UNDERSTANDING & EVALUATING ON-FARM LOSS AND WASTE IN THE UK

A report for the Transforming UK Food Systems SPF Programme

By Emmanuel Sawyerr, Gabriel Yesuf, Ruth Wade and Alp Yildirim

TRANSFORMING UK FOOD SYSTEMS
Strategic Priorities Fund

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Readers' Note

This report is an output of a Transforming UK Food Systems' Annual Synergy Fund project which aims to support cross project activities to add value to the funded portfolio, encourage cross-project collaboration, drive impact, build capacity and encourage linkages with related investments.

This project set out to achieve two objectives, namely,

- to conduct a comprehensive review of how extant literature has discussed the causes, management and solutions to food loss and waste pre-farm gate in the UK and
- to review the 15 ongoing Transforming United Kingdom Food System for Healthy People and a Healthy Environment (TUKFS) Strategic Priority funded projects and to ascertain how food loss and waste are being considered within the projects.

This report is therefore made up of two parts. The first presents the findings of a systematic literature review carried out to investigate the extant literature on on-farm food loss and waste in the UK. This is a first step towards investigating the phenomenon in greater depth, synthesising agronomy and supply chain insights, to improve the alignment of production and consumption as well as to improve the compliance of on-farm food waste management practices to the UK government's food waste hierarchy.

The second part of the report investigates the projects funded under the TUKFS Strategic Priority Fund programme to ascertain how food loss and waste at various stages of the food supply chain are being considered within the projects. Recommendations for extended research and impact are presented. In this part, we emphasise the need for greater consideration of food loss and waste for future projects aimed at transforming the UK's food system as neglecting it could have significant adverse environmental and social sustainability implications.

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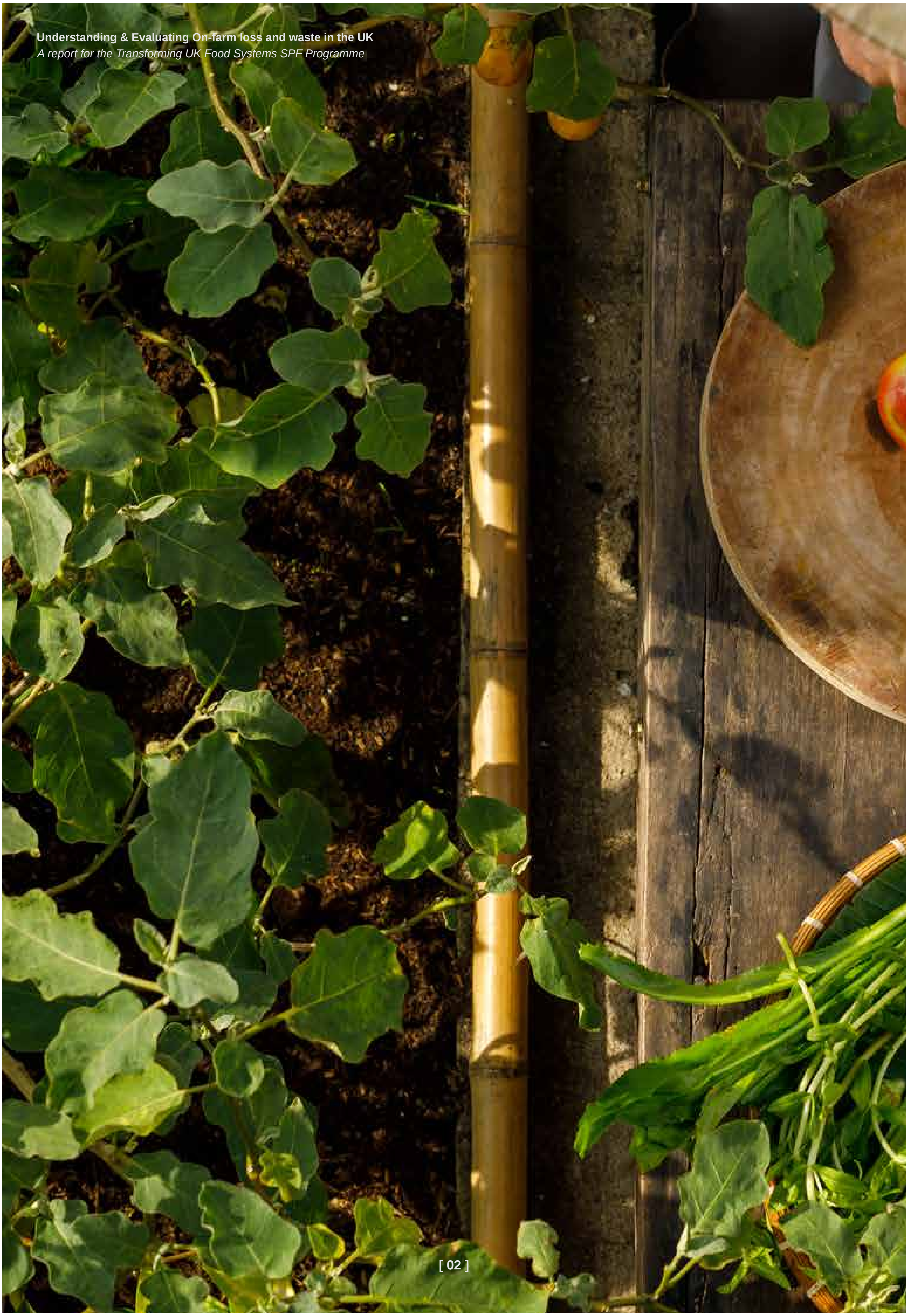
Part 1:

Causes, Management and Solutions to On-farm food loss and waste in the UK



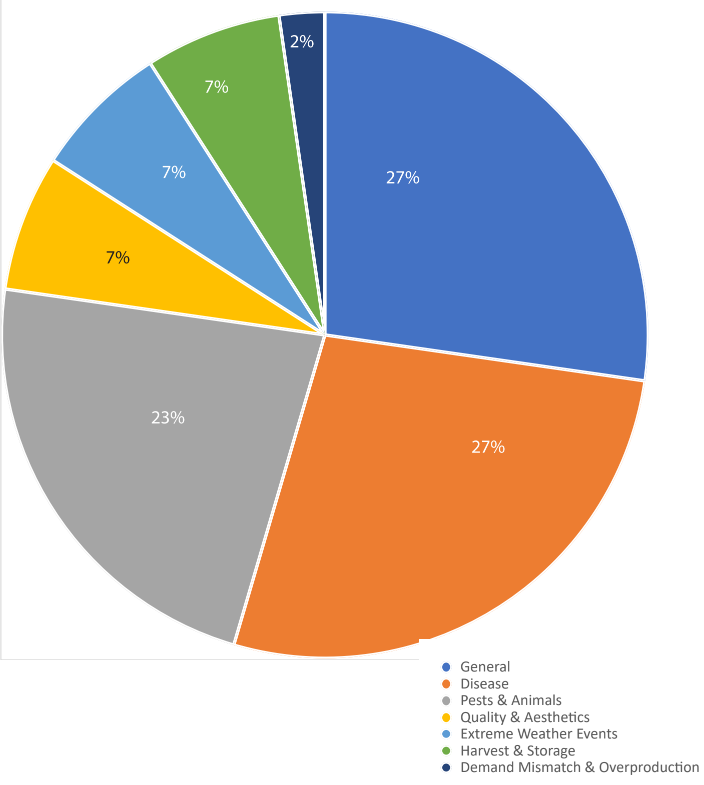
Executive Summary

We present the findings from a systematic literature review of forty-four peer-reviewed journal articles and five government reports investigating the causes of food loss and waste in the primary production of crops in the UK and the management strategies and solutions proposed to address them. Six major causes were identified in the literature:

- diseases
- pests & animals
- extreme weather events
- aesthetic requirements
- harvest & storage, and
- demand mismatch & overproduction.

Figure I below shows the distribution of articles that covered each of these causes. Half of the research papers reviewed either focused on pests & animals or diseases. Of the remaining, twelve studies focused generically on on-farm food loss and waste, identifying multiple causes.

Figure I Causes of on-farm loss and waste in the UK



Management strategies and solutions proposed for diseases and pests & animals were unique to the crop, diseases, pests or animals under consideration. However, proposed crop-agnostic solutions could have wider-reaching impacts and target additional pests and crops, other than those focused on in the particular study. A summary of these management approaches and solutions is presented in Table I.

Table I Overview of Food Loss and Waste Causes and Solutions Discussed

	Causes of Food Loss and Waste	***Solution / Management Approach Considered in reviewed papers***
1	Diseases	Shorter / longer rotations
		Gene editing (super genes)
		Epidemic forecasting through weather/climate
		Fungicide and herbicide treatment and timing
		Disease and weed management strategies
		Altered sowing times
		Using crop cultivars with greater resistance or tolerance
2	Pests & Animals	Integrated pest management
		Pest outbreak forecasting through satellite and weather data
		Information sharing across countries
		Push-pull control method
		Border surveillance
		Scaring methods combined with sacrificial crops
		Buffer strips to enhance semi-natural habitat
		Using natural enemies, biocontrol agents, predators

	Causes of Food Loss and Waste		***Solution / Management Approach Considered in reviewed papers***
3	Harvest & Storage	Harvest	Improved plant management and husbandry
			Investing in improved machinery
			Controlled traffic farming
			Improved monitoring of crop maturity
			Weed management decision support system
		Storage	Investing in processing and freezing facilities
			Weather assessment before harvesting
4	Quality & Aesthetic Requirements		Collaboration with customers (retailers, wholesalers etc)
			Hiring agronomist specialist
			Direct sales to consumers
			Campaigns to change consumer perception and behaviour
			Redistribution
5	Extreme Weather Events	Extreme Precipitation Events	Waterlogging-tolerant genotypes
			Altered sowing times
			Improve soil structure to enable drainage
		Temperature Drought Stress	Improve soil structure to increase water holding capacity
			Policy assistance / Government support
6	Demand Mismatch & Overproduction		Collaboration with customers (retailers, wholesalers etc)
			Direct sales to consumers
			Greater transparency and feedback mechanism
			Policy assistance / Government support

Many studies have investigated specific causes of crop losses such as diseases, pests and animals. However, research quantifying, understanding and addressing all potential aspects of on-farm FLW is severely lacking. Despite reviewing forty-nine total publications, there are many facets of FLW which have not been covered in the academic literature with no suggested solutions to these. For example, weather resulting in lack of access to farms, transportation issues, reliance on contractor availability, access to facilities such as abattoirs, food produced by farms which do not satisfy food standards, change in market prices leading to re-cropping and so on. Despite this FLW occurring on farms, there are few studies on FLW which have accessed or requested data or information from farmers who are managing these systems. Therefore, our current understanding of the quantities of UK FLW are speculative and our understanding of the factors that have the biggest impacts on FLW and the opportunities on farms to reduce waste are lacking. This is currently a missed opportunity as there may be relatively easy ways in which FLW reduction could be supported.

