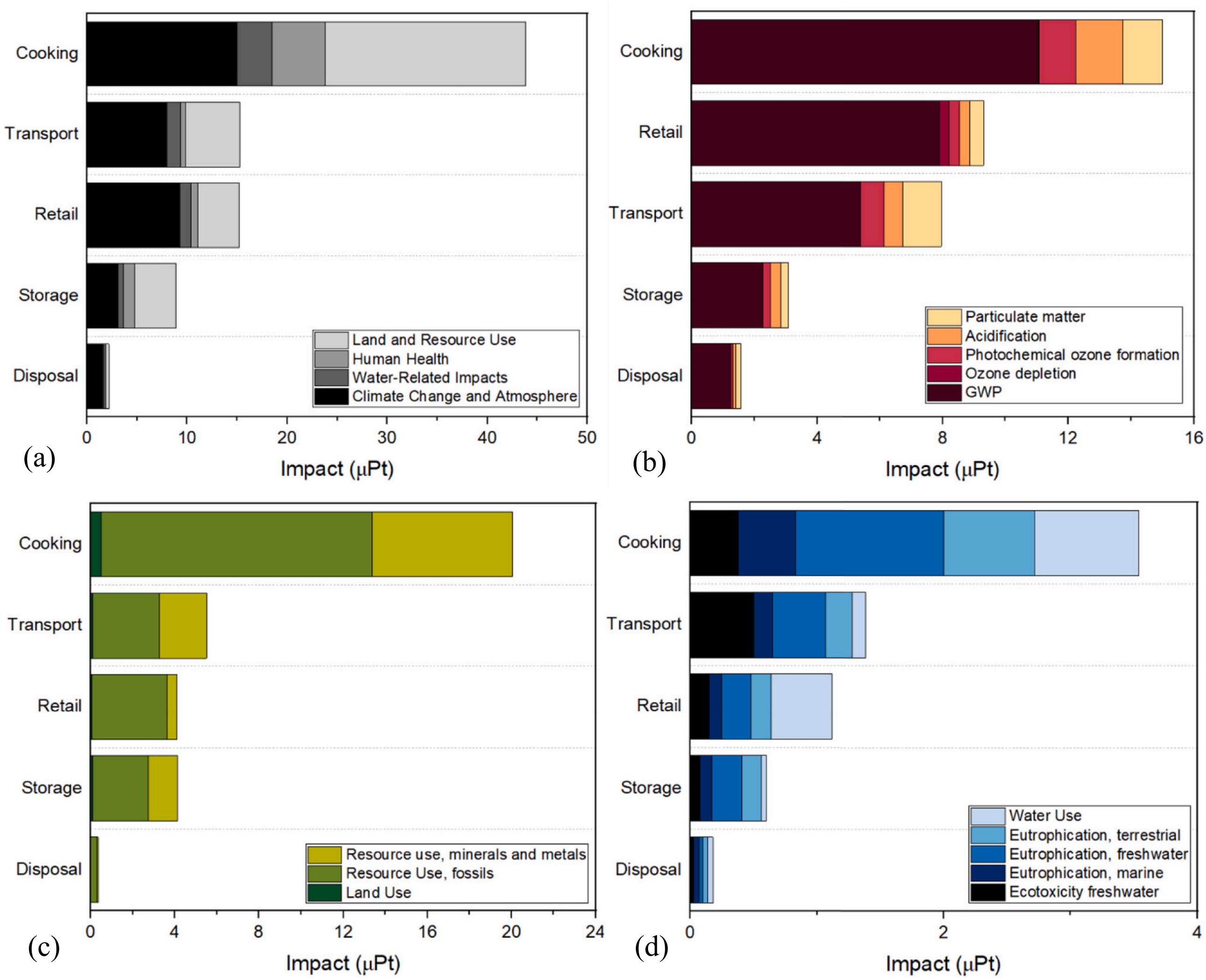

Fig. 4. Mid-point categories and details with (a) Human health (b) Climate change (c) Natural resources (d) Ecosystem quality in the default scenario for the UK average.

3.2. Comparison of different scenarios

The impact of the three interventions outlined in Section 2 on environmental footprints is expounded upon for both the UK average and the eight HAs. A comparative analysis is conducted on emissions from the entire process, food waste treatment, and packaging waste treatment processes, respectively. Fig. 5 comprehensively encapsulates the environmental ramifications across all 13 scenarios (including the default scenario) for the HAs, with Fig. 6(a) and (b) dedicated to delineating the effects on food waste and packaging waste, respectively. Observably, owing to disparities in quantity in the entire chicken pack, food waste induces a greater environmental impact than plastic waste. Further elaboration on these findings is provided in the subsequent subsections.

