Journal of Cleaner Production 451 (2024) 142068

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Reducing food loss and waste contributes to energy, economic and environmental sustainability

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A R T I C L E I N F O

Handling Editor: Panos Seferlis

Keywords:
Energy
Food policy
Postharvest
Logistics
Environmental impacts
Food loss and waste (FLW)

A B S T R A C T

Food loss and waste (FLW) reduction presents a major opportunity for enhancing the sustainability and resilience of the food supply chain. However, the lack of evidence regarding the scale and origins of FLW hinder determination of its environmental impact and prioritisation of mitigation action. We herein conducted a study to quantify FLW in the UK horticulture supply chain, and estimate its environmental impact as assessed through CO_2 equivalent (CO_2e) emissions. Through a metanalysis of existing literature supplemented with stakeholder engagement, we estimated that 2.4 Mt of fresh produce FLW is generated annually between farm gate and retail for home-grown and imported produce, representing 36% of total supply. FLW was perceived as an inevitable economic risk rather than a sustainability issue, driven by economic factors (e.g. labour shortage, price protectionism). The lack of economic incentives for FLW recovery (e.g. alternative processing) further compound FLW. Our results reveal that FLW contributes 1.7 Mt CO_2e annually, constituting 27.2% of the total emissions of the fresh produce supply chain. Resource-intensive production, prolonged storage and complex handling needs generates substantial energy demand and concordant environmental impacts. The current over-reliance on cold chain management should be re-examined to disentangle the FLW-energy-environment nexus, especially given that the effects of global warming on the horticulture supply chain has yet to be examined. To effectively mitigate FLW, a holistic approach is imperative, encompassing policy and consumer-level changes alongside development of novel postharvest management strategies.

1. Introduction

Food loss and waste (FLW) poses a formidable challenge with far-reaching economic, societal, and environmental implications. FLW encompasses both physical product loss and the waste of the inputs used during production (e.g. agrochemical use, blue water consumption) and the energy used to maintain quality and safety across the supply chain (e.g. refrigerated transport, storage, distribution). The application of these elements incurs the emission of greenhouse gasses (GHG), making the holistic understanding of the food system essential to tackle sustainability concerns. This challenge is particularly significant for highly perishable fruit and vegetables, where postharvest management heavily relies on high intensity cooling to prevent FLW, leading to energy demands (Chen et al., 2022; Trotter et al., 2023). Despite the presence of cold chain in developing countries, it is not always properly managed, making this food group is responsible for 42% of global GHG emissions linked to FLW (Porter et al., 2016). The escalating global temperatures associated with climate change further exacerbate the pressure on cold chain efficiency, impacting on energy demand of the cold supply chain. However, the quantification of this effect has yet to be fully examined (Foster and Evans, 2023) especially concerning horticulture crops that require rapid field heat removal and consistent temperature control. Various metrics, such as energy consumption and pollution generation have been used to quantify the FLW environmental impacts (Cuéllar and Webber, 2010; Grizzetti et al., 2013). GHG emissions consider methane, nitrogen dioxide and refrigerant leakage alongside carbon dioxide (CO_2) generation and is perhaps the most useful metric due to its universality between different supply chain stages, with current estimates of 27 Mt

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https://doi.org/10.1016/j.jclepro.2024.142068
Received 12 January 2024; Received in revised form 19 March 2024; Accepted 31 March 2024
Available online 5 April 2024

CO_2 equivalents (CO_2e) produced by the United Kingdom (UK) annually from FLW (Jeswani et al., 2021). CO_2e are produced at each stage of the supply chain from fossil fuel use (e.g. tractor/truck fuel, glasshouse heating) fertiliser production and use, electricity generation (refrigeration) and packaging production/disposal. If food product is lost, the emissions generated from farm to fork would be in vain, causing the need for a replacement product with the additional emissions associated to its production. While efforts to mitigate fresh produce loss have been explored in the current literature, it often lacks comprehensive assessments of both efficacy and economic/environmental impacts, does not link postharvest behaviour of fresh produce with postharvest management and quantification is based on estimations, rather than primary data (Goossens et al., 2019). This knowledge gap hinders coordinated mitigation action and contributes to wider divergence on carbon neutrality efforts at a policy level (Xu et al., 2023). Therefore, evaluating the interplay between systemic behaviour of the supply chain, FLW risk and overall environmental impacts is imperative. This approach can alleviate pre-existing impacts in developed regions whilst offering sustainable approaches for developing countries.

The reliance on an international supply chain for fresh produce supply also risks inequitable distribution of energy-related burdens (Skare et al., 2024) particularly where the greatest CO_2e contribution (and FLW risk) occurs during primary production prior to export and during subsequent transport. Therefore, there is a need to appraise the contribution of FLW impacts at each supply chain stage to identify priority areas for mitigation. Furthermore, carbon neutrality policy shows significant international divergence (Xu et al., 2023) and concerted mitigation is required to address the environmental impacts of FLW risk given the diffuse nature of the supply chain. Lastly, it will also be necessary to appraise the economic impacts of FLW prevention, especially where economic and environmental drivers may be in conflict (Muth et al., 2019). Our research aimed, for the first time, to understand the link between food loss and waste and economic/environmental impacts through a metanalysis of existing data and national surveys with key supply chain stakeholders, using the fresh product supply chain in the UK as a case study. The novelty of this approach enables us to provide new evidence generated from a multidisciplinary perspective to address the confounding drivers of FLW generation and subsequent environmental impacts.

Our paper begins with our research methodology including system boundary definitions, survey-based data collection and literature review methodology (**Section 2 Materials and Methods)** Our results are discussed in **Section 3 Results and Discussion**, covering i) quantification of FLW CO_2e emissions and ii) qualitative dissection of FLW drivers. **Section 4** develops actionable methods for FLW reduction used as the basis for our conclusions in **Section 5**.