Even though waste resulting from overproduction and demand mismatch have been identified as concerning, limited studies focus on these. The difficulty in matching supply with demand is a management challenge (specifically, operations and supply chain), but none of the articles reviewed in this study is published in an Operations and Supply Chain Management journal. Quality & aesthetic requirements as a cause of on-farm waste requires consumer behaviour and marketing perspectives. There are opportunities for exploring alternative processing and distribution options for surplus on-farm food. Additionally, crops such as lettuce, onions, peas and carrots which have been estimated to have the highest levels of on-farm waste relative to primary production volumes have received little attention while more economically attractive crops such as oilseed rape and strawberries have attracted the most attention, despite their relatively lower levels of estimated waste. There is a critical need for increased research on those crops that are associated with high levels of waste. This is especially important in lettuce production, considering that freezing and drying are not viable storage options.

This report highlights the need for increased research effort and greater collaboration between agronomy and management researchers in the UK in addressing the less studied causes of on-farm food waste such as quality & aesthetic requirements and demand mismatch & overproduction. Furthermore, it emphasises the need to redirect on-farm food loss and waste research focus on the crops that need intervention more urgently.

1. Introduction

The Food and Agriculture Organisation (FAO)[1] defines the loss of mass or nutritional quality of food upstream of the food supply chain (primary production to manufacturing and processing) as 'food loss' whereas the food lost downstream (retail and consumption) even though it was fit for human consumption as 'food waste'. There are challenges with this definition of food loss and waste and its implication for quantification[2]. For instance, waste at the wholesale distribution stage was overlooked in the 2011 FAO definition, even though it appears now classified as part of the downstream[3].

Food loss and waste resulting from issues such as overproduction, damaged but consumable food due to pest infestation, as well as food exempted from sale due to retailer quality & aesthetic requirements, tend to be overlooked when quantifying food loss[4–6]. Additionally, the idea of "loss" may water down the consciousness of the potential of recovery of surplus at primary production. There is therefore limited data on redistributed food sourced pre-farmgate[7,8]. For most foods lost to diseases, pests, weather and poor storage, "loss" is an appropriate descriptor. However, for surplus food resulting from overproduction[9,10] that may be left unharvested[11,12] and reploughed, or unsold produce that may be sent for anaerobic digestion or disposed[13], "waste" may be the better descriptor. This helps highlight the recoverability of such food for redistribution for human consumption before alternative usage options are explored, leading to better adherence to the food waste hierarchy. We will, therefore, use the term "food loss and waste" (FLW) in this report to encompass all food lost or wasted across the supply chain.

An estimated 13.3% of the world's food was lost after harvesting in 2020 and about 931 million metric tons of food available to consumers is wasted at household, food service and retail levels[14]. Associated with this are huge economic losses and water and land resources that could be allocated elsewhere as well as added greenhouse gas emissions which have negative implications for the health of the environment. Reducing food loss and waste is, therefore, critical for ensuring food systems are environmentally and economically efficient. Apart from waste prevention, an hierarchy of other options defined in the food waste hierarchy framework[9] have been prescribed to deal with food surplus and waste. Food redistribution for human consumption is the next most sustainably desirable option after prevention. This is important because over 30% of the global population do not have access to safe, nutritious and sufficient food[15]. In the UK, reliance on food banks has tripled over the past decade[16,17]. With the rising cost of living, food insecurity is worsening and this has a direct adverse effect on health inequalities and life expectancy—which is on the decline in the UK)[18].

Over 3.3 million tonnes of food are lost and wasted in UK primary production (on-farm) annually, representing about 25% of total UK food loss and waste[19]. Available data on UK food waste provided by organisations such as the Waste Resources Action Programme (WRAP) are predominantly post-farmgate, with a particular lack of data on on-farm losses and waste—potentially underestimating the loss and waste problem. Yet, they have estimated food waste in the primary production of several fruits and vegetables[20]. When expressed as a proportion of total edible production, horticulture is estimated as the second highest source (behind aquaculture) of FLW in primary production[21].

To date, efforts at reducing FLW across the food supply chain have largely focused on the consumption and manufacturing part of the supply chain, while there is limited knowledge about on-farm loss and waste[8,22]. Further, there is the need to begin thinking of on-farm waste as a resource management problem, rather than a waste management one[23] so that beyond prevention, legitimate reuse and recycling options can be explored. This part of the report aims to review the literature on on-farm FLW in UK crop production to identify causes, management and solutions. A systematic literature review method was used as it is more transparent, rigorous and robust, compared to a traditional literature review[24]. Three keyword groups were used, one for primary production, another for the UK and a third for crops and types of loss and waste. Keyword strings were then used to search Scopus, Web of Science, EBSCO and ABI Inform databases. After an initial result of 913 articles, 44 final articles were reviewed after applying the selection criteria for quality and relevance. Five UK government reports were also included as they were deemed relevant from the read articles. Further details on the methodology are presented in the Appendix.

We identified six primary causes of FLW pre-farmgate, namely, pests & animals, diseases, extreme weather events, aesthetic requirements, harvest & storage and demand mismatch & overproduction. For pests & animals, and diseases, management practices and solutions were specific to the causes, while more generally applicable approaches for multiple crops have been prescribed for aesthetic requirements, demand mismatch & overproduction, harvest & storage and extreme weather events. Each of these causes and the prescribed management strategies and solutions are discussed below.

2. Pests & Animals

Pests are frequently mentioned in the extant literature as a cause of FLW. Vegetable farmers are concerned about pests such as diamondback moths, root flies, and damage by pigeons whereas the major pests for soft fruits include birds, mice, and slugs[25]. Cereals are also subject to a huge loss on-farm because of pests and pathogens. A Department for Environment, Food & Rural Affairs (DEFRA) study[26] estimated a 5-20% annual loss of UK cereal productivity due to pests and pathogens. Slugs damage multiple fruits and vegetables but are incredibly difficult to control.

However, the UK Agriculture and Horticulture Development Board (AHDB) intimates a failure to control slugs could cost UK agriculture over £100 million annually[27]. With chemical products such as molluscicide products, methiocarb and metaldehyde, which could be used to control these pests, considered dangerous to the environment and thus banned by the government, the urgent need for alternative non-toxic solutions cannot be overstated.

Some pests and animals target specific crops. For instance, oilseed rape, which can be used to produce biodiesel and is considered highly profitable in the UK is chronically plagued by cabbage stem flea beetles (CSFB). In 2014, 76% of total oilseed rape crops in the UK were affected by CSFB, leading to about 5% crop loss and an estimated loss of £13 million in the eastern regions alone[28,29]. Neonicotinoids were applied to the crops to control the pests but this caused further damage by increasing the pest's resistance and is hazardous for bees[28,29]. Farmers had to resort to re-drilling and re-planting to salvage their losses and this cost an extra 5-10% of the costs already incurred through lost areas[28]. Wheat production represents up to 40% land use of the national arable area. Grain aphid is one of the key pests for this crop. Farmers generally use chemicals such as pyrethroid to control these pests, but they are reported to gain resistance over time. Pests such as phorid and sciarid flies cause diseases in mushrooms or drop their larvae which feed on the mycelia or carpophores[30]. Thrips cause significant losses in strawberry production as they feed on them and spread plant viruses. They are quite resistant to common pesticides and can easily reproduce in new habitats[31].

Animals such as geese can cause FLW by reducing sward structure and causing puddling and compaction. Farmers report geese to be responsible for about 20% of losses annually, with associated on-farm costs estimated at around £11,000 per farm in Islay, Scotland[32]. When extrapolated nationally, this can become drastic.

To control pests, multiple solutions have been presented in the literature. The most common is pesticides but their production and use are detrimental to the environment and can be harmful to human health, including being potentially responsible for some cancers[33]. Integrated pest management (IPM) is a comprehensive solution for dealing with pests and related losses. It consists of a group of methods and helps reduce dependency on insecticides, thereby facilitating sustainable farming practices[26,29,31,34,35]. It is expected to play a critical role in DEFRA's National Action plan currently being developed. Besides IPM, DEFRA is also involved in setting up warning systems at the border and surveillance systems inland for inspection purposes as well as in collaborating with landowners to remove disease trees/pest reservoirs[26]. With Sustainable Intensification (SI), which is a process by which agricultural productivity is enhanced without adverse environmental impacts, practices such as using weather and satellite data to predict pest outbreaks and using these to optimise inputs have been recommended[36].

Using agents such as natural enemies, biocontrol agents, and predators would be another significant method to avoid pests[27,30,34,37]. For example, for phorid flies' damage to mushrooms, farmers may use predatory mites, entomopathogenic nematodes, entomopathogenic bacteria, and entomopathogenic fungi[30]. To protect wheat from pests such as grain aphids and Metopolophium dirhodum, predators, parasitoids, and pathogens may be used[34]. For strawberries, farmers may release predatory mites (e.g., Neoseiulus cucumeris) and predatory bugs (e.g., Orius species) to control thrips[31]. Biocontrol agents can also be used to control slugs. In the UK, nematodes and carabid beetles are reported to be promising biocontrol agents for slugs. Slugs can also be controlled using bio-rational control measures such as garlic or spearmint oils, plant extracts, and caffeine[27].

Another risk to primary production and increase in losses is the decline in natural habitats affecting beneficial insects that have a significant impact on primary production. For instance, the population of bees is declining rapidly. Honeybee colony numbers have halved over the past couple of decades in the UK[38]. Yet, 70% of major crops such as oilseed rape depend on bee pollination[37,38]. The reducing beetle population in the country is another source of concern as they help control populations of economically critical pests such as aphids, slugs, root-feeding flies, and phytophagous beetles[37]. To support populations of beneficial insects, buffer strip areas and more hedgerows can be created[37,38]. It is worth stating that while the creation of semi-natural habitats fits with sustainable environmental goals, constant monitoring is needed to ensure net-positive change[37].