3.2.1. Pack size availability intervention

For the UK average, S1 generates the least waste (81.2 g) among all the scenarios in this intervention, indicating reduced unnecessary purchase, though slightly higher than the default scenario (80.9 g). However, S1 involves less purchase and consumption compared to the default scenario, with slightly more storage. Notably, for chicken waste, S2 excels in waste reduction (56.4 g). However, both purchase and consumption are more than the default scenario, but with less storage. Nevertheless, the packaging waste in S2 is 53 % higher than in both S1 and the default scenario. In terms of environmental impact shown in Fig. 5, there was no substantial difference between S1 and the default scenario, with only a marginal 3 % increase observed for S2. This illustrates that the proliferation of diverse packaging sizes within the market contributes to heightened environmental sustainability for the broader public. The findings from S2 indicate a trade-off dilemma between food waste and packaging waste. Hence reducing the package weight of the larger pack (1128 grammes and 752 grammes for large and medium pack, respectively, in this study) can effectively eliminate both food and packaging waste and reduce environment impacts.

When comparing S1 to the default scenario for specific HAs, FF Couple demonstrates the highest impact increase of 3.13 % on the waste environmental impact in accordance with the waste flow change trend. On the contrary, AD Family shows the most considerable reduction in impact, amounting to 2.78 %. Regarding the retail to consumption stage, there is not much difference in the environmental impact. This illustrates that larger packs do not automatically yield environmental benefits for all families. And pack size diversity has a greater impact on waste-related emissions rather than on consumption. Comparing S2 to the default scenario as shown in Fig. 6(a) and (b), the releases of waste environmental burdens vary across a range of 0.04 % to 20.28 %, with the exceptions of FF Couple, SC Single and IA Couple. SC One child achieved the most impact reduction of 20.58 %, trailed by PP Family 14.35 % and AD Family 11.78 %. Thus, it shows that larger packs are

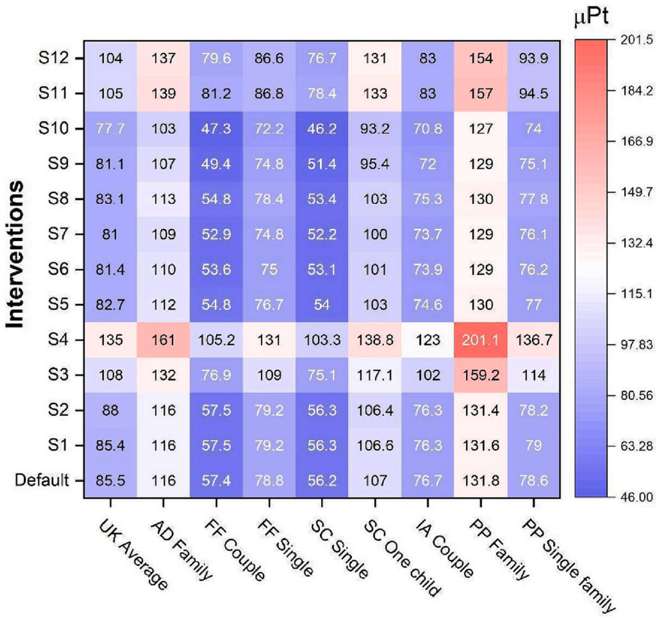

Fig. 5. Environmental impacts for all the 12 scenarios in the 3 interventions and the default scenario.

more suitable for families with higher consumption demands, exceeding the UK average consumption of 643.3 grammes per week per household as determined through simulation, such as AD family and PP family.

Comparing S2 to S1, the impact difference is negligible for all the HAs. On average, the impact is higher for the UK average. The contribution of waste environmental impacts is less pronounced in S2 in general, indicating purchasing at retail and home consumption carry a less significant environmental impact in S1. Therefore, it is imperative to minimise waste in order to alleviate environmental burdens. Upon closer examination, S1 demonstrates higher emissions from chicken waste yet lower emissions from packaging waste compared to S2. This suggests that for households with larger requirements, opting to buy 6-pieces can be an efficient strategy to curtail food waste. This underscores the idea that the acquisition of fewer (but larger) packs can alleviate environmental burdens, especially concerning chicken packaging for larger households.

The environmental burdens experience a sharp increase in S3 or S4, with a 26.6 % increase and a substantial 57.49 % rise for the UK average household in the two respective scenarios. Comparing S3 to the default scenario, it is noteworthy to emphasise that compared to other HAs, SC One child and AD family undergo only a 9.75 % and 13.35 % increase in environmental impacts, which is lower than the average situation. Likewise, PP Family leads to a 20.8 % increase. On the other hand, PP Single family demonstrates the most substantial increase (44.75 %) in the environmental impact, followed by FF Couple (38.25 %). The remaining HAs yield comparable environmental impact increase, around a 34 % rise. In the context of waste impact, there is a significant increase that ranges from 35.84 % to 281.92 %, with SC One child experiencing the smallest rise and PP Single family encountering the largest. It is evident that food and packaging waste play a more critical role in contributing to the environmental burdens in S3, due to the generation of a higher amount of avoidable waste.