2. Materials and Methods

Our definition of FLW covers all edible produce at harvest not used for its original purpose between production and sale as being subject to FLW, aligning with previous work such as that of Boiteau and Pingali (2023). However, we have made some modifications to recognise the economic impact of FLW. Furthermore, we include non-edible portions

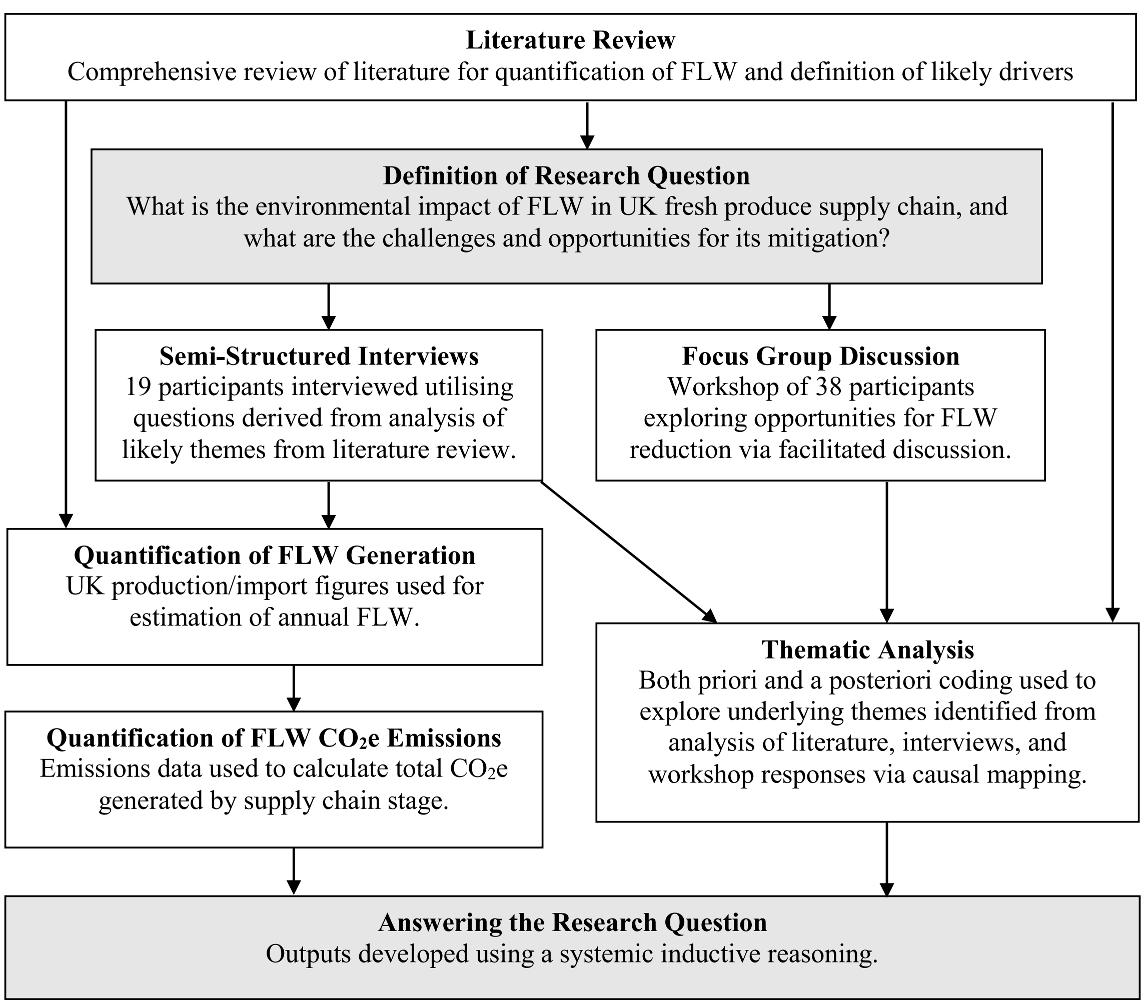

Fig. 1. Research methodology outline.

(e.g. leaves, skin) as this will be included in the marketable product. It is important to know that produce which remains in the food chain (e.g. alternative processing) will still incur an economic and environmental impact due to the need for surplus production. Through targeted analysis we sought to quantify the environmental impacts of FLW in the UK fruit and vegetable supply chain, whilst identifying barriers and opportunities for its sustainable reduction. To achieve this, we conducted an initial literature review to develop estimates of FLW incidence, and to define the research questions to be addressed through the stakeholder survey (Fig. 1). The research questions were defined as: 1) What is the magnitude of FLW in UK horticultural produce, and what are the corresponding CO_2e contributions? 2) How do perceptions of FLW relate to current and future mitigation actions? 3) What multidisciplinary research is required to address current gaps in the existing literature? 4) What future directions are most appropriate for sustainable FLW reduction?

Our study focused on FLW in the UK horticulture supply chain. To maximise data availability, we included evidence from countries with comparable agrosystems to the UK or from countries that are significant sources of UK imports. Our selection criteria were designed to capture regions with similar levels of supply chain intensification and high commonality of FLW risk and environmental impact, resulting in the inclusion of studies from the EU, North America, New Zealand, Australia, China, Japan, and South Korea.

We deliberately excluded non-conventional production systems (e.g. organics) due to their relatively small (<10%) contribution to total production, whilst being subject to significantly different FLW risks and CO_2e factors which are inadequately quantified in existing literature. We focused on products with a significant market share that were both grown and imported to the UK. This approach ensured complete coverage of the supply chain. The selected products included: brassicas (cauliflower, cabbage, broccoli), carrot, potato, lettuce, onion, cucumber, tomato, pepper, strawberry, raspberry, apple, and pear. This encapsulated 72% of the UK horticulture market by volume with the remainder dominated by imported banana, citrus and melon (Defra, 2022). Cauliflower and broccoli were treated as a combined product type (Curd Brassica) due to combined reporting of import volumes.

2.1. System boundary

For quantification of FLW volume and CO_2e emissions, our system covered all supply chain stages until retail (Fig. 2). We exclude consumer-level FLW as this is generally associated with behavioural (e.g. over purchasing, inappropriate storage), rather than systemic causes. All produce was assumed to be marketed through retail as fresh, unprocessed produce as accurate data partitioning produce between retail and alternative marketing routes (e.g. frozen or wholesale/food service) is unavailable, except for potato which is subject to significant processing demand for which only 25% of total supply was quantified as the retail market share (Statistica, 2022).

For CO_2e calculations, emissions from processing (e.g. postharvest trimming, packaging) and transport (including from importation) were allocated to "Handling". Onion curing and pear ripening were assigned to "Storage". We do not account for emissions from waste disposal or carbon sequestration during cultivation due to insufficient evidence of the prevalence of waste disposal routes and a paucity of accurate quantification of carbon sequestration in horticultural production systems (Morgan et al., 2010).

2.2. Food loss and waste quantification

We generated FLW estimates through a systemic literature review combined with updated estimates from the stakeholder survey. For the literature review, our search strategy involved the utilisation of specific search terms, namely, "*crop food loss* OR *waste*" in Google Scholar and Scopus. Secondary searches were performed using more generic keywords of "*fruit*", "*vegetable*", "*supply chain*", "*primary production*" and "*farm*" together with reference tracking to identify further studies published since 2010. Additional FLW records were taken from the UN Food and Agriculture Organisation (FAO) FLW Database.