Implementing push-pull control methods is another proposed alternative to pest control. To eliminate tarnished plant bugs in strawberry crops, semiochemical synthetic traps may be used to attract pests and insecticide spray is then used. With this strategy, the amount of damaged strawberry fruits can be reduced by approximately 50%[35]. Similar trapping strategies may be used to minimise thrip damage to strawberries. In controlled tests, implementing blue sticky roller traps alone, or with additional thrip aggregation pheromone, reduce adult thrips numbers by up to 73% and FLW by up to 68%[31].

Finally, to eliminate animal damage, farmers implement a variety of scaring methods such as scarecrows and gas guns to chase animals (e.g., geese) away. This approach may be combined with sacrificial crops or alternative animal feeding areas to dramatically reduce the on-farm animal damage which causes FLW[32].

3. Diseases

Many organisms such as fungi, oomycetes, bacteria, viruses, and parasitic plants cause diseases, greatly reducing crop yield of many economically significant crops (such as potato, wheat, oilseed rape, rice)[39]. Some studies estimate the food lost to diseases is about 55 kg per person per season for the four largest crops (rice, wheat, maize, potato) in worldwide losses to diseases[40]. The percentage of diseases in total crop losses world-wide is estimated at 16%[41,42]. The situation is no different in the UK. There are many studies focusing on diseases in crops. It has been argued that crop protection could reduce the loss rate by up to 40%[42].

Geography plays a significant role in diseases—even for the same crops. For instance, wheat growers in Lincolnshire are more concerned about yellow rusts whereas Herefordshire growers focus more on the threat from Septoria (leaf blotch of wheat)[42]. The main diseases that affect winter oilseed rape crops in the UK are phoma stem canker and light leaf spot and, on average, they are reported to cause an annual loss of between £70 to £140 million altogether per growing season[41,43,44]. Global warming is predicted to increase the range and severity of phoma stem canker and yields will further decrease[43].

Wheat is one of the most common arable crops in the UK. This crop suffers from fusarium ear blight. Ear blight's epidemic strength can be greatly enhanced with rising temperature or increased rainfall in key periods of the disease cycle[44,45]. Further, changes in the air gaseous composition can directly affect the severity of crop disease epidemics through effects on the host, the pathogen, and their interaction[40,46]. Many farmers do not have any formal crop or disease management plans but they do have a well-organised fungicide programme guided by AHDB guides, agronomists and experience from previous growing periods[42]. Nevertheless, this approach can be insufficient in stopping fusarium ear blight. Using a wheat growth model and a weather-based model, Madgwick et al.[45] used daily weather data, generated for 14 sites in arable areas of the UK as a baseline (1960–1990) scenario and for high and low CO2 emissions in the 2020s and 2050s, to project wheat anthesis dates and fusarium ear blight incidence for each site for each climate change scenario. They projected wheat anthesis dates to be earlier with the fusarium ear blight being more severe in Southern England and Scotland, where there currently is relatively little incidence of the disease.

Potato also suffers many types of diseases due to bacteria, oomycetes, ascomycetes, and basidiomycetes, which lead to losses. An example of such diseases is potato blight which can lead to substantial yield loss and loss of investment[42]. Farmers have historically used chemical sprays (e.g., fungicides) when the weather permits, and copper as effective solutions against diseases[42,47] but accumulated copper has been identified to damage the soil and indirectly reduce the total yield[47]. Copper usage has therefore been restricted in the UK and farmers are now seeking alternative solutions.

In the UK, barley is sown as both a winter (autumn-sown) crop and a spring crop; these crops have different exposures to pathogen inoculum. Many fungal pathogens cause diseases, leading to crop losses in barley production. Examples of these fungal diseases are leaf blotch, net blotch, brown rust, and yellow rust. Fungicide treatment, therefore, remains important in disease control in barley, as evidenced in the application of fungicides to 98% and 87% by area, of UK winter and spring barley, respectively, in 2008[48] in the absence of which an additional 17% of arable area would have been required to match yield. Despite the limited levels of loss in barley production due to fungicide application, we find that new types of fungal diseases become prevalent due to climate change and the resulting change in air composition40. These need to be closely monitored to ensure losses are kept minimal.

As is the case for barley, fungicides are critical for controlling many types of diseases in several crops[41,42,48]. Deciding when to apply fungicide spray for disease control is based on the perceived risk of disease, which is determined mainly through a visual assessment (by grower and/or agronomist)[42,46]. The evidence suggests that to overcome diseases with fungicides, the effect of climate change also plays a crucial role[41,43,44,46,49]. Research that focuses on the identification of potential impacts of climate change on crop diseases is needed, to determine how to apply the current fungicides in the future and to develop new ones—particularly considering how long it takes to do so[40,42]. Moreover, implementation of policy alteration in primary production often takes time[44]. Notwithstanding, using fungicides and crop cultivars with improved resistance to diseases is estimated to save over 15 kg per person on average seasonally[40].

It is important to combine crop and disease models with climate scenarios to produce more accurate projections of the impacts of climate change on diseases[45]. Detailed modelling approaches that combine future climate simulations, crop growth models and disease models have been developed for phoma stem canker of oil seed rape and fusarium head blight of wheat[46]. For instance, combining climate scenarios and crop models predicted that climate change could increase the yield of fungicide-treated oilseed rape crops in the UK by up to 15%, whereas untreated crops will have yield loss by up to 50%[46].

Some indirect effects of climate change on crop diseases may induce the implementation of different adaptation strategies such as altered crop rotations, cultivar choice, spraying times, and sowing dates[42–44,46]. As an example, spring-sown linseed crops have been observed to escape exposure to most of the primary inoculum (that are often released in autumn) or that they have fewer disease cycles in their short growing seasons compared to those sown in autumn[46]. Another adaptation strategy example is having a 4-year break between oilseed rape crops which has been indicated to decrease yield losses from phoma stem canker disease compared to currently used shorter rotations[43]. However, altering crop rotations could also increase the potential and severity of other diseases such as clubroot, depending on the previous crop. Some authors have suggested that farmers should be careful when modifying crop rotations[43].

Another disease management approach that is widely being adopted by farmers is gaining disease resistance through gene modification[39,40,42,43,50]—an approach the UK government is increasingly incentivising. Methods such as pathogen-derived resistance, pathogen-targeted resistance, and RNA silencing all aim to increase the pathogen resistance in crop crops through gene modification[39].

An adaptation strategy recommended by Barnes et al.[43] was to plant seeds of a cultivar with greater resistance against the pathogen, using the Home-Grown Cereals Authority (HGCA)—now part of the AHDB's recommended list ratings for disease resistance. Even though this might be expensive, such cultivars almost guarantee a higher yield while reducing FLW. For instance, when combined with shorter rotation cycles, it could potentially double oilseed rape yields[43].

Despite reservations about its use, plasticulture is another way to protect crops from diseases, thereby reducing losses. Plasticulture refers to a system of growing higher-value crops such as tomatoes, cucumbers, peppers and soft fruit under more sophisticated protected cropping systems involving glasshouses or polythene tunnels and crop mulches[50]. Raspberry yields, for instance, were doubled by growing them in polytunnels and are 12% less likely to develop a fungal disease compared to those grown in the open field in the UK[50,51]. Plasticulture also helps grow higher quality raspberries throughout the entire year as well as reducing spoilage and low-grade fruit[50]. Strawberry is an economically important fruit crop worldwide[52,53]. Approximately 3900 hectares of strawberries in the UK are either grown under polytunnels, mulches or fleece and this is estimated to have resulted in an increase in average yield from about 9.9 tonnes per hectare in 1996 to 22.3 tonnes per hectare in 2015[54]. These new growing techniques have provided effective protection against fungal diseases, particularly Botrytis cinerea[53,55].

Although on-farm implementation and experimentation is regularly undertaken by farmers and agronomists, several of the management options and solutions presented here require increased applied research to be effectively reflected in the industry[40].

4. Extreme Weather Events

Extreme cold or heat (e.g., cold snaps, heat waves, droughts) and downfalls (e.g., hailstorms, heavy rains, floods) can cause food loss on farms. Many of the fruits and some vegetables consumed in the UK cannot tolerate freezing or even chilling temperatures 50. These weather conditions can result in waterlogged, lodged, or cosmetically damaged crops. To cover for such potential yield losses; farmers sometimes overplant as insurance against such poor weather conditions. Overplanting can cause overproduction and the excess yield can end up as waste[11].

1. Extreme Precipitation Events

Each year, 27% of cultivated lands are impacted by flooding with an annual cost of US$19 billion globally[56]. Flooding causes a variety of crop damages including waterlogging and lodging[56,57]. Lodging is the permanent displacement of plant stems from their vertical position. Further to waterlogging and lodging, farmers also mention how heavy rain and hailstorms can damage crops even causing them to crack or have oedema, making them unfit for sale[25].

Oilseed rape is an example of a crop that suffers lodging under poor weather conditions. Although there are other reasons than the weather, it is common for oilseed rape to lodge after periods of heavy rainfall Lodging reduces the yield of oilseed rape by 16–52% depending on the degree of lodging (45° or 90°), costing the UK, with respect to this yield reduction, between an estimated £47 to £120 million per year[57].

Barleys suffer yield losses due to waterlogging. There is an average yield penalty of about 11% for winter barley and 3% for spring barley. These are expected to, at least, double by 2080 due to climate change[56]. A suggested solution to address this in environments with longer, cooler, and more temperate growing seasons (such as the UK) is the adoption of waterlogging-tolerant genotypes along with altered sowing times, which can alleviate waterlogging yield penalty by up to 18% depending on early or late sowing and the climate[56].

Overall, extreme precipitation events cause significant losses and waste on farms and the impact of these events is likely to increase considering climate change.

2. Temperature Stress

Climate change (and resulting extreme heat and drought) adversely affects crop yield. An example is hops—a core ingredient of beer. When damages between April (bud burst to leaves) and August (cone development to harvest) are integrated, there is approximately 62.7% of total yield losses due to high temperatures in the top hop-farming regions in Europe, including the UK58. In the past couple of decades, the occurrence of dry-hot days in growing seasons has more than doubled and there are indications that these heat waves started happening in the UK after the 2010s[58]. The resulting dry-heat stress reduces crop yield. For the UK, this yield loss is observed especially in May and June, where dry-hot days are seen more frequently.