Much like in S3, S4 witnesses a significant and noticeable increase in environmental burdens, ranging from 30.1 % to 83.91 %. Additionally, waste generation contributes substantially to this rise, showing an increase spanning from 150.22 % to 610.74 %. It can be deduced that S3 and S4 are not environmentally favourable options due to the increased waste generation, even for larger families. Interestingly, despite only a slight uptick in the amount of food and packaging waste compared to the

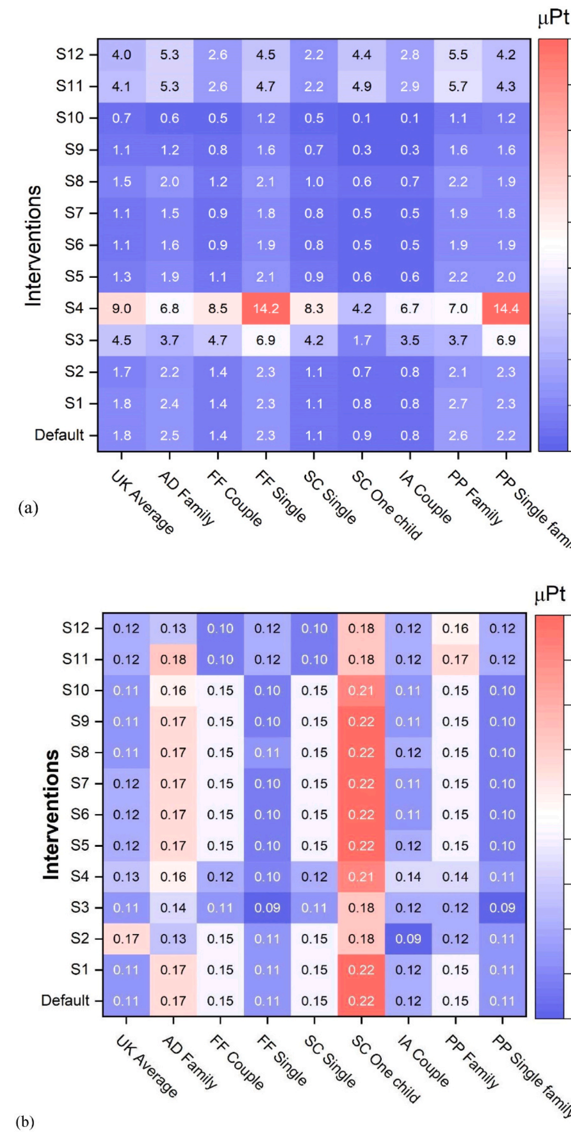

Fig. 6. Environmental impacts of (a) food waste and (b) packaging waste for all the 12 scenarios in the 3 interventions.

default scenario, there is a more substantial increase in the associated environmental burdens.

3.2.2. *Shelf-life extension interventions*

In this section, three interventions are explored: extending the shelf-life of i) unopened packs (3 scenarios), ii) opened packs (1 scenario) and iii) both unopened and opened packs (2 scenarios). The extension of shelf-life is achieved by modifying the value in the HHSM, with all other parameters held unchanged. It is important to note that the model's focus leads to the exclusion of food preservatives from consideration, thus no associated environmental impact is accounted for in this investigation. Of the six scenarios considered across the three interventions, the extension of shelf-life for opened packs exhibits the least reduction in food and packaging waste, whereas the combined shelf-life extension of unopened and opened packs results in the most substantial waste reduction. The overall reduction in environmental impacts from these three interventions varies between 1 % and 18 % across all the HAs. In the context of the waste treatment phase, the reduction extends from 9 % to 69 % across all the HAs. In the cases of open pack shelf-life extension and combined extension, the quantity of packaging waste is lower than that observed in the remaining intervention. The following subsections elucidate the environment impact variations associated with the material flows in each respective scenario.

3.2.2.1. Unopened pack shelf-life extension intervention. Extending the shelf-life of the unopened packs by one day (S5) resulted in decreased environmental burdens across all HAs, varying from 1.4 % to 4.58 %, compared to the default scenario. This change has a minimal effect on PP Family and most critical effect on FF Single. The impact reduction for both SC Single and SC One child is nearly identical, at 3.88 % and 3.84 %, respectively. Examining waste impact closely highlights a greater reduction, ranging from 9.86 % for SC Single to 25.93 % for PP Family. For chicken waste, there is a notable decrease ranging from 10 % to 33 %. As for packaging waste, there is a slight increase, ranging from 0 % to 2 %. Among these changes, PP Family experiences the most substantial reduction in the impact of chicken waste, while only achieving a 0.3 % reduction in packaging waste impact. Similarly, both PP Single family and AD Family observe significant reductions in the impact from chicken waste but negligible changes in packaging waste impact. This indicates that the environmental burdens arising from food and packaging waste can be more prominently alleviated in comparison to other activities, especially for family households.

Likewise, S6 led to more considerable reductions in impact, from 1.75 % for PP Family to 6.73 % for FF Single, compared to the default scenario. Nevertheless, the distinction in impact reduction on SC Single and SC One child is more noticeable, with SC Single showing a greater reduction. In contrast, concerning packaging waste, there is a reduction of approximately 0 % to 0.9 % for most HAs, except for PP Family. In this context it is worth implementing S6 to reduce the environmental burdens from waste.