Initially, we identified 126 sources, which were carefully screened based on title, abstract and methodology content for alignment to our system boundary and FLW definition. Literature reviews were excluded to avoid duplication of results, and only studies published in peer-reviewed journals or from public bodies (e.g. USDA) were included. After filtration, 401 FLW estimates from 37 sources were identified (**Appendix 1**) and these were allocated to supply chain stages of harvest, storage, handling, and retail.

In addition to published estimates, we gathered evidence from supply chain stakeholders to provide updated estimates of FLW incidence and develop qualitative perspectives on FLW in the UK supply chain. A total of 19 stakeholders at managerial/director level involved in the main UK growers' associations, producer and distribution businesses, and independent consultants and representatives were engaged through semi-structured interviews conducted between April 2021 and July 2023 (**Appendix 2**). Furthermore, an industry-facing workshop

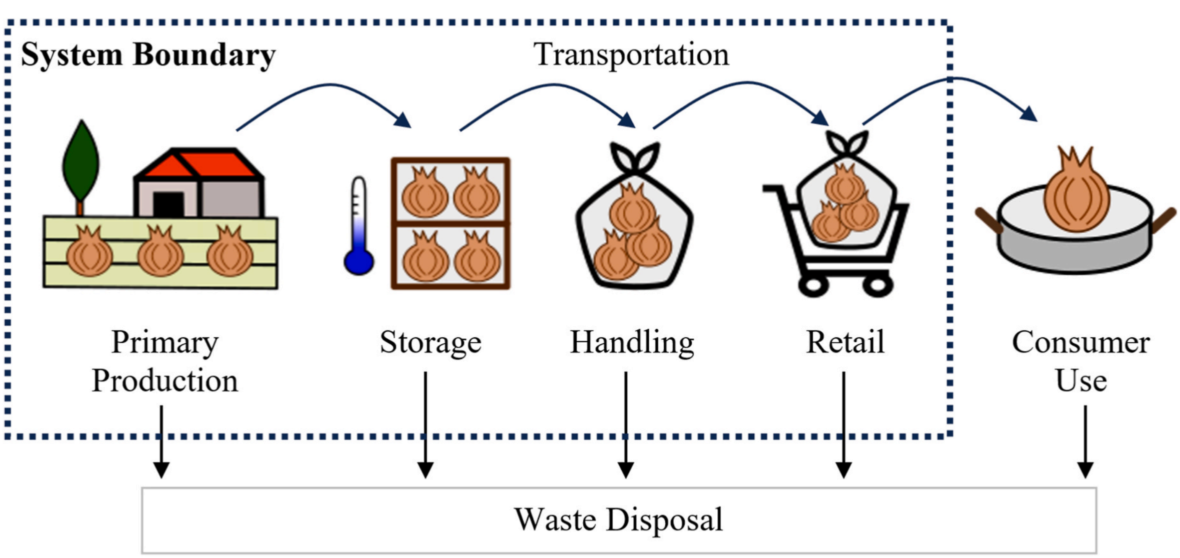

Fig. 2. System boundary used for FLW quantification.

attended by 38 stakeholders was held July 2023. FLW estimates were sought from respondents to validate/update literature review estimates to reflect current practice and address local aspects of FLW generation. Qualitative evidence was coded using themes identified in the literature review, and causal mapping was performed to examine interrelationships between FLW risks and economic/sustainability objectives through thematic analysis (Scavarda et al., 2006; Braun and Clarke, 2006).

Average FLW values were used to estimate the proportion of FLW occurring at each stage of the supply chain using volume data for home production (excluding exports) and imported produce averaged between 2018 and 2020 (Defra, 2022). It is important to note that reported figures for UK production exclude harvest losses. Transportation losses were considered to be negligible due to short supply chains and produce shipment optimised to minimise transport spoilage risk. Where transport FLW did occur, it was allocated to the preceding supply chain stage in reflection of industry practice that rejected produce is returned to the originator for replacement. FLW incidence was assumed to be equal between home grown and imported produce irrespective of origin.

2.3. Carbon footprint estimation for UK horticultural food loss and waste

Quantified estimates of FLW were then used to calculate CO_2e emissions from FLW for UK grown and imported produce. Values for CO_2e emissions per product and supply chain stage were adapted from Frankowska et al. (2019a/2019b) and allocated to each supply chain stage within our system boundary (Table 1). A single life cycle analysis was utilised for all product types to ensure comparability of methodologies and system boundaries for CO_2e emissions estimation. For curd brassica, only 25% of imports were for cauliflower as this can be cultivated in the UK year-round, unlike broccoli. It was assumed that FLW occurred at the end of each stage and resulted in the total loss of all accrued CO_2e from previous stages. An exemplar calculation for FLW CO_2e emissions is given in Appendix 3.

3. Results and Discussion

3.1. Origins of food loss and waste

Table 2 presents an average estimate of FLW identified from the literature review and stakeholder survey. The greatest contributions of FLW were observed in field vegetables, notably with the largest cumulative loss in cabbage amounting to 50.9% between production and retail. In contrast, soft fruit and protected salad crops exhibited the smallest FLW, with only 14.2% total FLW observed in raspberries. Primary production and handling FLW were key contributors, with relatively minor contributions from storage and retail (Table 2). The feedback from the survey characterises FLW as primarily driven by factors such as produce quality, and lack of market due to supply/demand mismatch (Fig. 3). Market conditions can significantly influence FLW risk, especially through a specific subcategory of FLW, where market conditions may increase FLW from quality limits. Under conditions of undersupply or high demand, lower quality produce may become marketable due to relaxed specifications. On the other hand, during periods of oversupply, rejection risk tends to increase as retailers may enforce stricter quality specifications.

Table 2
Estimates of food loss and waste in percentage (%) by supply chain stage identified through the literature review and stakeholder survey.

