Greenhouse Gas Emissions of Food Waste Disposal Options for UK Retailers

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Abstract

Food retailers are under increasing political and social pressure to reduce both the amount of food that they waste and the amount of greenhouse gases (GHGs) that their food retailing activities incur. For completeness, when assessing the 'carbon footprint" of their business activities, food retailers should also included the greenhouse gas emissions caused by their disposal of waste food, which will vary with the waste disposal option used. However, there is lack of quantitative guidance for food retailers on the net GHG emissions that are incurred in the disposal of specific food types by the various disposal options available. Here, we calculate the net GHG emissions of eight different waste disposal options for five core food types using life cycle assessment, accounting for both emissions incurred in transport and processing, and those mitigated by the creation of useful products. We also assess the extent to which the embodied emissions in waste foods at the retail checkout can be mitigated by each disposal option. In addition to food specific results, we calculate mass-weighted averages using data from a mid-sized retail chain. We find a strong correlation between net emissions and the energy density of foods, and the following mass weighted disposal hierarchy (from best to worst, with respect to greenhouse gas emissions): donation of edible food to food banks; anaerobic digestion; conversion to animal feed; incineration with energy recovery; aerobic composting; landfill with gas collection and utilisation; landfill with gas collection and flaring; landfill without gas collection. If waste food from retailers is unfit for human consumption, to minimise greenhouse gas emissions it should be disposed of by conversion to animal feed or anaerobic digestion. For all food types, landfill is the worst disposal option.

Key Words

Food waste; Disposal options; Carbon footprint; Greenhouse gas emissions; Food retailers

1. Introduction

Food waste is major global problem with social, economic and environmental implications. Reducing food waste is a challenge faced by governments, charitable organisations, corporations and individuals alike, with the United Nations aiming to halve global food waste per capita at the retail and consumer level by 2030 (UN, 2015). Despite innovations in consumer demand modelling, storage, packaging and the use of price-cutting to reduce waste, some retail food waste is inevitable, leaving food retailers with decisions as to how to best dispose of this waste.

The disposal options available to a food retailer for any given food depend on several factors: the food's condition; whether the food's expiry date has passed; and whether the food is plant-derived or contains components of animal origin. Where it is safe to do so, unsold foods can be donated for human consumption; however in Europe at least, foods that have spoiled or passed their 'use-by' date cannot be donated or redistributed for human consumption (European Commission, No 1169/2011). Foods unsuitable for human consumption can be used for animal feed, providing they do not present any health risks (European Commission, No 68/2013). The recycling of 'vegetal' foods (fruits, vegetables and cereal grains) as animal feed is generally encouraged (Wadhwa & Bakshi, 2013), providing the foodstuff has not contacted animal products during its lifetime or spoiled (Lancashire County Council, 2016). The use and disposal of animal by-products (ABPs; foods no longer intended for human consumption consisting of or containing animal products) from food retailers is strictly regulated (European Commission, No 142/2011; European Commission, No 1069/2009), with only 'lower risk' ABPs (vegetarian bakery and confectionery products, milk and products, eggs and products, animal fats and fish oils) eligible for use as feed (DEFRA & APHA, 2014b). Greater risk ABPs ('medium' risk foods containing cooked or fully pre-cooked meat or fish products; and 'higher' risk foods containing raw, cured or partially cooked meat or fish products) can be sent to landfill (with a 20 kg/week limit applying to higher risk ABPs) (European Commission, No 142/2011). Other disposal options for food waste by retailers include conversion to pet food (except for higher risk ABPs) (DEFRA & APHA, 2014c); rendering (ReFood, 2014); ensiling of fish wastes, incineration; anaerobic digestion; composting; land application (direct for egg and shellfish shells, after heat-treatment for all other ABPs) and conversion to fertilizer or soil approver (DEFRA & APHA, 2014a).

Anaerobic digestion (controlled anoxic microbial degradation of organic matter) of commercial food waste is increasingly popular (Ariunbaatar, et al., 2016; Carlsson, et al., 2015). It is now generally favoured over composting as a means of processing commercial food waste (DEFRA, 2011a; ReFood, 2014), producing methane-rich biogas and nutrient rich digestate. Incineration is also growing in popularity (DEFRA, 2014) as a means of deriving energy from high-energy foodstuffs (San Martin, et al., 2016), particularly high risk ABPs (ReFood, 2014). Landfill remains a major end-destination for food waste from retail despite taxation (currently £84.40/tonne in the UK) (HM Revenue & Customs, 2016a) and incurring substantial methane emissions.