The impact reduction in S7 accumulates in the range of 1.76 % to 7.88 %. Further, the differentiation in impact reduction between SC Single and SC One child is even more conspicuous, with SC Single achieving more reduction. Shifting the focus to waste impact mitigation, the decrease expands within the range of 19 % to 44 % for chicken waste and 0 to 2.8 % for packaging waste. It's evident that the reduction in waste burdens for PP Family is primarily due to a decrease in chicken waste compared to other HAs. On the other hand, for FF Single and SC Single, the reduction in the impact of packaging waste is relatively higher (2.8 %). This suggests that by extending the shelf life of chicken products, these two HAs may be able to reduce unnecessary purchases more effectively. Further notably, despite PP Family demonstrating a relatively high waste impact reduction, the overall burdens for the entire process reduce the least compared to other HAs. Hence, domestic cooking and storage have a more decisive influence on the environmental performance of PP Family. On the contrary, the situation is reversed for FF Single.

Compared among S5, S6 and S7, the additional intervention is low impact. The least reduction is observed in PP Family, whereas the most notable reduction happens in SC single for all the three scenarios. And the reduction is inversely proportional to the shelf-life extension; specifically, the longer the extension, the smaller the reduction. When we factor in waste impact reduction, a similar trend emerges. PP Family achieves the smallest decrease, with a 6 % reduction in chicken waste and 0.5 % reduction in packaging waste compared S6 to S5 and 1.1 % reduction in chicken waste and no improvement in packaging waste compared S7 to S6. Conversely, AD Family achieves the largest reduction, with a 14 % and 5.4 % decrease in chicken waste from S5 to S6 and S6 to S7, respectively. Indeed, packaging waste remains constant for most HAs. However, AD Family experiences a 0.6 % reduction for both comparisons, while FF Single and SC Single achieve a 1 % reduction comparing S7 to S6 and unchanged impact comparing S6 to S5. This indicates that S7 is notably effective in reducing both the quantity of purchases and waste for these three HAs. Regarding the remaining HAs, they tend to consume more without necessitating supplementary purchase, thereby contributing to a reduction in chicken waste.

3.2.2.2. Opened pack shelf-life extension intervention. In comparison of S8 to the default scenario, the environmental impact reduction varies in the range of 0.5 % to 4.9 % across the HAs. The mitigation on FF Couple is minimal at 0.5 %, and the elimination on FF Single and SC Single is the biggest at 4.6 % and 4.9 %, respectively. The retail to consumption process has a relatively prominent influence on PP Single family and PP Family. In comparison to other HAs, the environmental burdens of waste have a comparatively stronger influence on FF Single and SC Single. Similar circumstances apply for SC One child.

Regarding environmental impacts of waste, there is a noticeable reduction in chicken waste for all HAs, ranging from approximately 10 % to 25 %, as shown in Fig. 6. Among these archetypes, PP Family experiences the most substantial reduction, while IA Couple experiences the least. The decrease in waste can be attributed to reduced waste generation stemming from increased consumption along with the extension of shelf life. This intervention proves to be more efficient for families with higher consumption needs since they can make use of longer-lasting food items without the need to buy new ones. However, when it comes to packaging waste, three HAs - AD Family, FF Single and PP Family- witness a slight increase. Meanwhile, half of the HAs-FF Couple, IA Couple, SC One child and SC Single- experience a slight decrease. PP Single family remains unaffected by the intervention. These situations may arise because AD Family, PP Family, and FF Single tend to buy and consume more, leading to increased packaging waste. However, for the remaining HAs, there is either no change or even a decrease in purchases, coupled with increased consumption in S8. When we consider the overall impact, the reduction in waste varies from 8.64 % to 19.37 %, with the smallest reduction seen in IA Couple and the most significant reduction observed in PP Family. This suggests that the increased impact of packaging waste can be offset by the decreased impact of chicken waste in S8. Therefore, it is imperative to prioritise the reduction of food waste.

3.2.2.3. Unopened and opened pack shelf-life extension. Extending shelf-life by 1 day for both unopened and opened packs (S9) results in varying degrees of reduction in environmental burdens. The smallest reduction is observed in PP Family at 2.4 %, however, FF Single yields the most substantial reduction at 13.9 %. SC One child sees the second largest reduction at 10.6 %. In terms of the waste impact, the decrease ranges from 30.3 % (SC Single) to 68.7 % (PP Family) for chicken waste. For packaging waste, there is a negligible increase for PP Family. The decreases range from 1 % to 4 % for other HAs. Bearing the full picture in mind, the environmental burden of waste has a lower impact on PP Family, while SC Single and FF Single face the opposite situation.

In the context of S10, the reduction in waste varies from 3.7 % for PP Family to 17.8 % for SC Single. When we specifically focus on the environmental impact of chicken waste, the impact decreases within a range of 45.7 % (SC Single) to 87.5 % (PP Family). As for packaging waste, the reduction falls within a range of 0.8 % (PP Family) to 6 % (FF Single). Interestingly, although PP Family experiences the most substantial reduction in chicken waste impact, PP Single family achieves the most significant overall waste mitigation, while SC Single sees the smallest reduction. This underscores the significance of minimising the impact associated with both chicken and packaging waste.