To address this, Potopová et al.[58] suggest keeping the feeder root system moist as well as policy assistance to facilitate the adaptation of growers to these changing climatic conditions. They also observed that the strongest influence on hop cones was exerted by temperature and rainfall patterns during the growing season. Considering hops are deep-rooted plants, for optimum yields and cone quality, the feeder root system should be kept moist during the critical growth period. Furthermore, Potopová and others indicated that previous patterns of yield reduction in hop yields due to heat stress over the past few decades is indicative of the new trend in crop yields and remedial action is needed.

5. Quality & Aesthetic Requirements

Customers' (particularly, retailers and consumers) expectation of purchased crops is another driving factor of on-farm FLW[25,59]. The food supply chains in many EU countries, including the UK, are highly integrated and even considered by some as oligopolies[22], where large retailers hold most of the power, among other things, to determine the cosmetic standards for fresh produce. They provide specification sheets; detailing the size, shape, and colour of produce required depending on consumer demand. Crops that fall outside of these requirements are considered 'ugly' and sometimes end up as waste[11]. Additionally, there are strict safety laws that define which produce is safe to consume. Unfortunately, some of these quality standards, more or less, expect a uniform appearance and do not account for the natural shape variability of fresh produce[22].

In the UK, what consumers and retailers accept is too narrow, and it is estimated that the range of losses due to quality and cosmetic reasons is between 7% and 65%, with a mean value of around 25% depending on the type of crop[22]. For instance, the length of strawberries is expected to be between 25mm and 45mm to be accepted[25]. A Waste Resources Action Programme (WRAP)[60] field study about strawberries showed that these strict expectations can cause waste of up to 23%. Table 1.1 below, presents the average annual crop losses for select fruits and vegetables due to quality and cosmetic reasons in the UK. The high mass of grade out loss in potatoes is because they represent 70% of the total fresh fruit and vegetable harvest in the country. However, in terms of the loss factor, carrots, lettuce and cabbages have the highest among these crops, with 31%, 26% and 22% respectively

Table 1.1 Average Yearly Crop Losses due to Quality and Cosmetic Reasons in the UK Adapted from 22

Crop	*Average Grade-out Losses (kt)*
Apple	37
Broccoli and Cauliflower	21
Cabbage	65
Carrot	325
Lettuce	38
Onion	69
Pear	3
Potato	1,147
Strawberry	16
Tomato	7

There are multiple management approaches to reducing FLW caused by quality and cosmetic requirements. Firstly, increased collaboration between farmers and retailers could help reduce these losses and waste. Sharing knowledge about how to attain the ideal specification for different crops and receiving support from an agronomist specialist can help reduce waste due to quality and cosmetics[61]. Further, farmers could also collaborate with local waste contractors and food redistribution charities to set up waste management strategies both to reduce and manage their losses and waste.

Secondly, direct sale to consumers, thereby bypassing retailer and market aesthetic standards, leads to increased sale of fruits and vegetables that would have been otherwise considered undesirable. Such direct-to-market approaches lead to about 23% sale of 'ugly' fruits and vegetables, compared to the supermarket average of 12%[22]. Further to these approaches, campaigns and advertisements about the benefits of fruit and vegetables, even if they are tagged as 'ugly', as well as using creative marketing (such as branding misshaped carrots as 'baby' carrots), may help alter consumer perspective and behaviour[22,25].

Considering that many farmers implement selective harvesting and train their pickers to only take the qualified produce and leave others unharvested[22], these measures will result in increased yield, purchase and consumption of these crops, and also reduce waste and associated carbon emissions.

6. Harvest & Storage

Harvesting and temporary storage of harvested produce contribute significantly to on-farm FLW. Yet, they are largely understudied, with only a few studies considering them. Crop loss and waste at harvesting and storage account for up to 25% of the produced yield[26]. For instance, for strawberries, up to 5% of the waste is due to spoilage in the storage as a result of rotting and bruising while about 22% of the waste is caused by unsuccessful harvesting on farms[60].

3. Harvesting

We find that most authors report that the manner in which harvests are handled could impact the amount of losses on the farm. For instance, broccoli heads, if they are not handled correctly while being picked from the field, can dehydrate which leads to waste while for strawberries, those picked without their stalks may end up as waste as consumers prefer the fruit with its stalk[25]. Other failures of manual harvesting are where the crop's quality is misjudged or the crop is overlooked during harvesting. **WRAP** posits over 30% of sellable strawberries wasted in the field were a result of these failures[60].

Mechanical harvesting may also lead to losses; for instance, in rainy weather, the damage to crops increases, leading to increased FLW[25]. Excessive use of machinery can cause soil compaction and sward damage, as well as direct crop damage. Though an average of 13% loss is estimated, it can be as high as 74%. Hargreaves et al.[62] recommend the total number of machine passes should be no more than 15 for normal traffic.

To address losses due to manual harvesting, better plant management and husbandry are crucial, even though, prohibitive labour costs and worker productivity are barriers to their implementation[60]. Introducing a controlled traffic farming system as compared to the normal traffic regime can increase the yield by 13.5%[62].

The way farms manage seed and sowing also affects harvesting yield. Carlton et al.[49] suggest that organic farming could decrease yield by up to 58% especially in oat, wheat, and oilseed rape production even though it enhances the fertility of the arable area by around 50%. Similarly, Smith et al.[63] found out that even though potatoes, oats, beans & peas, onions, brassicas, and carrots can have increased yields compared to their conventional production, sugar-beet, wheat, and barley do not necessarily respond well to some organic farming practices.

4. Storage

The storage times for fresh fruit and vegetables vary depending on the type of crop (see Table) and storage conditions, which sometimes negatively affect the product quality and lead to FLW. Furthermore, harvesting conditions (such as in rainy weather) greatly reduce the storage time after they are harvested.

Table 1.2 Average storage times for crops post-harvest[25]

Crop	*Storage time*
Strawberries	24 h
Lettuce	24 h
Brussels sprouts	24 h
Broccoli	10 days
Leeks	1 month
Swede	4 months

Thus, in the absence the relevant equipment and facilities to enhance storage and/or processing, losses and waste increase.

Investing in processing, freezing (for some fruits and vegetables) and ventilation systems (for grains) can help increase the durability of freshly harvested crops, increase the shelf life of the produce and therefore reduce waste25,26. Lastly, carefully assessing weather conditions before harvesting can also be useful in ensuring waste is reduced both in harvesting and storage.

7. Demand Mismatch & Overproduction

Among the identified causes of food waste in this review, this was the most underrepresented. It is mainly the supply-demand mismatch of the farmers and their customers (primarily, retailers and wholesalers, but also consumers) as well as intentional overplanting by farmers to meet contracted delivery quantities. Weather, retailer promotion patterns, changing taste of consumers, and labour costs contribute to this loss and waste phenomenon. During warmer conditions, demand for traditional vegetables such as broccoli, Brussel sprouts, leeks, and cabbage decline.

Similarly, orders for soft fruit (such as various types of berries and citrus plants) reduce during rainy weather. Further, ill-timed product promotions by retailers, though can be used to accelerate the sales of fruits and vegetables nearing shelf-life limit, can contribute to the unpredictable demand which then instigates overproduction (in a bid to overcome the opportunity cost) and then waste[25].

Another cause of FLW due to demand mismatch is the changing demography (age, culture and perspectives) of consumers. Crops such as jam berries and swedes which are popular among older consumers has lost their popularity among younger consumers. This leads to waste as actual demand falls below the typical production volumes farmers usually produce. With increasing labour costs, particularly post-Brexit, when market prices do not justify harvesting and storage expenses, farmers leave them unpicked[11].

Close collaboration and increased communication can help address the supply-demand mismatch caused by weather and unexpected promotions61. Greater transparency and feedback mechanism can enable primary producers to better respond to retailer decisions, fulfil their demands, increase income and reduce waste[26]. These approaches should also be supported by the government, which should first acknowledge the retailer-driven overproduction and the oligopolistic power of the retailers, and then try to reduce the surplus in the production with specific regulations[23]. England's 'Our Waste, Our Resources: A Strategy for England (the Strategy)' is a useful beginning effort towards acknowledging the problem of overproduction and food waste but has been criticised for the lack of clarity in resource management frames[23].

8. Conclusion and the Way Forward

Food loss and waste have significant implications for the health of the environment particularly as current food production methods degrade soil health, water quality, biodiversity and cause the release of greenhouse gases[41,64,65]. Continued losses on farms means that a depreciation of resources, time, land and money as well as worsening food insecurity.

Many studies have investigated specific causes of crop losses such as diseases, pests & animals, but research quantifying, understanding and addressing all potential aspects of **FLW** is severely lacking. Despite reviewing forty-four publications, there are many facets of **FLW** which have not been covered in the academic literature with no suggested solutions to these. For example, weather resulting in lack of access to farms, transportation issues, reliance on contractor availability, access to facilities, food produced by farms which do not satisfy food standards, change in market prices leading to re-cropping and so on. Despite this **FLW** occurring on farms, there are very few studies[e.g., 25,61] which have accessed or requested data or information on FLW from farmers who are managing these systems. Therefore, our current understanding of the quantities of **UK FLW** are speculative and our understanding of the factors that have the biggest impacts on **FLW** and the opportunities on farms to reduce waste are lacking. This is currently a missed opportunity as there may be relatively easy ways in which FLW reduction could be supported.

Demand mismatch & overproduction are an operations and supply chain management issue, but none of the reviewed articles in this study are published in an Operations and Supply Chain Management journal (see Table AII in the Appendix). Notwithstanding, authors such as Glendining et al.[33] and Firbank et al.[66] have made recommendations towards optimising primary production to reduce overproduction. A management lens (marketing, operations and supply chain) is required to address issues such as improved matching of supply with demand and improvement in collaboration with customers (wholesaler, retailer and consumer) to address quality and aesthetic requirements. There are also opportunities to explore alternative processing options for food with reduced quality due to poor weather conditions and/or pest infestation. This may be explored along with the market potential for value-added surplus food products as presented by McCarthy et al.[8].

There are genuine concerns about the adherence to the food waste hierarchy in primary production. As digestors used in anaerobic digestion require a continuous supply of waste to remain profitable, there are concerns about edible food being redirected from potential redistribution for human (and/or animal) consumption[59]. Following Ribeiro and colleagues'[67] study in Spain, studies to explore increased exploitation of surplus on-farm food for human consumption is also needed within **UK** primary production.

Finally, recent estimates by **WRAP**20 suggest lettuce, onions, peas and carrots suffer some of the highest average on-farm waste levels relative to production for human consumption in the UK (24.8%, 17.3%, 17% and 15.7% respectively). There was a greater focus on oilseed rape and strawberries in the reviewed articles than on lettuce, onions, peas or carrots. There is, therefore, the need for a closer look at addressing waste, especially in lettuce production where storage options such as freezing or drying may not be feasible.