	Food Loss and Waste Incidence (%)				
	Farm	Handling	Store	Retail	Cumulative Total
Curd Brassica	15.3	22.9	6.0	8.7	43.9
Cabbage	12.7	20.0	21.5	10.3	50.9
Carrot	18.6	15.9	6.5	17.3	47.1
Onion	8.6	15.6	15.9	6.5	39.4
Potato	7.0	21.6	3.2	4.1	32.4
Lettuce	20.6	10.6	1.3	10.7	37.3
Tomato	14.3	8.2	8.3	6.7	32.6
Pepper	4.8	8.2	8.3	6.7	25.1
Cucumber	1.3	8.2	8.3	6.6	22.2
Apple	10.1	10.8	4.9	8.5	30.3
Pear	5.3	21.0	4.9	9.2	35.5
Strawberry	9.4	5.8	0.9	8.3	22.4
Raspberry	3.5	2.0	0.9	8.0	13.7

A primary factor contributing to the supply/demand mismatch is the poor ability to align harvests with customer demand. Survey feedback indicating that supply/demand mismatch can approach 50% on a daily basis, reaching 25% in periods of oversupply in crops prone to high supply/demand variation such as strawberry. Weather changes further amplify supply/demand mismatch through unpredictable changes in yield and consumer demand. The increasing variability in weather patterns due to climate change further exacerbates the risks of oversupply. Historically, risk management behaviours such as overplanting (up to 15% to ensure minimum order volume) have played a role in oversupply. However, recent increases in labour and fertiliser costs have reportedly reduced the prevalence of overplanting.

Supply/demand mismatch stems from economic, infrastructural, or physiological capacity to hold produce in the supply chain. In the UK, produce is typically harvested at its peak maturity to meet customer quality expectations, although this compounds supply/demand FLW due to reduced ability to hold produce after harvest until markets can be identified. For example, survey feedback indicated that tomato losses

Table 1
Cumulative carbon dioxide equivalent emissions (CO_2e) estimates per kg of fresh produce present at each supply chain stage (as kg CO_2e kg^{-1}) for the United Kingdom (UK) horticultural produce. Values were adapted from Frankowska et al. (2019a/2019b).

	kg CO_2e kg^{-1}							
	UK				Imported			
	Farm	Storage	Handling	Retail	Farm	Storage	Handling	Retail
Curd Brassica	0.33	0.36	0.47	0.48	0.33	0.36	0.71	0.73
Cabbage	0.12	0.22	0.32	0.34	0.12	0.23	0.44	0.46
Carrot	0.16	0.46	0.61	0.63	0.22	0.56	0.92	0.94
Onion	0.22	0.48	0.58	0.60	0.22	0.49	0.86	0.88
Potato	0.14	0.44	0.58	0.60	0.17	0.50	0.79	0.81
Lettuce	0.40	0.41	0.52	1.08	0.40	0.41	0.78	1.35
Tomato	12.16	12.16	12.42	12.42	0.80	0.81	1.25	1.25
Pepper	1.72	1.72	1.84	1.84	1.27	1.27	1.67	1.67
Cucumber	2.01	2.02	2.13	2.15	1.29	1.30	1.58	1.60
Apple	0.14	0.27	0.39	0.40	0.25	0.40	0.96	0.97
Pear	0.10	0.30	0.45	0.46	0.24	0.48	0.95	0.96
Strawberry	0.99	0.99	1.25	2.10	0.76	0.76	1.30	2.14
Raspberry	0.99	0.99	1.25	2.10	0.56	0.57	2.11	2.96

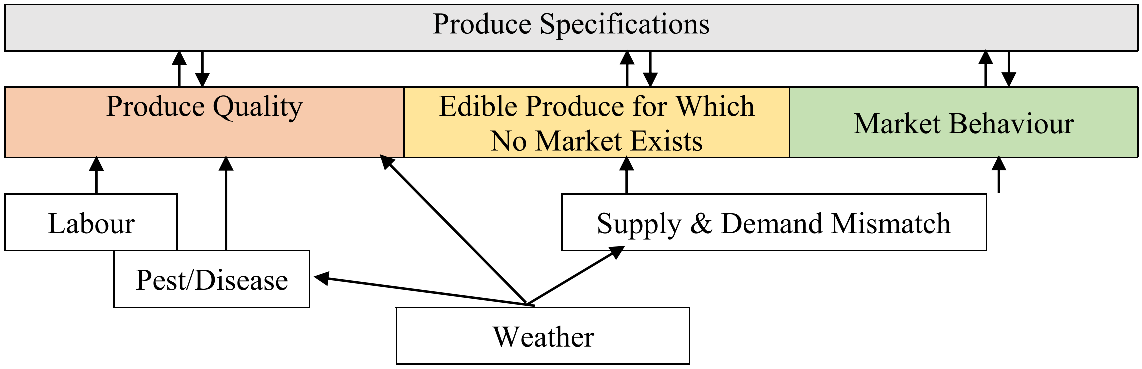

Fig. 3. Summary of food loss and waste drivers identified by the stakeholder survey.

could exceed 20% where storage exceeded six days, and retailers may impose maximum residency times to ensure minimum shelf-life expectations are met in the supply chain. Field vegetables may remain unharvested, but this approach increases FLW risks due to disease and weather damage. For multi-harvest crops such as tomatoes, surveyed growers reported a limited ability to hold produce on plants due to negative impacts on later production through reduced fruit inception following changes in sink-source relationships. Additionally, post-harvest storage contributes significant environmental burden, with approximately 32% of apple CO_2e emissions attributed to storage (Frankowska et al., 2019a), with prolonged storage described as necessary to achieve maximum market price.

3.2. Greenhouse gas emissions from food loss and waste

We estimated that annual generation of FLW in the UK supply chain amounts to 2.4 Mt of fresh produce, representing approximately 36.0% of total supply (Table 3). Three crops (potato, carrot, and onion) contribute to a substantial 57.5% of the total FLW generated due to large production volumes. Counterintuitively, soft fruit and salad vegetables showed proportionately lower total FLW compared with field vegetables, despite being more resilient in the supply chain. Field vegetables and apple/pear have narrow production/harvest windows, with reduced control options (due to lower produce value) increasing vulnerability to weather variation. This also increases storage demand, and can only be addressed to a limited extent by cultivar selection and planting scheduling.

The overall GHG emissions associated with horticultural produce in the UK was estimated to be around 6.15 Mt CO_2e yr^{-1}, of which 1.67 Mt CO_2e yr^{-1} (27.22%) was contributed by FLW (Fig. 4). Strikingly, just three crops (tomato [0.43 Mt CO_2e yr^{-1}], potato [0.26 Mt CO_2e yr^{-1}] and carrot [0.22 Mt CO_2e yr^{-1}]) contributed to 54.6% of total FLW CO_2e emissions. These data demonstrated that field vegetable crops (carrot, potato, brassica, onion, lettuce) show comparatively low CO_2e emissions per kg because of their low resource inputs for cultivation and post-harvest handling (e.g. 0.63 kg CO_2e kg^{-1} for UK grown carrot at retail), but incur significant environmental impacts caused by their extensive market volumes and elevated loss risk, accounting for 51.36% of the total FLW emissions.