As the reduction pattern slightly diverges from S9, the comparison of S10 and S9 is conducted. There are the least changes for PP Family, PP Single family and IA Couple at 1.3 %, 1.4 % and 1.6 %, respectively. The reduction impact on AD Family (3.4 %) and FF Couple (3.5 %) is similar. It is noteworthy that there is 10.2 % impact reduction comparing S4.3 to S4.2 for SC Single. Therefore, the strategy of extending unopened packs by 3 days is effective for SC Single. For chicken waste burden alleviation, the reduction stretches the least of 22 % to the most of 60 %. For packaging the reduction is negligible. Correspondingly, the chicken waste impact reduction level reaches 45.2 % and 41.8 % for AD Family and FF Couple, respectively. Thus, reducing food waste generated from

FF Couple can release more environmental burdens. Likewise, less waste contributes more to build a friendly environment by IA Couple compared to PP Family and PP Single family. Moreover, intervening from S9 to S10, PP Single family enables more waste environmental impact reduction. From a waste reduction perspective, the combination strategy in S10 is more effective.

3.2.2.4. Shelf-life extension interventions comparison. When comparing the 1-day shelf-life extension scenarios, namely S5, S8, and S9, it becomes evident that S9 (Extending shelf-life by 1 day for both unopened and opened packs) achieves the most significant reduction. The percentage decreases among these three scenarios are depicted in Fig. 5. In terms of chicken waste, there is less impact in S8 for FF Single, SC One child, and SC Single, while the reverse is true for the remaining HAs. The least affected HA is FF Single, with a 0.4 % increase, while the most impacted one is PP Single family with a 13 % decrease. Regarding packaging waste, the impact remains the same in both scenarios for SC Single and PP Single family, with only a notable 7 % reduction for FF Single when comparing S5 to S8. However, for FF Couple, the impact increases by 3 % in S5. Considering the overall waste impact, PP Single family experiences the most significant reduction at 10.2 %, while FF Single experiences the least reduction at 0.1 %. SC Single is the only HA where there is an increase in impact at 3.4 %. It can be deduced that extending the unopened pack shelf life by 1 day is more effective for couples and families in reducing environmental emissions from waste. Furthermore, FF Single can reduce food waste more when extending the opened pack shelf life, but this may lead to an increase in packaging waste. Hence, choosing between these two interventions involves a trade-off.

In comparison of S9 and S5, there are reductions within the range of 1 % to 10 %. The influence of switching between these two strategies is extremely close for FF Couple and PP Single family. The influence for FF Single is the most at 10 %. From the perspective of chicken waste burdens, for the UK average the reduction by S9 is 17 %. The least affected HA is IA Couple, while most affected is PP Family at 53 %. The influence for FF Couple and PP Single family is of limited difference considering the entire process or the packaging waste burdens; however, the influence of food waste burden is around 14 % difference. This shows that PP Single family can reduce more emissions from chicken waste rather than FF Couple in S9. Overall, all HAs reach lower chicken waste impact in S9.

Comparing S10 with S7, the best performer in each sub-intervention, S10 is more environmentally friendly, especially for FF Single and SC Single. Regarding the chicken waste performance, PP Family obtains the largest reduction more than half, followed by PP Single family. Overall, around 11,355 t of CO_2 emissions per year for all UK households can be saved in S10 compared to S7, and 32,638 t of CO_2 emissions can be saved from the default scenario for chicken waste impact, respectively. Regarding packaging waste impact in S10, the savings amount to 660 t of CO_2 emissions compared to S7 and 205 t of CO_2 emissions compared to the default scenario. In the context of overall waste management, S10 presents the potential to reduce CO_2 emissions by 11,955 t compared to S7 and by 32,843 t in comparison to the default scenario. When considering transportation for waste management as well, a total reduction of 12,835 t of CO_2 emissions are achievable in contrast to S7, with an even more substantial and 34,720 t reduction when compared to the default scenario. Regarding the entire process involved, 54,566 t of CO_2 emissions are saved in S10 compared to S7, and 130,722 t of CO_2 emissions compared to the default scenario, which is 0.16 ‰ and 0.39 ‰ of the UK's carbon emissions in 2022, respectively (Department for Energy Security and Net Zero, 2023).

In consequence, it can be concluded that the integrated shelf-life extension is more effective than the separate open or closed shelf-life extensions. This approach not only keeps food fresher but also reduces more food and packaging waste, thereby alleviating environmental burdens, particularly for family-type households with larger chicken requirements. When considering the choice between extending the shelf life of opened and unopened pack chicken, extending the open pack shelf life is a more constructive option for SC Single. However, for other HAs, extending the unopened pack shelf life is the better choice.

3.2.3. Portioning

Portioning is where consumers divide the chicken fillets into smaller units intended for domestic storage. These segmented chicken cuts are individually packaged with different containers, such as household containers or the original packaging, for freezing or refrigeration.

Looking into the scenario of portioning chicken packs in two reusable household containers (S11) and the scenario of portioning chicken into both a reusable household container and the original package (S12), the environmental impact increases significantly compared to the default scenario. SC Single and FF Single encounter the highest increase at 40 % and 41 % in S5.2 and 37 % and 39 % in S5.3, respectively. Domestic storage contribution increases significantly, contributing the most to environmental emissions, (rather than home cooking as in other scenarios) for the two single HAs. Hence, it is not advisable to use household containers for storage, especially for single households. For the chicken waste impact, the increase is dramatic from 88 % to 475 % across all the HAs in both scenarios. The huge increase may be attributed to longer storage in short shelf life (open life) reusable household containers leading to more waste.