Overall, there are significant efforts in the scientific research addressing specific areas of disease and pest management which as a secondary impact may reduce **FLW** on **UK** farms, but studies focusing on quantifying, understanding and managing **FLW** are limited. There are opportunities for greater collaboration, particularly between environmental scientists and management sciences to address the causes of on-farm **FLW** that originate post-farmgate.

Part 2:

Consideration of Food Loss and Waste in Transforming UK Food System Projects

Executive Summary

In the UK, about 6.65 million tonnes of edible food is wasted annually[7]. Food waste not only undermines food security, but the production of food has significant impacts on the environment and associated greenhouse gas emissions. Therefore, when considering transforming the UK food system, we must address food waste. UKRI and partners have recently invested £47.5M in a programme to 'Transform the UK food system for Healthy People and a Healthy Environment' (TUKFS). This report reviews the projects currently funded by this programme and determines how food loss and waste were considered and at what stages of the food supply chain the considerations were made.

Food loss and waste are considered in seven of the thirteen projects reviewed, even though reducing food waste is not the focus of any work package in the projects and is in most cases a secondary consideration or consequence resulting from other activities. All three Call 1 projects reviewed considered prevention in the overall supply chain, primary production and consumption. They also considered prevention and reuse in other stages of the food chain but only one had considered recycling. Food loss and waste considerations in these projects were more extensive due to their breadth and interdisciplinary nature compared to those in Call 2. All four Call 2 projects that considered food loss and waste either directly considered prevention in primary production or their work had implications for that stage of the food supply chain. Two of the projects consider prevention at consumption while the other could impact reuse options at primary production. Only one of the reviewed projects considered food waste at the hospitality and food service industry stage of the food chain. None of the projects considered recovery or disposal and none focused on the storage and logistics, manufacturing and processing as well as the wholesale distribution stages of the food supply chain. The number of projects that consider the different food waste management options presented in the food waste hierarchy at the different stages of the food supply chain are summarised in Table II.

***Table II** Number of projects considering food waste management options at different stages of the food supply chain. **NB:** Some projects consider options at multiple stages.*

	Prevention	Reuse	Recycle	Recovery	Disposal
Overall Supply Chain	4	2			
Primary Production	6	2			
Storage and Logistics					
Manufacturing and Processing					
Wholesale Distribution					
Retail Distribution	1	1			
Hospitality and Food Service	1				
Food aid Service Organisations	2	2			
Consumption	5	2	1		

Despite these considerations, we identify some opportunities for expanding research and innovation on food loss and waste. We highlight the opportunity within all the projects that a closer look at food loss and waste could present, not only for more holistic food systems intervention of the projects but also to better capture their impacts socially and environmentally. Our recommendations, notwithstanding, there are additional opportunities for further consideration of food loss and waste if they are not considered an afterthought. The causes of food waste along the food chain require closer attention and must be addressed as we seek innovations that will transform the UK's food system. Additionally, as some of the project innovations are looking to optimise primary production to better match consumption and reduce overproduction, it is critical to explore the implications these will have on the availability of surplus food, which is currently the primary source of food for millions in the UK. As more responsible primary production is being pursued, there are opportunities to improve the consideration of food loss and waste in the storage and transport, manufacturing and processing and wholesale distribution stages of the food supply chain as these could serve as critical sources for surplus food to support marginalised communities while food poverty is being addressed. We suggest that going forward, all projects seeking transformation in the UK's food system should acknowledge the implications of their work for food loss and waste (when they are not directly considered) and highlight adherence to the food waste hierarchy and any anticipated sustainability impacts across the food supply chain.

1. Introduction

It has become increasingly evident that the current UK food system has several vulnerabilities that adversely impact the delivery of optimal health and wellbeing for both humans and the environment. There is increasing food insecurity while food produced in the country is not aligned with what is being consumed. The quality of consumed food has declined precipitously with foods high in fat, sugar and salt now making up approximately half of all meals consumed in the average UK household. Further, 1 in 7 deaths in the country are diet-related and about two-thirds of adults in the country are either overweight or obese.

Addressing these concerns is the Transforming UK Food System (TUKFS) Strategic Priority Funds (SPF) Programme. The aim is to fundamentally transform the UK food system using a holistic systems approach, whereby healthy people and a healthy natural environment are at its centre. It looks to address questions around primary production and manufacturing, importation and consumption while taking into account the complex interactions of sustainability and health factors. This should lead to a disrupted and transformed food system which is resilient and has the public's trust.

Fifteen projects have been successfully commissioned over the past two years to work towards attaining the programme's aims. Four were from Call 1 in which up to £6 million in research grants were available to support a multi-centre, interdisciplinary 5-year project that collaborates with relevant stakeholders to shape the research and to help drive impact. The remaining 11 projects in Call 2 seek to integrate both social and natural sciences while collaborating with at least one stakeholder organisation (could be from the government, civil society or business) to address the government's priorities. These may be either two or three years and the research grants range from £250,000 to £2,000,000.

While looking to transform the UK food system, an aspect of that system that cannot be overlooked is the handling of waste. 6.65 million tonnes of edible food are wasted annually in the UK7. This has significant adverse effects on the environment, as current food production practices degrade the environment, causing soil quality decline, water pollution, GHG emissions and biodiversity loss. At the same time, food insecurity is worsening as evidenced by the astronomical dependence on redistributed food over the past decade[16,17]. Thus, any envisioned transformation in the UK food system has to be one where waste is minimised while unavoidable waste is handled as prescribed in the food waste hierarchy framework. This report reviews the 15 TUKFS-funded projects to ascertain the consideration of food loss and waste and the stages of the food supply chain these considerations are undertaken.

The cases for support for the projects were collected and analysed to identify the consideration of food loss and waste right from the original conception of the projects. We collected data for thirteen out of the fifteen Transforming UK Food System projects. The Call 1 projects were FixOurFood, FoodSEqual and H3. The Call 2 were BeanMeals, FIO-Food, Pasture to Plate, Raising the Pulse, Is Cultured Meat a Threat or Opportunity, Increasing UK Dietary Fibre, SNEAK, Social enterprise as a catalyst for sustainable and health local food systems, Sus-Health and TRADE. A questionnaire was distributed to the principal investigators of the projects to help capture any new developments towards the consideration of food loss and waste outside of what had been originally determined at the time of the submission of project proposals. To facilitate consistent analysis, a food waste hierarchy framework[9] and the UK government's Department for Environment Food & Rural Affairs' (DEFRA) statutory guidance[68] were used. This is presented in

Table 2.1. The food waste hierarchy is a framework of food waste management and handling options, where prevention is the most sustainably desirable option, followed by a series of sequentially mandated surplus or waste food usage extraction options including reuse, recycle and recovery, until the unusable waste reaches landfills or sewers.

Table 2.1 Food waste hierarchy[9,68]

	Hierarchical options	*Sub-hierarchical options*
1	Prevent surplus and waste	
2	Reuse	Redistribute surplus food to
		humans
		Animal feed
		Convert into biomaterials
3	Recycle	Anaerobic digestion
		Composting
		Landspreading
4	Recovery (Incinerate)	To generate energy
		Without generating energy
5	Disposal (send to landfill or sewer)	

This five-stage model was used to deductively code the collected data across the stages of the food supply chain (primary production, storage and logistics, manufacturing and processing, wholesale and retail distribution, hospitality & food service, and consumption)—including alternative routes for redistribution. This helped adequately capture which food waste handling option was occurring in each project and the stage of the supply chain this was occurring. Our findings in each project are summarised for Calls 1 and 2 in Table 2.2 and explained in the subsequent sections.

***Table 2.2** Consideration of food loss and waste using the food waste hierarchy options at different food supply chain stages in the **TUKFS** projects*

			Food waste hierarchy options within the projects																		
			Call 1							Call 2											
			1.1		1.2			1.3		2.1	2.2		2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	
			Prevention	Reuse	Prevention	Reuse	Recycle	Prevention	Reuse		Prevention	Reuse				Prevention	Prevention			Prevention	Reuse
Call 1	1.1	OSC	✓																		
		PP	✓																		
		FASO	✓	✓																	
		C	✓																		
	1.2	OSC			✓	✓															
		PP			✓																
		C			✓	✓	✓														
	1.3	OSC						✓	✓												
		PP						✓													
		R						✓	✓												
		FASO						✓	✓												
		C						✓	✓												
Call 2	2.1																				
	2.2	PP									✓	✓									
	2.3																				
	2.4																				
	2.5																				
	2.6	OSC														✓					
		PP														✓					
		C														✓					
	2.7	HFS															✓				
		C															✓				
	2.8																				
	2.9																				
	2.10	PP																		✓	✓

Key:
1.1 FixOurFood
1.2 FoodSEqual
1.3 H3
2.1 BeanMeals
2.2 Cultured Meat
2.3 FioFood
2.4 Increasing UK Dietary Fibre
2.5 Pasture to Plate
2.6 Raising the Pulse
2.7 SNEAK
2.8 Social Enterprise
2.9 Sus-Health
2.10 TRADE

OSC Overall Supply Chain
PP Primary Producer
R Retailer
HFS Hospitality and Food Service
FASO Food aid Service Organisation
C Consumer

Prevention
Reuse
Recycle

2. Call 1

1. FixOurFood

Project Overview

FixOurFood aims to assess regenerative food systems and how transformations might enable widespread regenerative systems across the UK. The project examines healthy eating for young children, hybrid food economies and farming systems as a means to achieve regenerative systems using Yorkshire as an exemplar region.

Consideration of Food Loss and Waste

The proposed plan of the FixOurFood project could lead to the reduction of food loss at primary production and improved food redistribution for human consumption in schools, holiday clubs and food hubs in Yorkshire. The regenerative approach to farming systems could lead to a reduction in food loss at primary production. Additionally, plans to develop new public procurement and retail supply chains that coordinate production to consumption regeneratively could result in a reduction in food loss and waste across the food chain. FixOurFood also intends to work with food redistributors including those that work in holiday clubs, schools and food hubs to ensure redistribution for human consumption is done sustainably and equitably. If existing opportunities for intervention identified in work package one (Regenerative dynamics, lock-ins, barriers and opportunities) activities, such as procurement through food hubs, are actualised, this could help enhance the volumes and quality of food redistributed through these channels.