Annual food wastages by the UK retail sector are estimated at 250 kt (WRAP, 2017). Of this, ~2% is redistributed (donated) to people, ~10% is converted to animal feed, and ~30% is managed through each of recycling (anaerobic digestion and composting), recovery (incineration and landfill with energy recovery) and disposal (sewer and landfill without energy recovery) routes (WRAP, 2015). Such proportions are contrary to the objectives of food waste management hierarchies published by US and European government agencies (EPA, 2017; European Commission, 2008/98/EC) which encourage donation and conversion to animal feed whilst discouraging disposal to landfill and incineration.

Environmental impact is an integral factor influencing food waste management decisions made by retailers. These impacts can include GHG emissions, water use and pollution of water, air and soil systems. However, for this study we focus on GHG emissions only. The carbon footprint of any given food waste management pathway is inherently dependant on the composition of the food being disposed of and of the disposal pathway used. However, there is currently little information on food-type specific waste management emissions for food retailers, with most published food waste management hierarchies being based on a heterogeneous mix of food waste.

In prior work, the food wastage from a mid-sized food retail chain in the UK was investigated (Figure 1). Bakery goods, dairy, fruit & vegetables, meats and fish collectively accounted for 82% of waste by weight. Similar results were reported by a major food retailer, with bakery, fresh fruit and vegetable produce, dairy, meat and fish making up 74% by weight of the chain's food waste in 2014 (Tesco, 2014).

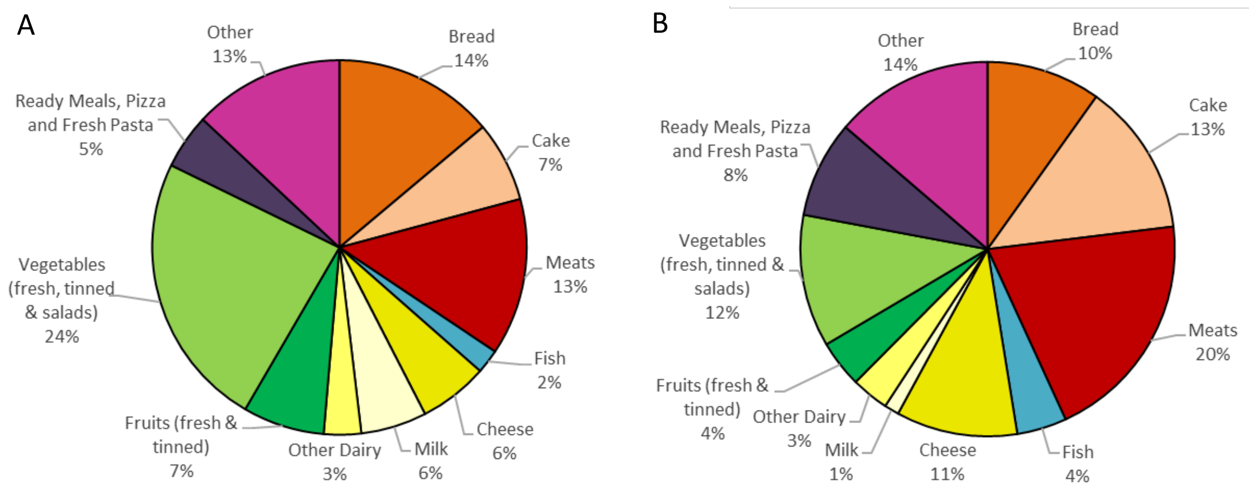

Figure 1: *Annual food retail waste from a mid-sized (~28 outlets) supermarket chain in the UK, proportioned:* ***a)*** *by mass (kg)* ***b)*** *by value (£).*

In this study, we evaluate the net greenhouse gas emissions resulting from the individual disposal of unsold bread, cheese, fruit and vegetables (F&V), fish and meat from the point of potential sale in a supermarket through eight disposal options: donation of edible food to a food bank or redistribution charity for human consumption (‘donation’); conversion to wet animal feed at a feed processing facility (‘animal feed’ or ‘conversion to feed’); anaerobic digestion; composting; large modern UK landfill capturing 70% of produced methane (Gregory, et al., 2014); and global average landfill with 20% methane capture (IPCC, 2006); landfill with no gas collection infrastructure. Some of these disposal options are hypothetical for certain foods, such as conversion to raw meat and fish to animal feed, due to the aforementioned regulations in the UK, but are included for completeness of GHG emissions.

2. Methods and Data

We employ a life cycle assessment (LCA) approach to evaluating net GHG emissions from each disposal option. We do not consider food-carbon returned to the atmosphere as carbon dioxide, since it was originally sequestered though photosynthesis, but do consider other emissions both incurred and mitigated at all stages of each disposal option, from transportation to processing facility or end of life destination. Our system boundaries are shown in Figure 2 and the assumptions used are listed in Table 1. GHG emissions are evaluated in terms of carbon dioxide equivalents per tonne of food waste (kg CO_2e/t FW). We use a global warming potential (GWP) of 25 for methane emissions (IPCC, 2007). Nutritional content/profile/chemical composition data and embodied carbon (E_{store}) values for each food type are shown in Table 2. E_{store} values include all major life cycle stages up to the checkout: production, processing, transport, packaging and supermarket operations, and were obtained from previous work (Hoolohan et al., 2013). The emissions factors used to generate these values are detailed elsewhere (Berners-Lee & Hoolohan, 2012). Emissions factors used in this analysis are detailed in Table 3.