For the packaging waste impact, the situation is different. In S11, despite the impacts increase for five HAs, there is a reduction in impacts for FF Couple, IA Couple, and PP Family when compared to the default scenario. Similarly, in S12, in addition to the three aforementioned HAs, the packaging waste impact is reduced for the AD Family. This phenomenon can be attributed to the use of reusable household containers, which encourage longer domestic storage and consequently lead to reduced consumption before the products expire. This is supported by the observation that in S12, where partial original packaging is used, the chicken waste impact is lower than in S11. In the case of the other five HAs, the rise in packaging waste impact might stem from increased purchase behaviours and extended domestic storage practices. Therefore, it can be inferred that opting for the original packaging is a more favourable choice with short "open life" foods such as chicken fillets.

3.3. Sensitivity analysis

In this study, a comprehensive LCA is conducted to evaluate the influence of various interventions on environmental impact for UK households. To ensure the robustness of our findings, we incorporated a sensitivity analysis that focused on three critical variables: cooking methods, food waste collection distance and the method employed for waste treatment. By systematically examining the influence of these variables, we aimed to gain deeper insights into their effects on the environmental performance, thereby providing a more nuanced understanding of the sustainability implications. The following subsections deliberate the sensitivity analysis.

3.3.1. Different cooking methods

The environmental impact of cooking chicken was initially derived from the literature of Schmidt Rivera et al. (2014) and Castellani and Cardamone (2022) in the built model. According to a survey conducted by Frankowska et al. (2020), the majority of respondents preferred roasting or baking chicken in the oven (64 %), followed by shallow frying on a stove (25 %). Other cooking methods included toasting, broiling or grilling in the oven (6 %), using a slow cooker (4 %), deep frying (4), steaming (4 %), boiling on the stove (2 %) and using an electric grill (2 %). Therefore, to examine the influence of various cooking methods, four scenarios are established. First, the integration of cooking methods with the weights from the survey is adopted. Additionally, since the most prevalent cooking methods are roasting in the oven and shallow frying on the stove, the environmental impact associated with these two methods has also been calculated. The cooking method- broiling in the oven is also considered due to high electricity usage. The data for water and electricity consumption is presented in Table C1 in Supplementary information.

The sensitivity analysis revealed notable variations in environmental impacts across different cooking methods. Compared to the default scenario discussed in Section 3.1, all the other scenarios demonstrated lower impacts across most categories as illustrated in Table 2. Shallow frying on the stove showed the least environmental burden, particularly in climate change, freshwater ecotoxicity and resource use. In contrast, oven broiling presented the highest impacts, especially in climate change, marine eutrophication and ionising radiation categories.

It becomes evident that within the scenario incorporating a variety of cooking methods, there is a discernible reduction in energy consumption, thereby resulting in a decrease in the overall environmental footprint compared to the default scenario. Therefore, to minimise individual environmental impact, it's advisable to select an appropriate cooking method. However, using open shelf-life intervention as an example, the environmental reduction is similar across all scenarios considered here. However, using open shelf-life intervention as an example, the environmental reduction is similar across all scenarios considered here. Hence, the influence of all the interventions on the environmental footprints still follows the trend.

3.3.2. Food waste collection distance

Two scenarios are considered to compare with the default scenario, one is setting the waste collection distance to 10 km per trip, and the other is 50 km per trip. As we study one-week generated waste per household, the amount is relatively small. Hence, the environmental impacts have small values. As shown in Table 2, when the collection distance is 10 km, the environmental burden is released a bit. Conversely, the environmental burden increases when the distance becomes 50 km. To be noticed, the impact of particulate matter, eutrophication and photochemical ozone formation changes explicitly among the three scenarios. Like the last sub-section, in the open shelf-life intervention, the environmental reduction is nearly identical across all scenarios considered here.

3.3.3. Waste treatment

In this subsection, four scenarios are studied to compare with the default scenario, which are only AD for the food waste, only food waste composting, only incineration and only landfill, as illustrated in Table 2. It can be seen that the environmental impacts of waste are reduced in the range of 10 % to 19 % except the scenario of only food waste composting. There is a substantial increase in the impacts of acidification, particulate matter and eutrophication in the composting scenario, and an increase of 49 % regarding the waste impact. Hence, it shows the importance of selecting the appropriate waste treatment method to save the environment. Regarding the intervention influence, there is still not much difference among the scenarios, which is expected.

3.3.4. Weighting factor

An alternative set of weighting factors, sourced from Chau et al. (2021) and detailed in Table A.9 in the Supplementary information, is incorporated and compared to the default scenario. As shown in Table 2, the impacts of climate change, particulate matter, land and water use, resource use and photochemical ozone formation are reduced with the use of the derived weighting factors, due to the absence of consideration for the global emissions as in the default scenario. However, the impact of climate change remains predominant. Moreover, similar to the preceding three sub-sections, the environmental reduction is nearly indistinguishable across all scenarios considered herein.