When we examine the supply chain stages, the impact of harvest-related FLW is relatively small, accounting for 352.7 kT yr^{-1} or 21.1% of total CO_2e emissions from FLW (Fig. 5). For all crops besides tomato, handling was responsible for 33.7% of all FLW CO_2e emissions, particularly due to contributions from packaging and transport for imported produce. However, the separation of harvest and handling stages can be challenging, as activities such as selection may occur at different points in the supply chain. For example, selective harvesting takes place for certain crops such as soft fruit, before packing (for automatically harvest field vegetables), and before/after storage. Low FLW at retail meant that only 22.9% of FLW CO_2e emissions were generated at this stage, despite the highest accumulation of CO_2e from produce moving through a completed supply chain.

Crops with low FLW volumes may also contribute significant FLW CO_2e emissions where production and handling are disproportionately resource intensive, such as tomato which contributes 25.6% of CO_2e despite producing only 7.3% of FLW by volume due to large CO_2e emissions from glasshouse heating. Conversely, crops with low CO_2e emissions per kg can still contribute substantial CO_2e emissions from FLW where FLW volumes are high, such as carrot.

Table 3
Estimates of food loss and waste (FLW) in kilotonnes per year (kT yr^{-1}) by supply chain stage incorporating imported and home-grown produce utilising production and import figures from Defra (2022).

	FLW (kT yr^{-1})					Proportion of total supply (%)
	Farm	Storage	Handling	Retail	Total	
Curd Brassica	51.9	17.3	62.0	18.1	149.3	43.9
Cabbage	27.2	40.3	29.3	12.1	108.9	50.9
Carrot	205.7	58.3	134.3	122.8	521.1	47.1
Onion	72.4	121.7	100.5	35.5	330.1	39.4
Potato	115.1	49.0	318.5	47.3	529.9	32.4
Lettuce	88.5	4.3	35.6	32.3	160.6	37.3
Tomato	77.0	38.0	34.4	26.1	175.5	32.6
Pepper	11.2	18.5	16.8	12.6	59.1	25.1
Cucumber	2.9	18.8	17.0	12.6	51.2	22.2
Apple	69.9	30.8	64.2	45.2	210.1	30.3
Pear	7.8	6.8	27.6	9.6	51.9	35.5
Strawberry	19.6	1.6	10.8	14.7	46.8	22.4
Raspberry	1.4	0.3	0.8	3.1	5.6	13.7
Total	750.5	405.7	852.0	391.9	2400.1	36.0

3.3. Limitations on food loss and waste quantification

Poor FLW quantification, linked to lack of a standardized methodology, hinders the opportunity to have accurate environmental assessments of these losses. Whilst there has been substantial focus on the quantification of CO_2e emissions from primary production, most studies tend to concentrate on a narrow range of crop types or production systems, hindering extrapolation to multi-origin supply chains which cover a diversity of production system types. Furthermore, variation in life cycle assessment (LCA) methodologies and system boundaries creates uncertainty in CO_2e estimates, and inconsistent and inaccurate modelling of crop life cycles precludes comparisons between alternative supply chain systems (Meier et al., 2015). This is particularly relevant for minor crops such as raspberry for which limited LCA evidence is available and therefore is vulnerable to methodological and systemic differences. There is also scarcity of LCA evidence relating to postharvest handling (Boschiero et al., 2019), impeding detailed analysis of complete supply chains. These factors collectively result in highly variable

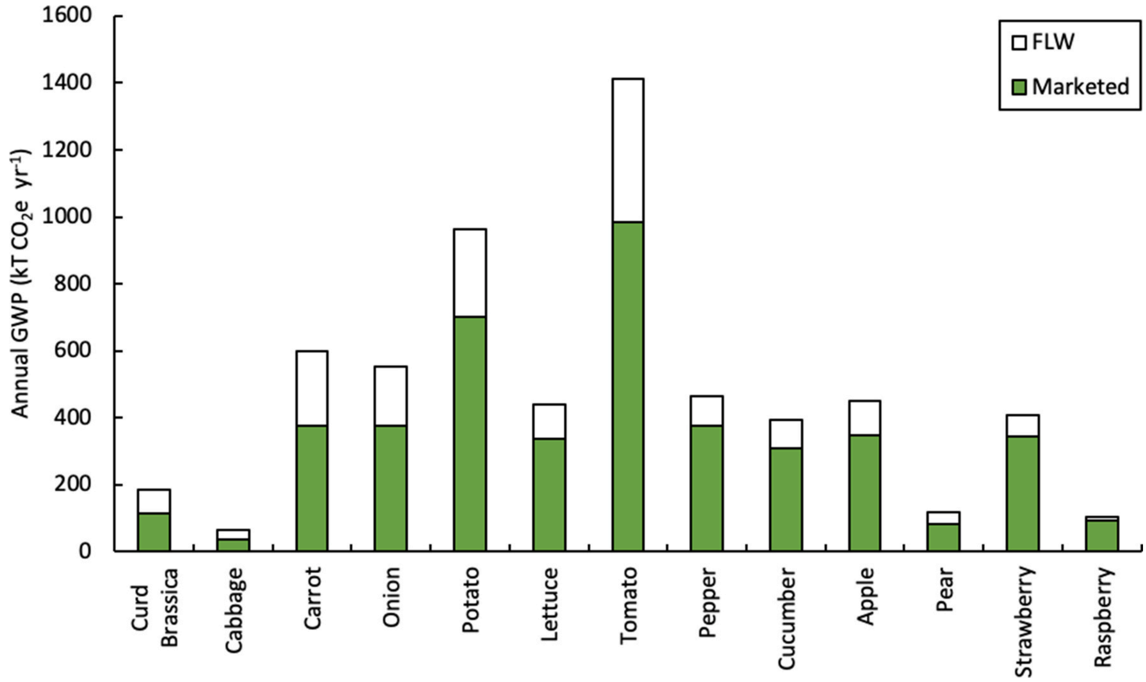

Fig. 4. Estimated carbon dioxide equivalent emissions as annual Global Warming Potential – GWP - (kT CO_2e per year) from produce marketed and lost to food loss and waste (FLW).