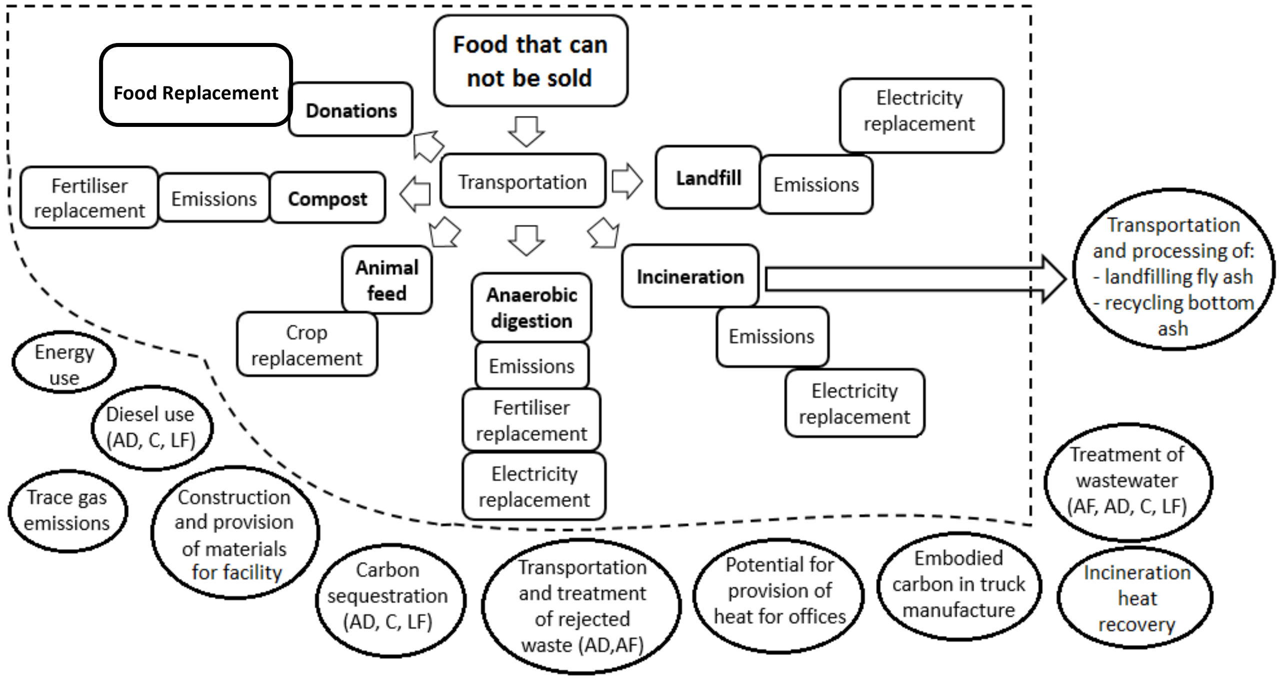

Figure 2 System boundaries for the LCA of food waste management pathways. Adapted from (Rajaeifar et al., 2015). System boundary is denoted by the dashed line. AF- animal feed; AD- anaerobic digestion; C- compost; LF- landfill.

Table 1 Assumptions used for all food waste disposal scenarios.

Assumption	Relevant Scenario
All food masses were exclusive of food packaging.	All
Food waste separation was assumed to occur at the retail store, causing no emissions.	All
Transportation to the nearest available facility for each scenario was assumed.	All
All food waste processing systems process all received waste.	All
Round trip distance is approximate to the square root of the average land area served per disposal site.	All
Each leg of a transport route, i.e. the outward and return journeys, are identical in every respect.	All
Supermarkets and all process/end of life destinations are evenly distributed across the UK. Every site within one site type serves the same land area, with no overlap. Average land area served by each site is equal to the total UK land area divided by the number of the type of site.	All
All food is edible for humans, and thus also suitable for animal feed.	Donation, Animal Feed
A refrigerated 3.5-7.5t heavy goods vehicle (HGV) is used for transport of perishable food types (cheese, meat and fish), whilst a non-refrigerated equivalent was used for semi-perishable foods (bread, fruit & vegetables).	Donation
Mitigated emissions from consumption of the food (M_D) is equal to the embodied emissions of the food at the supermarket (E_{store}).	Donation
Food waste is transported in a 26 tonne HGV (akin to waste collection vehicles in common use across the UK)	All except donation
Long term soil carbon sequestration from food compost and digestate is not significant.	Anaerobic Digestion, Composting
No losses of nitrogen, phosphorous or potassium occurs during digestion.	Anaerobic Digestion
For composting 6% losses of nitrogen (1% to N_2O, 5% to NH_3).	Composting
100% of CH_4 produced was assumed to be collected and converted to electricity on site.	Anaerobic Digestion
Electricity and heat requirement for the anaerobic digestion process is approximately proportional to the total solids (TS) content of the foods (although the energy used is typically sourced from the process itself)	Anaerobic Digestion
No fossil fuel-derived emissions were incurred in the incineration process.	Incineration
Transportation distance to each landfill type was the same.	Landfill