3.4. Discussion

As demonstrated in the preceding section, various interventions can result in varying levels of environmental impact reduction depending on the specific HAs. In areas with a higher concentration of singles and couples, it is recommended to maintain three types of packaging options

Table 2
Environmental impacts involving different cooking methods, transport distances, waste treatment methods and weighting factors of the impact assessment.

			Cooking method			Waste collection		Waste treatment method				Weighting factor
	Default	Cooking method combinations	Shallow fry	Oven roast	Oven broil	10 km	50 km	Anaerobic digestion	Compost	Incineration	Landfill	No global emissions considered
Acidification	2.85	2.47	1.76	2.60	4.66	2.84	2.87	2.81	3.34	2.80	2.80	2.84
Climate change	27.81	24.99	19.82	25.97	41.01	27.77	27.89	27.63	27.72	27.67	27.77	23.47
Ecotoxicity, freshwater	1.13	1.04	0.86	1.07	1.59	1.13	1.14	1.13	1.14	1.13	1.13	1.13
Particulate matter	3.31	2.99	2.40	3.10	4.79	3.27	3.36	3.23	3.85	3.25	3.24	1.17
Eutrophication, marine	0.83	0.71	0.50	0.75	1.36	0.82	0.84	0.82	0.84	0.82	0.82	1.29
Eutrophication, freshwater	2.10	1.80	1.25	1.90	3.49	2.09	2.10	2.08	2.09	2.09	2.09	3.02
Eutrophication, terrestrial	1.27	1.09	0.76	1.15	2.13	1.27	1.29	1.24	1.36	1.26	1.26	2.57
Human toxicity, cancer	0.48	0.42	0.32	0.44	0.74	0.48	0.48	0.48	0.48	0.48	0.48	0.73
Human toxicity, non-cancer	1.57	1.31	0.84	1.40	2.77	1.57	1.57	1.57	1.57	1.57	1.57	3.59
Ionising radiation	5.57	4.53	2.63	4.90	10.42	5.57	5.57	5.57	5.58	5.56	5.57	8.91
Land use	0.76	0.63	0.39	0.67	1.36	0.76	0.76	0.76	0.76	0.76	0.76	0.50
Ozone depletion	0.37	0.37	0.36	0.37	0.40	0.37	0.37	0.38	0.37	0.37	0.38	0.46
Photochemical ozone formation	2.55	2.25	1.70	2.35	3.94	2.53	2.58	2.53	2.56	2.54	2.54	1.86
Resource use, fossils	22.62	19.32	13.29	20.47	38.03	22.59	22.66	22.62	22.60	22.64	22.58	15.01
Resource use, minerals and metals	10.74	9.03	5.92	9.63	18.69	10.74	10.74	10.74	10.73	10.74	10.73	8.66
Water use	1.49	1.40	1.29	1.41	1.69	1.49	1.50	1.49	1.50	1.50	1.49	0.96

in the market. Conversely, in family-oriented neighbourhoods, retailers may choose to offer only 2-piece and 6-piece packs to enhance environmental sustainability. Adhering to the research conducted by Williams et al. (2020), the situation of only medium-size and large-size packs available should be avoided, as they result in increased waste generation and environmental burdens. Additionally, promoting shelf-life extension for both unopened and opened packs could be encouraged through initiatives such as seminars or public announcements for all the HAs. Furthermore, it is worth suggesting the adoption of the sharing economy concept, such as food-sharing practices, among households to enhance food supply chain sustainability (Ibn-Mohammed et al., 2021). It is also advisable to establish partnerships with local food banks or shelters to donate excess edible food. This can be an effective way to both reduce food waste and contribute to society. Among all the damage categories, the impact of climate change is the most significant except for PP Family. To reduce global warming, it is necessary to control the whole consumption and disposal stage. Among all the interventions, S10 achieves the best performance. And compared to the intervention of extending open and unopened shelf-life separately, extending both concurrently has proven effective in preserving the freshness of the chicken to a notable extent.

Taking into account that dividing the purchased chicken into portions increases both the amount bought and waste generated, which in turn raises environmental burdens, it is advisable to store chicken in its original packaging. Throughout the entire purchase-to-disposal lifecycle, it is noteworthy that domestic storage exerts the most pronounced environmental impact for every 1 gramme of chicken. Therefore, it is recommended to minimise the storage duration and consume chicken soon after purchase, especially for Single archetypes. Given that cooking has the greatest environmental impact, opting for clean cooking fuels or energy-efficient cooking appliances and sustainable technologies are prudent choices to enhance environmental and social sustainability (Bharadwaj et al., 2022; Jia et al., 2022; Aberilla et al., 2020). As FF Couple and IA Couple contribute more on travelling to retailers for purchase, it is suggested that they buy more chicken per trip without increasing the waste.

Furthermore, it can be noticed that in the intervention of extending open shelf-life, there are cases the packaging waste is increased though the chicken waste is reduced. In this context, it is suggested that light-weighted package materials should be used. And more sustainable materials should be studied and adopted in the market. And to raise consumers' awareness, public educational campaigns can be conducted to convey knowledge about the critical environmental impact of packaging and food waste, which may alleviate over-consumption (Horton et al., 2017). The policy makers can also make relevant regulations to nudge retailers towards environmental-friendly behaviours. For instance, eco-labelling with carbon emission information can be requested on the chicken packs. And they can decrease tax on usage of sustainable packaging materials.