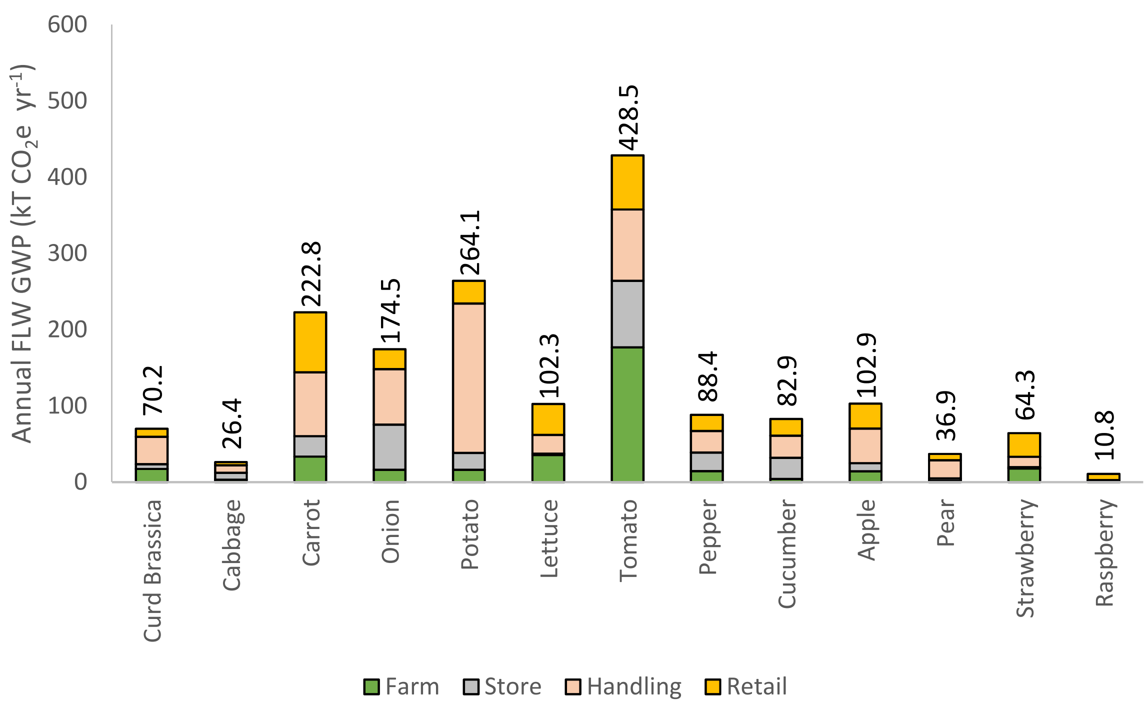

Fig. 5. Annual food loss and waste CO_2e emissions allocated to supply change stage. Total FLW CO_2e emissions are given above each column.

estimates of crop CO_2e emissions. For example, farm gate emissions for heated tomato ranged from 0.67 kg CO_2e kg^{-1} to 12.13 kg CO_2e kg^{-1} (Davis, 2011; Frankowska et al., 2019b), primarily due to variations in heat and CO_2 generation during cultivation. Although our study attempted to mitigate this variation by using harmonised LCA data from a single source (Frankowska et al., 2019a/b), data limitations still restrict the ability to appraise the environmental impacts of FLW and mitigation options. Furthermore, Frankowska et al. did not include embodied carbon from building construction (e.g. glasshouses), which may impact CO_2e estimates for protected crops. Further uncertainty will result from variation in electricity generation methods, refrigerant leakage and materials production such as increased use of renewables and progress towards net zero in supporting sectors. FLW and CO_2e will show variation (e.g. due to season, location), but insufficient granularity is present in the available data to accommodate such variation and so fixed values have been utilised here. Lastly, utilisation of a single source for CO_2e may not encapsulate changes in emissions from modified practice. Current supply chain practice is unlikely to be different from those documents in Frankowska et al. (2019a/b) although import origins may have been modified following Brexit which may impact CO_2e calculations.

However, the commonality of CO_2e emission calculations used here is considered sufficient for testing the relationship between environmental impacts and FLW to facilitate the prioritisation of mitigation measures. A greater lack of available evidence surrounding FLW using alternative metrics (e.g. biodiversity) may hinder analysis of impacts and mitigation which do not directly correlate with GHG emissions (Muth et al., 2019), and these may be relevant when examining aspects such as pesticide usage or bluewater use on FLW.

3.4. Economic pressures during oversupply contribute to food loss and waste

The reduction in prices driven by oversupply stands out as a pivotal factor contributing to FLW, as highlighted by survey respondents. This occurred as the oversupply of unmarketable produce fails to cover picking and handling costs, leading to wastage. Oversupply may exert downward pressure on price, with reductions of up to 30% described by soft fruit producers during production gluts, exacerbating FLW as growers may opt for wastage to protect prices rather than selling crops at reduced prices. Marketing tactics such as promotions have been used to enhance fresh produce affordability, although their overuse may disrupt the pricing structure of the fresh produce category (Terry et al., 2013), with survey feedback indicating that premium lines may suffer when discounts are applied to cheaper bulk-buy lines. While this strategy may temporarily increase sales (Terry et al., 2011), it can also translate FLW risk by cannibalising of sales of other products or increase FLW through increased suboptimal handling due to increased produce flows in the supply chain. Promotions have largely been phased out by retailers in favour of price reductions, with feedback indicating that multi-buy promotions were perceived as driving consumer-level waste.

Where FLW is risked from oversupply or cosmetic quality standards, FLW recovery by donation, processing or alternative marketing is given high priority in the FLW management hierarchy as benefit from the accrued CO_2e can still be derived (Papargyropoulou et al., 2014). However, survey responses indicated that recovery practices were generally not common due to lack of economically viable processing routes, except for field vegetables/potatoes where existing processing contracts were in place.

Most processing outlets require a scheduled and consistent supply of produce, which is incompatible with the unpredictable generation of FLW, while logistical and cost barriers hinder donations (Kinach et al., 2020). Shelf life stabilisation through processing (e.g. freezing, preserving) often incurs additional environmental impacts from initial processing, longer term storage and packaging needs (Allouche et al., 2023). GHG emissions, for example, are increased by 35% or >100% for freezing or juicing respectively (Milà i Canals et al., 2010; Khanali et al., 2020), increasing emissions particularly when the processed product is supplemental to demand.

The primary obstacle to FLW recovery lies in economic viability, especially in a market that is orientated towards retail. For instance, processing apples into juice results in an 85% reduction in price, rendering processing of fruit unviable given the high labour cost associated with harvest. Survey sentiment described a mindset that the "*cheapest waste is the easiest waste*", where produce for which no market exists was unlikely to be harvested to minimise wasted labour.