Research Opportunities on Food Loss and Waste

FixOurFood project has the potential to impact food loss and waste across the food supply chain through its regenerative approaches. There is, however, an opportunity for it to capture quantitatively, regenerative agriculture's impact on food loss and waste in Yorkshire. The volumes of food to be generated through the project's regenerative farming can be quantified and compared with loss that is typically associated with similar volumes in traditional farming approaches for the grown crops. This could serve as a strong empirical outcome of the project and serve as the basis for replication across the UK.

At a micro-level, under Intervention 3 in Subsystem 1, the project outlines several activities "to embed and test feasible, regenerative interventions that are culturally appropriate and have the potential to benefit both health and the environment." A highlighted example was the development of a new model of food procurement for schools and nurseries. In addition to the intended outcomes here, there is an opportunity to explore a reduction in food waste by measuring current levels of waste, incorporating within the new models improved ways of matching demand with supply. The resulting reduction in food waste can be compared with the previous levels to provide further evidence of improvement in sustainability resulting from the new procurement model.

2. Co-production of Healthy, Sustainable Food Systems for Disadvantaged Communities (FoodSEqual)

Project Overview

Food Systems Equality (FoodSEqual) seeks to co-produce innovative products, supply chains and policy frameworks that deliver culturally-diverse, affordable, healthy and sustainable diets to disadvantaged communities. Community engagement, business partners and academic researchers are exploring avenues to co-design new products that satisfy the project's main objectives. The project is working with four focal communities in South England including Whitley Reading, Tower Hamlets, Plymouth, and Brighton and Hove.

Consideration of Food Loss and Waste

The FoodSEqual project considers food loss and waste across the food supply chain from its conception. It has identified that access to food among the disadvantaged included factors such as food waste and that the analysis of food supply chains delivering key food groups to consumers at its benchmarking phase, would provide insights on current failures in the conventional food supply chain to help identify opportunities to prevent surplus food and food waste. The expectation is for this to provide relevant insights for the co-development of alternative and/or new, more resilient and flexible supply chains and distribution networks in the project's innovation phase that will enable access to co-developed exemplar food products in disadvantaged communities. Life cycle analysis to quantify the impact of food choices on various parts of the food chain including the occurrence and treatment of food waste in both the benchmarking and innovation stages to facilitate comparisons and identify the benefits regarding food waste obtained from the product and supply chain innovation.

Since the commencement of the project, there is now increased efforts towards ensuring a food aid supply chain that delivers quality and accessible surplus food for disadvantaged communities. As part of community engagement activities in one of the communities in the project, Brighton and Hove, there are efforts towards showing routes for composting food after human consumption needs are met.

Research Opportunities

There are still opportunities for more research into food waste within FoodSEqual. As part of the effort towards considering the impact of the project on food producers, there is an opportunity to explore the challenges to the redistribution of surplus food from primary producers in the food chain.

3. Healthy soil, Healthy food, Healthy people (H3)

Project Overview

The H3 project follows a whole systems approach to transforming the UK food system through novel growing technologies as alternatives to conventional soil-based agriculture and the landscape scale impact of widespread transitions to regenerative agriculture.

Consideration of Food Loss and Waste

There are both direct and indirect attempts at addressing food loss and waste in H3. The technological innovation targeted at food production and supply could lead to lower levels of waste at primary production. The expansion of these innovative production methods into urban and peri-urban environments could shorten the food chain, thereby reducing losses that result from the handling and transport of food in longer supply chains. As more low-income UK households become reliant on redistributed food[16,17,69], the work within work package six (disrupted supply chains), focusing on the development and testing of adaptation methods with retailers to improve the supply of healthy food for such low-income households could mean an improved redistribution system. There are plans within the same work package to build a resilient and agile supply chain that reduces food waste and enhances food redistribution, thereby leading to improved adherence to the food waste hierarchy. Further, the translation of learnings into effective interventions on policy and practice by working with Sheffield City Region's food partnership and the Bristol Food Network should help drive impact on food waste nationally.

Since the project's commencement, there have been discussions within work package four (Biofortification through nutrient enhancement) on the prevention of food loss and waste in wholegrains and fibre. There are efforts towards the rescue and reuse of bread products for human consumption through schools and other food aid service organisations.

Research Opportunities

As highlighted above, the innovative production of food in urban and peri-urban environments could lead to reduced waste and increased redistribution of surplus for human consumption. There is currently no indication within the project on how this may be quantified to evince the immense benefits these could present for the UK's food system. As FixOurFood is also exploring regenerative farming, a collaborative research project to compare the reduction in losses based on the life cycle analysis both projects seek to undertake for the different innovations in primary production, variations across different crops as well as benefits in supply chain modifications could present useful insights, particularly on the reduction of food loss pre-farmgate. Considering current difficulties in matching forecasted demand with actual supply, how can the proposed primary production innovations, if scaling up is successful, lead to better alignment within the supply chain? Should these interventions lead to reduced surplus in the commercial food chain, how can low-income households access healthy, sustainable food products, considering the food aid supply chain is currently the primary alternative means by which such food is accessed?

4. Transforming Urban Food Systems for Planetary and Population Health (The Mandala Consortium)

Project Overview

The Mandala project aims to develop a model that provides healthy food and reduces the cost of food and environmental impacts while satisfying businesses. It also plans to map the food system and engage with communities in Birmingham.

We did not receive the relevant data to facilitate the review of this project.

3. Call 2

'Thinking Beyond the Can': Mainstreaming UK-grown Beans in Healthy Meals (BeanMeals)

Project Overview

BeanMeals plans to develop a fork-to-farm approach for systemic innovation and dietary changes that reduce high fat, salt and sugar in home-cooked meals resulting in net positive gains for the environment. This model is tested with two varieties of beans, Capulet and Godiva. The project will enlist stakeholders from Leicestershire including Leicester City Council, Food for Life, and Leicestershire Enterprise Partnership.

Consideration of Food Loss and Waste

Food waste management is not identified in the proposed plan—this in itself represents an opportunity for future research that aligns with the overarching aim of BeanMeals which is to develop and analyse systemic innovations for lower environmental impacts by using UK-grown beans.

Research Opportunities

The project's second and third objectives ("to determine how to produce and supply bean-based low FSS foods and ingredients" and "to estimate health, environmental and enterprise benefits/trade-offs of scaling UK beans") offer opportunities to include the assessment of waste and to proffer innovative methods for avoiding and/or reusing surplus beans for human consumption. With the Capulet bean's disease resistance, what are the implications for matching projected yield with customer demand to ensure overproduction is minimised? Research question 1.3 under work package one (Determine how to promote healthy diets with bean-based low-FSS meals) seeks to innovate public procurement, what considerations can be made regarding volumes to be purchased, and which stage of the supply chain storage will maximise efficiency while minimising waste? Furthermore, what storage conditions will be optimal for these pulses to ensure availability and lower levels of waste? These may also be included in ongoing efforts under research question 2.3. Considering research question 2.1 (How to innovate in growing common beans at scale in the UK?) under work package two (Determine how to produce and supply bean-based low-FSS foods and ingredients), there may be an opportunity to explore the susceptibility of the pulses within this project to pest infestation. Since current practices result in such infested beans being sent straight to animal feed, what opportunities are available to prevent or minimise weevil infestation and when not successful, how can such beans be processed for human consumption—if nutritional integrity is not compromised? This could be explored under research question 2.2 (How to innovate in processing beans for alternative food products?).

2.3.2 Is Cultured Meat a Threat or Opportunity for UK Farmers?

Project Overview

The project focuses on how cultured meat could affect farming in the UK. It looks at UK farmers' perception of cultured meat, the threats and opportunities for the development of cultured meat on the farm business and the practicality of on-farm production of cultured meat.

Consideration of Food Loss and Waste

The project is inherently designed to create an alternative food product for conventional meat sources. Despite this uniqueness, we identify the following opportunities for future research that relates to food waste.

Research Opportunities

Opportunities for research within this project may lie in a comparative analysis of the reduction of food loss and waste throughout the supply chain due to cultured meat production as compared to losses in conventional livestock farming due to diseases and deaths, reduction in demand for animal feed, and losses in meat processing.

2.3.3 FIO-FOOD, Food Insecurity in People Living with Obesity—Improving Sustainable and Healthier Food Choices in the Retail Food Environment.

Project Overview

The FIO project aims to bring together food insecure people who are living with obesity, consumers, retailers, policy makers and academic researchers to co-develop and test strategies that support future transformation potentials of the food system. It plans to use large data on shopping habits from retailers as well as to co-design solutions that test in-store and online access for healthier and sustainable food purchasing behaviours.

Consideration of Food Loss and Waste

Due to the unique focus on vulnerable people with obesity, food waste management as defined in the hierarchical framework is scarcely mentioned. Notwithstanding, there may be opportunities to extend its remit directly or through a separate smaller project with the suggestions below.

Research Opportunities

There are plans to collect data on the food people buy from the project's retail partner to model and identify in-store and online changes that would encourage healthier and more sustainable food purchasing. This provides an opportunity to research the effects of the resulting proposed changes on how much food is wasted, as well as the implications for surplus food that will be redistributed from the supermarket into the food aid supply chain. Furthermore, as disadvantaged groups disproportionately suffer from obesity and this is worsened by the sub-optimal nutritional value of food that is redistributed to them[70], what and how may changes be enacted to ensure such persons who access food through these alternative means get food of good nutritional value?

2.3.4 Increasing UK Dietary Fibre—The Case for the Great White British Loaf

Project Overview

This project plans to combine behavioural science, food technology and predictive modelling approaches to explore the transformation needed in the UK wheat agri-food chain to deliver high-fibre white loaf bread to consumers. It plans to collaborate with ASDA, associated millers and bakers, seed producers, UK wheat chain and grain brokers.

Consideration of Food Loss and Waste

In this project, there are plans to collaboratively develop a predictive UK Wheat Chain Model which will account for the whole supply chain and to quantify the environmental impact of any changes to the current UK wheat chain as fibre-rich domestic UK flour production increases. There is a reference to collecting a wide variety of data, including waste data, under work package three (Wheat Chain Behaviour and Data). It is unclear how the waste data translates to food loss and waste management.

Research Opportunities

The project could explore within the predictive WCM model, the impact of land usage and climate impacts on overproduction. Similarly, it could account for surplus food at each stage of the wheat supply chain while undertaking the life cycle analysis to quantify disposal relative to the food waste hierarchy framework. The final predictive model could then incorporate these considerations. The barriers to adherence to the food waste hierarchy may also be explored and recommendations made to actors within the supply chain. As the project already plans on quantifying losses and waste, it may be expected that a strong impact case can be made for the social and environmental benefits of improved adherence to the waste hierarchy within the wheat supply chain.