Promoting pertinent educational initiatives within higher educational institutes can be further incentivized, as they have shown a proactive disposition towards waste reduction, as indicated by Shboul et al. (2023). Faculty members may be incentivized to integrate curriculum modules related to food waste reduction, particularly within academic disciplines such as environmental science, sustainability, and nutrition. Moreover, enhanced support and engagement can be cultivated through strategic partnerships with campus sustainability organisations and environmental clubs.

Regarding waste treatment; considering the increased environmental burdens associated with longer collection distance, it is advisable to optimise the network of waste treatment facilities network to minimise the overall transportation distance. According to the last section, it is notable that chicken waste composting imposes the greatest environmental burdens compared to other treatment methods, because the incineration and landfill incorporate energy recovery. Thus, selecting the appropriate treatment methods can be more environmentally friendly, such as AD of the chicken waste. In addition, increasing the recycling rate of the packaging waste is encouraged. It is also suggested to regularly monitor and assess food and packaging waste generation to track progress and identify areas for improvement. Results of monitoring can be shared with the public to maintain transparency.

4. Conclusion

This is a first study that integrates LCA and the simulation of household consumption and waste together to model the UK households' poultry and packaging waste environmental impacts. The material flow data is averaged on 80 years of simulation data. Three interventions including 12 scenarios were considered. The scenario in which extending 1 day shelf-life of open packs and 3 days shelf-life of unopened packs achieves the largest reduction of environmental emissions. 34,720 t CO_2 emissions can be saved from waste treatment and 130,722 t saved from the entire process in this scenario from the default scenario in the UK annually.

Moreover, the analysis of various interventions and scenarios has provided valuable insights into the environmental impact of chicken consumption across different HAs in this study. Cooking, especially with specific methods like broiling, and domestic storage have emerged as key contributors to environmental burdens, emphasising the need for energy-efficient cooking methods and minimising storage duration.

Packaging size interventions revealed that larger packs are not universally beneficial; their impact depends on the household size and consumption patterns. Extending the shelf-life of both opened and unopened packs proved to be effective in reducing waste-related environmental burdens, with integrated extensions yielding the most substantial reductions. Portioning, especially when using household containers, led to significant environmental impacts due to extended storage. Opting for original packaging was found to be a more favourable choice. Waste treatment methods demonstrated varying environmental impacts, emphasising the importance of appropriate waste management strategies. Sensitivity analyses underscored the significance of cooking methods, waste collection distances, and waste treatment choices in influencing environmental burdens. Energy-efficient cooking, optimising waste collection networks, and selecting suitable waste treatment methods are crucial strategies for reducing environmental impacts.

In summary, a holistic approach that combines different modules for sustainable cooking practices, appropriate packaging, waste management, and consumer behaviour changes is essential for mitigating the environmental impact of chicken consumption and optimising household-specific consumption patterns. Tailoring interventions to specific HAs and considering local contexts are key factors in developing effective and environmentally friendly strategies.

There are some limitations regarding the data uncertainty, no study, the authors are aware of, thoroughly assessed the uncertainty of food domestic purchase and consumption data. There is typically a shortage of specific information and literature in this regard. This highlights the need for further research to enhance the quality of the data utilised in the assessment. A similar situation is observed concerning the energy expended on cooking, where a wide range of data exists in the literature. In this study, for example, we mostly relied on processing datasets adapted from other literature, as ecoinvent v3.3 only provides data up to the farming stage for the majority of the food products. Likewise, our modelling covers "typical" household consumption and cooking patterns. The practice of bulk cooking, freezing, and then re-heating (see Pickering, 2023) would have potentially lower cooking impacts, but is not simulated in this paper. Moreover, background processes, such as the inclusion of preservatives for extending shelf-life, can be incorporated into the HHSM to assess the corresponding environmental impacts. These are aspects that may be improved in future studies. Additionally, this work provides a static model. In future, a dynamic or time-related food LCA model can be studied, as suggested by (Khoo et al., 2019).

Furthermore, the entire food supply chain can be evaluated in the future to observe the influence of diverse consumer behaviours.

CRediT authorship contribution statement

Rui Guo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Virginia Martin Torrejon:** Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Christian Reynolds:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Ramzi Fayad:** Data curation, Investigation, Software. **Jack Pickering:** Writing – review & editing. **Rachel Devine:** Data curation, Validation, Writing – review & editing. **Deborah Rees:** Funding acquisition, Methodology. **Sarah Greenwood:** Conceptualization, Data curation, Writing – review & editing. **Cansu Kandemir:** Funding acquisition, Investigation, Conceptualization. **Lorraine H.C. Fisher:** Methodology. **Adrian White:** Project administration. **Tom Quested:** Conceptualization, Funding acquisition, Methodology. **Lenny S.C. Koh:** Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing, 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.

Data availability

I have shared the data in the article and the supplementary information

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Appendix A. Supplementary data

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