Alternative marketing holds potential for minimising the environmental impact of recovery, contingent on the extent to which the produce is consumed as a replacement foodstuff rather than supplementary one (Eriksson et al., 2015). However, the environmental effects of alternative processing for FLW reduction remain poorly explored (e.g. increased in GHG emissions from processing), hampered by a relative lack of evidence on the environmental impacts of food processing techniques (Chung et al., 2022). Despite potential economic and environmental impacts, it is crucial to recognise that the greatest impact is likely to be achieved through FLW prevention rather than recovery (Muth et al., 2019).

3.5. Barriers to food loss and waste prevention: misperception and misunderstanding

Survey responses indicated that FLW is often viewed as an unavoidable economic challenge rather than an environmental issue. This perspective aligns with previous studies, highlighting that FLW tends to be addressed when it is financially viable to do so (Beausang et al., 2017). Unfortunately, there appears to be a lack of awareness regarding the magnitude of FLW, which hampers mitigation efforts. Moreover, we found that FLW was typically not quantified in detail due to high labour requirements and the inability to respond effectively to the information gained. Furthermore, the disproportionate allocation of FLW to primary production may reduce motivations for its reduction higher in the supply chain. Growers, in particular, bear a disproportionate economic risk from FLW as they will be liable for rejections made higher in the supply chain and low retail tolerance for repeated rejections jeopardising contractual relationships. This creates a risk-averse climate where growers discarded produce to avoid potential rejection higher in the supply chain despite being marketable at harvest, whilst disincentivising higher supply chain actors to react to FLW, as they are removed from major economic impacts. For example, FLW risk was described as not contributing to marketing decisions, with high-risk cultivars (e.g. disease susceptibility, poor environmental match) commonly chosen based on customer demand alone.

While systemic recognition of FLW can contribute to its reduction, the dominance of economic drivers suggest that significant action will only be taken when there is a strong economic motivation, particularly through increasing the value of produce that is currently at risk of FLW by end consumers. Awareness campaigns that targeting FLW have shown some benefit, although they have focused on reducing FLW caused by spoilage of food due to over-consumption or improper storage (Porat et al., 2018). However, these campaigns do not adequately address FLW risks associated with suboptimal quality produce. It will be necessary to encourage consumers to accept produce of a lower quality than is currently viewed as acceptable. Further understanding of the relationship between customer perceptions of quality and willingness to purchase lower quality fruit will be required to understand how to encourage consumers to accept lower quality produce. For example, interactions between socioeconomic groups and purchasing behaviour will also interact with perceptions of quality acceptability and its relationship with price (Terry et al., 2013).

Consumer sustainability concerns could potentially be leveraged to increase the purchases of lower quality produce, such as for sustainability reasons. However, consumers often prioritise factors such as price over sustainability (Grunert et al., 2014), and survey feedback suggested that produce sustainability resonated only with a limited consumer group. Older generations, who purchase a higher proportion of fruit and vegetable products are less likely to show concern for environmental effects, reducing the potency of environmental impacts as motivation for reducing FLW (Terry et al., 2013; Gifford and Nilsson, 2014). Furthermore, while increasing the proportion of harvested produce which could be marketed may reduce production costs for growers the economic effects of FLW prevention through increased supply is poorly understood.

Consumers may also prioritise health considerations over environmental concerns (Jakubowska and Radzymińska, 2019), and misconceptions that malformed produce has lower nutritional value negatively impacts consumer acceptance of suboptimal produce, particularly when sold at full price (Hartmann et al., 2021). Survey feedback suggested that suboptimal quality "wonky veg" lines that have been co-opted into lower value offerings indicates that consumers will be reluctant to pay full price for suboptimal produce, although discounting prices will contribute to consumer perceptions that malformed produce has lower health benefits (Haws et al., 2017).

To address the economic drivers behind FLW, it will be necessary to promote step-change in consumer behaviour to attach value to suboptimal quality produce. However, this is contrary to current trajectories of increasing quality standards and profit margins, and so prevention of FLW through reducing the incidence of suboptimal quality produce is likely to be more effective in the short term.

4. Opportunities for change

We can simultaneously reduce energy consumption and emissions whilst maintaining food security and quality. Although there may not be a "silver bullet" for FLW reduction, a combination of mitigation measures, particularly when combined with other supply chain objectives such as reducing costs from lowered energy consumption and increasing profit with longer shelf life, may make sustainable FLW reduction achievable.

4.1. Data collection and forecasting for sustainable food production and preservation

Comprehensive data collection across the supply chain should be conducted to i) facilitate food recovery by improving connections between stakeholders and alternative users; ii) improve forecasting and modelling to match production with actual demand; iii) provide accurate quantification of FLW in the supply chain supported by in-depth qualitative evidence of FLW drivers to provide accountability for its creation and track the impact of mitigation actions; and iv) establish connections between energy, food production and preservation, and economic feasibility of potential solutions utilising empirical evidence.

Establishing transparent, continuous information flow among supply chain stakeholders will enhance connections between produce at risk of FLW (especially due to oversupply) and alternative consumers, addressing the need of the processing sector for continuity of supply (Mena et al., 2011). Furthermore, providing pre-harvest data proves invaluable in identifying produce at elevated risk of quality deterioration. This information can guide marketing decisions to respond to variable produce FLW risk, or to minimise energy consumption during postharvest handling and storage (e.g. onion curing) through dynamic process modification tailored to produce condition at harvest. Accurate planning of storage release will minimise energy demands during storage, particularly for long-term storage crops like apples and onions, which require substantial refrigeration whilst reducing FLW risks associated with prolonged storage to match variable marketing pricing. Improving cold chain management offers the potential to reduce food loss and energy cost while preserving product quality and extending shelf life. However, due to the complexity of the cold chain systems, tailored solutions must be designed according to the storage temperature required for different types of food products, the routes and vehicle capacity and ranges, and to trade-off different objectives in relation to cost, emission, and quality (Fan et al., 2021; Liu et al., 2021).

4.2. Valorisation

Valorisation and alternative use models have been identified as a priority for FLW reduction through FLW recovery (Morone et al., 2019). This addresses FLW generation through both oversupply and reduced quality by providing economic justification for use of produce where high costs are seen early in the supply chain, such as labour during harvest, preventing loss of produce that would otherwise be considered unmarketable due to lack of economic return. However, survey feedback indicated poor economic returns made processing unviable and lack of reactive supply chains to unpredictable availability of processing material. Furthermore, processing for increased shelf stability may substantially increase the environmental burden of produce handling through increased packaging need or resource intensive processing, reducing the sustainability gains where the resultant product is consumed as an addition rather than a replacement foodstuff. Whilst increasing valorisation should be supported by development of reactive logistical networks, and the promotion of low-energy shelf stable products (e.g. freeze-dried additives and colourants) this is unlikely to provide a meaningful impact on FLW for the UK horticulture supply chain.