2.3.5 Pasture to Plate (P2P): Realising the Enormous Potential of UK Grasslands

Project Overview

Pasture to plate seeks to create a substitute for palm oil, soya protein and other imported food ingredients by using novel chemical processing methods to extract mycoprotein and lipids. Unsuitable and un-utilised grassland will be the focal raw material used during chemical processing.

Consideration of Food Loss and Waste

The proposed approach does not enable direct comparison with the food waste hierarchical framework. However, using grasslands for nutrient production would lead to a lower need for more land for food production, thereby contributing to reducing current levels of overproduction – implying a reduction in on-farm food waste.

Research Opportunities

There is an opportunity to potentially model the impact of the proposed approach in P2P. If successful with consumers, then it is possible to determine how much food loss prevention will be achieved in primary production of both livestock and crop production. Similarly, at the consumption end of the supply chain, quantifying the potential resultant reduction in food waste as a result of the newly developed products in comparison with the food products they will replace could be a useful means to accentuate the impact of this project.

2.3.6 'Raising the Pulse' (RtP): Systems Analysis of the Environmental, Nutritional and Health Benefits of Pulse-enhanced Foods

Project Overview

Raising the Pulse explores the potential of faba beans as a naturally high protein substitute for soya beans and a major ingredient for bread. It posits that there are nutritional and environmental benefits to using faba beans in bread. It plans to convene a consortium of experts to address the environmental impacts of faba beans grown to meet local bread production, its effects on nutritional intake and human health.

Consideration of Food Loss and Waste

Even though there are no direct inferences to food loss and waste, there are parts of the project that could lead to prevention. For instance, the project aims to establish a quality-oriented supply chain that can deliver products of specified quality and traceable environmental footprint. It also indicates that its system-wide model will provide a predictive tool of unprecedented scope and flexibility that will allow the estimation of impacts of interventions in pulse-based and other supply chains on nutrition, environment and health. There could be impacts on food loss and waste from these activities, but this is not yet explicit. Consequently, we present the following propositions on the potential to more explicitly explore additional insights regarding food loss and waste.

Research Opportunities

There is an opportunity to estimate the implications on food loss by the project's planned increase in pulse content as compared to wheat. Should the aim of the project be attained, this may lead to an increase in pulse production and a reduction in wheat production. Comparing the causes of losses (such as overproduction, diseases, pests and storage mechanisms) in wheat and pulse production, and how surpluses are or could be used in reference to the waste hierarchy could help address any food loss and waste concerns which may have hitherto not been considered. Additionally, it may help to drive home the project's added social and environmental impact if losses are reduced, and surpluses are redistributed and/or processed for human consumption. Similarly, there is an opportunity to estimate food waste at the points of consumption. 'Raising the Pulse' could adopt 'SNEAK's' approach to estimating this waste (Hinton et al., 2013) in trials to fully account for consumer acceptability and resultant waste. Insights from here could facilitate planning to address resulting waste at the consumption end of the supply chain. Furthermore, in the establishment of the quality-oriented supply chains that will deliver the products, there are opportunities to explore innovations that will lead to reduced losses and waste along the supply chain and optimise adherence to the food waste hierarchy right from the design stage.

2.3.7 Sustainable Nutrition, Environment, and Agriculture, without Consumer Knowledge (SNEAK)

Project Overview

'SNEAK' uses a combination of behavioural psychology, agricultural modelling and commercial catering to determine the nutritional and environmental impact of re-organising menus in school canteens. The project is being carried out at the University of Bristol with Bristol City Council and Bristol Food Network as partners.

Consideration of Food Loss and Waste

In addition to its primal objectives of delivering meaningful reductions in dietary intakes of sugar, fat and salt, along with a reduction in climate change impact, 'SNEAK' also makes considerations for food waste at the points of consumption where its intended optimised menu combinations will be undertaken. The project also seeks to demonstrate how predictive modelling of students' choices can reduce food waste.

Research Opportunities

There are opportunities for further consideration of food waste in the project. Even though the project is looking to estimate food waste by the consumer, there is also the opportunity to consider this from the perspective of hospitality & food service organisations. Estimating the implications of the menu changes on the procurement and storage of the food products used to prepare the foods on the menus could help estimate waste, and create opportunities for food waste reduction. Furthermore, there are currently no indications on how surplus and waste foods are handled by the canteens. There may be opportunities under work packages two (Broadening application to a commercial food outlet environment) and three (Demonstrating potential for change and preparing for immediate application) to improve redistribution of surplus food in these organisations for human consumption for better adherence to the waste hierarchy, while unusable waste can be directed towards other reuse (animal feed) and recycle (anaerobic digestion, composting, land spreading) options. All these will contribute to the project's impact on both social and environmental sustainability.

2.3.8 Social Enterprise as a Catalyst for Sustainable and Healthy Local Food Systems

Project Overview

This project focuses on the role of social enterprises in achieving a more inclusive, sustainable and healthy food system. Social enterprises of interest include those providing community growing spaces and distribution schemes, leisure and fitness centres, children's nurseries and other community-based services. Several partner social enterprises will be considered: Community Transport Glasgow, Cultivate Powys, London Early Years Foundation (nursery chef initiative), Selby Trust London, Social Adventures Salford, Windmill Hill City Farm Bristol.

Consideration of Food Loss and Waste

The social focus of this project means that achieving community and individual wellbeing rightfully accounts for the most desired impact. Opportunities in some of the prescribed work packages exist, for example, work stream three (Developing evidence of environmental health and nutritional impact), has a Life Cycle Analysis (LCA) element with each of its participating social enterprises required, to think about the sustainability and environmental impacts of their activities. More details are presented below.

Research Opportunities

One of the major sources of food for social enterprises is surplus and/or redistributed food from partnering organisations[13,71,72]. There are, therefore, opportunities to explore the role of the studied social enterprises in reducing and improving the management of food waste as food redistribution for human consumption. The work within work streams one (Understanding social enterprise contributions, capabilities, and challenges faced) and two (Local understandings of healthy and sustainable food) could incorporate the sourcing and storage of food, as well as the handling of resulting waste by social enterprises and use insights to further highlight the project's social and environmental impact. There may also be opportunities to impact current practices by social enterprises to pursue a more stringent adherence to the food waste hierarchy, thereby further improving the project's sustainability impact.

2.3.9 Sustainable and Healthy Diets for All

Project Overview

'Sus-health' seeks to co-design an indicator that measures the environmental impact and nutritive value of foods, meals, and ingredients. It will also co-create a systemic strategy for influencing food choices and consumption for a sustainable impact on the environment. The project aims to determine the impact of interventions in Northern Ireland and upscale to the rest of the UK.

Consideration of Food Loss and Waste

Sus-Health's proposed approach does not seek to intervene in the area of food waste management. Nevertheless, there may be opportunities to expand the existing remit of the project to include some of these options in relation to the objectives of the project.

Research Opportunities

The project seeks to use existing research and the new UK eco-labelling scheme to help inform the selection of the environmental components of its index (e.g. greenhouse gas emissions/carbon footprint, energy use, land use, water footprint and impact on water quality, including impacts such as acidification and eutrophication). It may be useful, under work package two (Co-developing the Sus-Health Metric), to also incorporate food loss and waste along the food supply chain (including at consumption) in the Sus-Health index. Reliance on redistributed food among lower socio-economic groups is increasing[69] and childhood obesity is also particularly high among these groups[73]. Investigating current levels of redistributed food from the channels identified from mapping the system (under work package one (Mapping the system and implementing change)) could provide novel insight into childhood obesity among disadvantaged groups. These can inform the solutions the project seeks to produce to ensure sustainable health for all.

2.3.10 TRAnsforming the DEbate about Livestock Systems Transformation (TRADE)

Project Overview

'TRADE' seeks to identify the consensus for the role of livestock production in the UK agricultural economy, by balancing its market value and opportunities for innovation in terms of contribution to human health, rural economies and social wellbeing. The project plans to map stakeholders and determine baseline production and consumption patterns, understand competing views on the technical and market policies of production technologies and supply side shifts for livestock products.

Consideration of Food Loss and Waste

This project considers food waste prevention and the reduction (and potentially, removal) of the consumption of environmentally destructive crops such as soy, as animal feed (presumably, including redistributed food) at the primary production level of the livestock food chain. Under its work package two (A taxonomy of system trade-offs and technical change), the project seeks to reduce waste by removing losses from diseases in livestock production through selection and gene editing. It further looks to identify alternative feedstocks (such as insects) to replace soy as a protein source for livestock.

Research Opportunities

In addition to current considerations for food loss within the project, there are opportunities to include further considerations for lost and wasted meat along the livestock supply chain. Despite meat's relatively low contribution to food waste, it contributes over 20% of the total food waste carbon footprint[74], which means reduced losses and waste translate meaningfully for environmental sustainability. It is estimated that 64% of meat is wasted at consumption while 32% is wasted through processing and distribution[75]. Thus, incorporating consideration of losses and waste along the livestock supply chain, especially at the point of consumption into the project (work packages two (A taxonomy of system trade-offs and technical change), three (Consumer roadmap for more sustainable livestock consumption) and four (Modelling systems innovation and pathways to a sustainable livestock configuration)) could contribute to its overall aim of transforming the future of UK livestock.

2.3.11 Transformational Blueprint for a Blue Economy on UK Terrestrial Farms: Integrating Sustainable Shrimp Production in a Changing Agricultural Landscape

Project Overview

This project aims to facilitate the expansion of shrimp so that it becomes a major seafood for UK consumers by proposing ways of increasing the economic and environmental sustainability of shrimp farming practices.

We did not receive the relevant data to facilitate the review of this project.

4. Conclusion

Prioritisation of people's health and the environment represent consistent and key targets for food system transformation. Activities expected to lead to food system transformation should also guarantee long-term food security. In this regard, food loss and waste in the UK food system must be considered. This is critical on multiple fronts. An efficient food system requires production to be closely matched with consumption, keeping waste minimal. It is therefore unacceptable for there to be significant levels of waste while about twenty percent of the UK population live in food poverty[76]. Additionally, the environmental cost due to food production necessitates that consumption is as closely matched to demand as reasonably possible.