4.3. Improved postharvest handling

The ability to stabilise produce after harvest is integral to both systemic supply chain modifications and enhancing valorisation. Optimal postharvest management enhances the capacity of forecasting to match demand and promotes valorisation opportunities by maximising supply chain geographic and temporal reach. This increases the opportunity for produce to reach a suitable market before quality loss occurs, and the role of postharvest technologies in preventing FLW has been highlighted in prior studies (Alamar et al., 2018). The ongoing need for low-energy postharvest handling solutions is evident. This is particularly relevant for crops stored for long periods under high refrigeration such as onions, where storage accounts of 37% of primary energy demand between production and retail (Frankowska et al., 2019b). Maintaining or improving current FLW risks whilst facilitating reduced energy intensity during storage will directly address the cost/energy/FLW nexus. Understanding the mechanisms behind quality loss, their relationship with temperature and the development of biologically-driven solutions which possibly enable warmer storage temperatures should also be priority to address both FLW reduction and the need for high intensity chilling. For example, advances in sensor technology and artificial intelligence may facilitate improved storage optimisation and supply chain coordination (Mastilović et al., 2024). However, in addition to definition of optimal storage conditions, systemic changes will also be required for optimal supply chain handling. Feedback indicated that the use of more than two to three chiller set points was logistically unviable, particularly during retail transport and storage, and therefore technological innovation and investment in required infrastructure will be necessary to facilitate the diversification of handling methods across the supply chain. Reducing postharvest energy burdens may also be driven by economic factors – the fresh produce sector was subject to an estimated annual increase of 165% in energy costs in 2022 (NFU, 2022) creating significant industry pressure to reduce energy consumption due to limited ability to transmit increased resource costs onto consumers. Alternative solutions which reduce energy-associated costs without increasing FLW are therefore required to address economic, as well as sustainability, objectives of the fresh produce sector. The need to reconcile costs against alternative postharvest FLW mitigation strategies has been recognised by the wider literature (Chauhan et al., 2021), this should also be extended to include the environmental perspective in the wider context of sustainable supply chain development.

4.4. Policy landscape

Legislative action is crucial to promote accountability for FLW throughout the supply chain, supported by in-depth qualitative data to determine optimum methods for its reduction. This includes considering legislative changes surrounding supply chain operation particularly where existing regulations may not align with technological advancement. For example, current food hygiene regulations specify that frozen bread be stored at – 18 °C or below (UK Regulation 852/2004; EU Parliament, 2004), although a 3 °C increase in storage temperature could reduce energy demand of the cold chain by up to 12% (Allouche et al., 2023). However, enabling such change is hindered by a lack of knowledge surrounding the response of fresh produce to warmer storage temperatures, and how quality can be maintained whilst reducing chilling. To facilitate sustainable FLW prevention, legislative frameworks should prioritise research and development strategies, with more funding made available for multidisciplinary research focusing of sustainable FLW prevention (Alamar et al., 2018). Regulatory approval processes should also prioritise novel approaches, particularly for the control of postharvest disease and dormancy break where current options are limited or face deregistration.

Policy instruments should be developed to incentivise the uptake of new approaches by the supply chain, particularly where alternative management practices may incur additional costs (Chauhan et al., 2021). Stakeholder feedback suggested that economic factors remained significant barriers to investment in sustainable technologies, and therefore support should be provided to facilitate the uptake of novel approaches where economically and environmentally viable such as through favourable tax climate or grant subsidies for new investments. Economic drivers for FLW could also be addressed through policy changes that incentivise its mitigation as part of wider governmental regulatory approach. Finally, FLW should be considered when appraising other environmental priorities such as management of blue water resources for irrigation and pesticide legislation (Knox et al., 2010; Hillocks, 2013), to prevent unintended consequences that may increase FLW by reducing the growers' ability to manage crop quality within marketable ranges.

5. Conclusions

Food loss and waste reduction has been recognised as a significant mechanism to enhance the sustainability and resilience of the food supply chain, and our results support this through demonstration of the significant greenhouse gas emissions burden associated with horticultural food loss and waste generation. However, the current framing of food loss and waste as an economic issue creates additional barriers to its reduction, and further evidence is required to address the relationship between food loss and waste, energy use/economic and environmental drivers. The lack of consistency in quantification methods for food loss and waste impedes accurate environmental assessments and hinder effective mitigation strategies. Despite the existence of some standardized approaches, this inconsistency poses a significant challenge. Exploring alternative metrics like biodiversity could provide valuable insights for enhancing mitigation efforts. Historically, the food supply chain has heavily relied on cold chain management. There is a need to identify opportunities against a background of reducing food loss and waste risk whilst enabling warmer storage temperatures, or reconciling food loss and waste reduction with the resultant increase in environmental impacts. The role of conflicting environmental priorities such as reducing pesticide use and resultant increase in food loss and waste risk, together with comparatively minor role of sustainability in the wider context of consumer demand drivers, is also not widely acknowledged or addressed in the existing literature. Therefore, a multidisciplinary approach, combining expertise from biology, engineering, and energy themes, is necessary to unpick the complex nexus between energy, food loss and waste, and sustainability. Fundamental shifts are needed at all levels of the supply chain to develop infrastructure, manage customer expectations, and shape the policy landscape to optimise food loss and waste reduction efforts. Future research should also focus on clarifying the magnitude of food loss and waste creation and developing of mitigation actions that are both economically viable and environmentally effective. This includes identifying strategies for food loss and waste prevention and management that strike a balance between economic feasibility and environmental sustainability.

CRediT authorship contribution statement

Ewan Gage: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Xinfang Wang:** Writing – review & editing, Investigation. **Bing Xu:** Writing – review & editing, Investigation. **Alan Foster:** Writing – review & editing, Investigation. **Judith Evans:** Writing – review & editing, Investigation, Funding acquisition. **Leon A. Terry:** Writing – review & editing, Investigation, Funding acquisition. **Natalia Falagán:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Data curation, 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

Data supporting this study are included within the article and/or supporting materials.

Acknowledgements

The authors thank Engineering & Physical Sciences Research Council for financial support through the project EP/V042548/1. We also thank the stakeholders involved in the survey for their time and contribution to this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142068.

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