The TUKFS SPF programme has to date funded fifteen projects, all of which aim to make meaningful contributions towards the long-term sustainability and security of the UK food system. Seeking to ensure food waste is sufficiently considered, we have reviewed these projects using the food waste hierarchy and the stages of the food supply chain. Of the projects reviewed, seven (three in Call 1 and four in Call 2) considered food waste. Prevention of food waste is the most considered option from the waste hierarchy options. There are implications for food waste prevention in primary production within 6 projects, overall supply chain and consumption in 4 each, and retail and hospitality and food service industry considered in one project each. Reuse is also being considered in the overall supply chain, primary production and food redistribution in two projects each and in retail and consumption in one project each. Recycle is only considered at the consumption stage of the food supply chain in just one project. Recovery and Disposal were not considered at any stage of the food supply chain in any of the projects. These have been presented in Table 2.2. The storage and logistics, manufacturing and processing, and wholesale distribution stages of the food supply chain did not have any considerations for food waste management in any of the projects. Following the review, we have provided indications of avenues by which these projects can extend their impacts on food waste.

Table 2.3 highlights the stages of the food chain and the waste management options to be considered in these recommendations.

Adherence to the food waste hierarchy in the UK is lax, as significant quantities of redistributable food fit for human consumption are either not redistributed at all or go to animal feed or anaerobic digestion13. The government regulates the last three stages of the food waste hierarchy, that is, recycling, recovery and disposal, but only provides guidance on prevention and reuse68. This may contribute to the laxity in adherence to the waste hierarchy. There are opportunities to rectify these issues and to ensure that all innovative interventions in the food system contribute to waste reduction and optimised surplus use. Even though we have made some recommendations for the reviewed projects, there may be additional opportunities if food loss and waste are not considered an afterthought. The causes of food waste including those discussed in part 1 of this report must be carefully considered and addressed with the innovations targeted at transforming the UK's food system. Furthermore, with the increasing number of persons relying on redistributed surplus food, it is important to acknowledge the impact regenerative agriculture or agroecology reduction in yield will likely have on the availability of surplus food to be redistributed for the marginalised so that food insecurity is not inadvertently worsened for such populations. This will be particularly critical in the absence of any short to medium-term solutions to food poverty. The limited consideration of food loss and waste in food storage and transport, manufacturing and processing and wholesale distribution must also be addressed as these could contribute to surplus redistribution as more responsible primary production is being pursued. We, therefore, suggest that going forward, all projects aimed at transforming the UK's food system should acknowledge the implications for food loss and waste, adherence to the food waste hierarchy and anticipated sustainability impacts across the food supply chain.

Table 2.3 *Research Opportunities on food loss and waste using the food waste hierarchy options at different food supply chain stages in the TUKFS projects.*

				Food waste hierarchy within the projects																	
				Call 1					Call 2												
				1.1	1.2		1.3		2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8		2.9		2.10	
				Prevention	Prevention	Reuse	Prevention	Reuse	Prevention	Prevention	Prevention	Prevention	Reuse	Prevention	Prevention	Reuse	Recycle	Prevention	Prevention	Prevention	Reuse
food	Call 1	1.1	OSC	✓																	
			PP	✓																	
			FASO	✓																	
		1.2	PP		✓	✓															
		1.3	OSC					✓													
			PP				✓														
			C				✓	✓													
	Call 2	2.1	PP						✓												
		2.2	PP							✓											
		2.3	R								✓										
			C								✓										
		2.4	OSC									✓									
		2.5	PP										✓								
			C										✓								
		2.6	PP											✓							
			C											✓							
		2.7	HFS												✓						
			C												✓						
		2.8	FASO													✓	✓				
		2.9	OSC															✓	✓		
			C															✓	✓		
		2.10	PP																	✓	✓

Key:
1.1 FixOurFood
1.2 FoodSEqual
1.3 H3
2.1 BeanMeals
2.2 Cultured Meat
2.3 FioFood
2.4 Increasing UK Dietary Fibre
2.5 Pasture to Plate
2.6 Raising the Pulse
2.7 SNEAK
2.8 Social Enterprise
2.9 Sus-Health
2.10 TRADE

OSC Overall Supply Chain
PP Primary Producer
R Retailer
HFS Hospitality and Food Service
FASO Food aid Service Organisation
C Consumer

Prevention
Reuse
Recycle

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Appendix

Methodology for the Systematic Literature Review

The rationale behind this Systematic Literature Review (SLR) was to have a clear view of the causes, management and solutions for food loss and waste pre-farm gate in the UK. Compared to a traditional literature review, an SLR is robust, scientific, and transparent and summarises existing information in a thorough and unbiased manner[77].

The research protocol followed in this review was adapted from Tranfield et al.[77] and started with a scoping study that informed the research question in primary production and food loss and waste (FLW) in the context of the UK. Based on the scoping study, keyword groups were formed (S1 for primary production, S2 for the UK, and S3 for crops and types of waste). Keyword strings were gathered and combined with the 'AND' operator (Figure AI) to search Scopus, Web of Science, EBSCO, and ABI Inform.

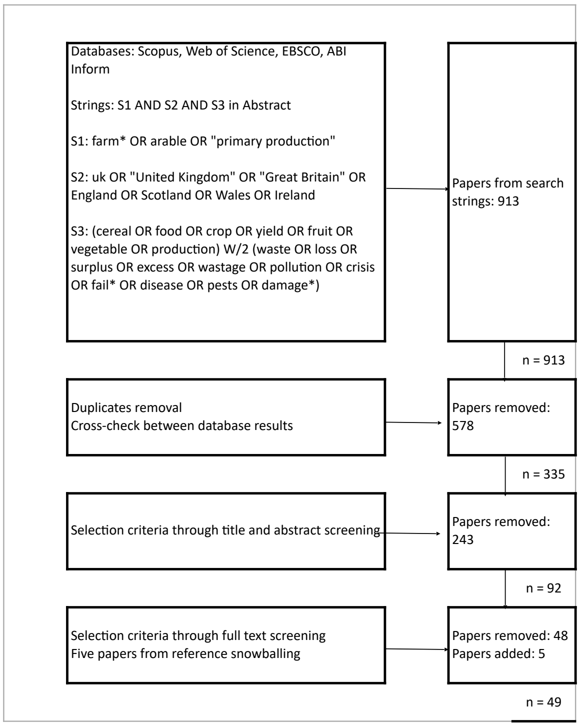

Figure AI The Article Selection Process

A list of selection criteria was considered during the scientific study selection process (Table A1). Only articles and books from 2008 were considered relevant to help capture the most recent insights on the phenomena. From 2008, 44 peer-reviewed final set of papers in English on primary production and FLW in the context of the UK were included. Five UK government reports were included as they were deemed relevant from the read articles. Figure AII presents the methodologies adopted in these papers while Table A2 shows the journals within which the final articles were derived from.

Table A1 Selection criteria

Selection Criteria	***Inclusion***	***Explanation***
Language	English	It is the language of this study
Accessibility	Full text of papers	Papers should be fully evaluated
Quality	Peer-reviewed papers	Quality and validity of the papers to be ensured
Type of Publication	Academic journals and books	To keep the quality high and the number of papers manageable, conference papers and grey literature are out of the scope of this review
Year of Publication	Published later than January 2008	This study only covers the last fifteen years to understand and evaluate the recent literature on the nature of on-farm waste in the UK
Scope and Context	On-farm waste in the scope of the UK	This review focuses only on on-farm food waste in the UK. Studies focusing on FLW in the other parts of the food supply chain, such as consumption and manufacturing, are out of the scope of this review

Figure AII Methodologies used

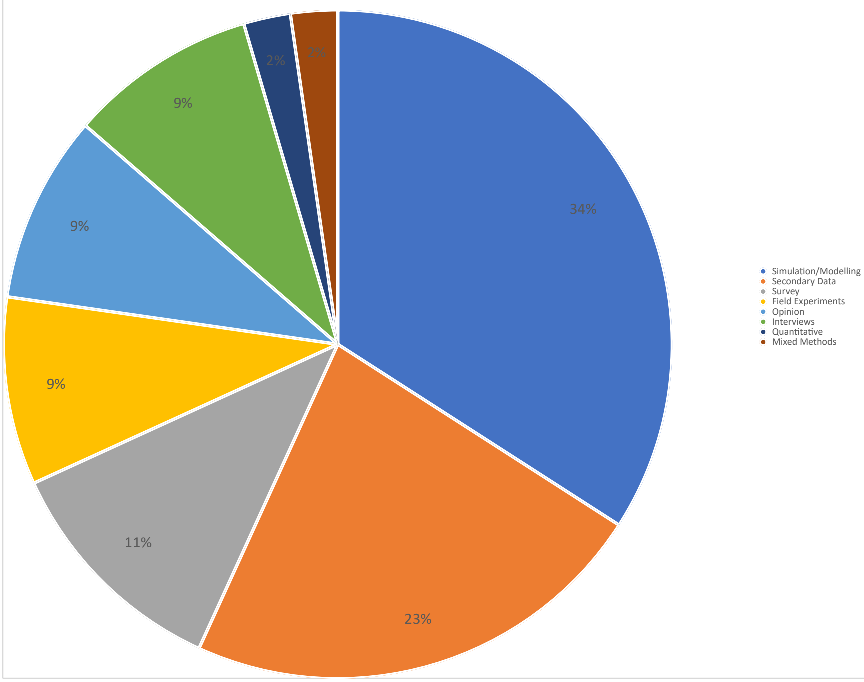

Table A2 Number of Articles per journal

Journal	*Number of Articles*
Agricultural Systems	1
Agronomy	2
Ecosystem Services	1
Energy Policy	1
European Journal of Plant Pathology	3
Food and Energy Security	3
Food Policy	1
Food Security	1
Geographical Journal	1
Global Change Biology Bioenergy	1
Insects	1
International Journal of Agricultural Sustainability	1
International Journal of Climate Change Strategies and Management	1
International Journal of Climatology	1
Journal of Agricultural Science	3

Journal	*Number of Articles*
Journal of Applied Ecology	1
Journal of Cleaner Production	4
Journal of Environmental Management	1
Journal of Industrial Ecology	1
Legal Studies	1
Nature Communications	1
Outlooks on Pest Management	2
People and Nature	1
Pest Management Science	3
Plant Pathology	1
Plant Science	1
PLoS Computational Biology	1
Precision Agriculture	1
Resources, Conservation and Recycling	1
Science of the Total Environment	1
Sustainable Production and Consumption	1