Table 2 Nutritional content, chemical composition and embodied carbon emissions for each food type

Property	Food Type					Reference(s)
	Bread	Cheese	F&V	Fish	Meat	
Embodied Carbon (kgCO_2e/t)	1400	13700	2500	2700	13800	(Hoolohan et al., 2013)
Energy (kcal/kg)	2740	4040	369.5	1178.7	2187.5	(FAO, 2016) (USDA, 2017)
Protein (g/kg)	106.7	228.7	10.2	192.8	152.9	(FAO, 2016) (USDA, 2017)
Kjedahl Nitrogen (g/kg)	17.07	36.59	1.64	30.85	24.47	(AOAC, 2000)
Phosphorous (g/kg)	1.29	4.55	0.31	2.05	1.58	(FAO, 2016) (USDA, 2017)
Potassium (g/kg)	14.1	0.76	3.65	3.60	2.31	(FAO, 2016) (USDA, 2017)
Water (%)	35	37	85	75	66	(USDA, 2017) (USDA, 2013)
Total Solids, TS (%)	65	63	15	25	33	Calculated from USDA data on water content
Volatile Solids/Total Solids, VS/TS	0.87	0.95	0.95	0.98	0.98	(Carlsson & Uldal, 2009)
Specific methane potential (m^3 CH4/t VS)	350	520	666	930	930	(Carlsson & Uldal, 2009)

Table 3 Emissions Factors for all Scenarios

Emissions Factor	Emissions	Relevant Scenario(s)	Reference(s)
Transport, Rigid HGV (>3.5 - 7.5 tonnes)	0.64 $kgCO_2e/(km\ t\ FW)$	Donation: Bread and F&V	(BEIS, 2017b)
Transport, Rigid HGV (>3.5 - 7.5 tonnes), Refrigerated	0.77 $kgCO_2e/(km\ t\ FW)$	Donation: Cheese, Fish and Meat	(BEIS, 2017b)
Transport, Rigid HGV (>17 tonnes)	0.20 $kgCO_2e/(km\ t\ FW)$	All except Donation	(BEIS, 2017b)
Food to Feed Process	7.28 $kgCO_2e/t$ FW	Animal Feed	(Kim & Kim, 2010; Takata, et al., 2012)
Embodied emissions in animal feeds	Oats: 380 $kgCO_2e/t$ Soybean Meal: 2700 $kgCO_2e/t$	Animal Feed	(Mogensen, et al., 2012)
Parasitic Electricity and Heat requirement of the anaerobic digestion process for heterogeneous food waste	82.83 $kgCO_2e/t$ FW	Anaerobic digestion	(Banks, et al., 2011b) (Banks, et al., 2011a).
Embodied emissions in mineral fertilizers	N-fertilizer: 5.62 $kgCO_2e/kg$ N P-fertilizer: 1.47 $kgCO_2e/kg\ P_2O_5$ K-fertilizer: 1.45 $kgCO_2e/kg\ K_2O$	Anaerobic digestion, Composting	(FAO, 2015; Kool, et al., 2012).
Embodied emissions in grid electricity	0.446 $kgCO_2e/kWh$	Anaerobic digestion, Incineration, Landfill	(BEIS, 2017b).
Composting Process	44.26 $kgCO_2e/t$ FW	Composting	(Kim & Kim, 2010; Nilsson, 2013; Takata, et al., 2012)

2.1. Transport Modelling

We assume that waste food is transported from the retail outlet to the nearest appropriate facility for each disposal option. Emissions are based on round trips of distance approximate to the square root of the average land area served per site, calculated by dividing the number of each site type in the UK (Table 4) by the total UK land area (see *S.I. Transport*). Resulting distances compared favourably to the data used in the Waste and Resources Assessment Tool for the Environment (WRATE) on average journey distances to landfills and incinerators (BEIS, 2017a). Vehicle type and emissions data were taken from the most recent UK Government Department of Business, Energy and Industrial Strategy dataset on GHG Reporting (BEIS, 2017b); emissions were converted from $kgCO_2e/km$ to $kgCO_2e/t$ FW by calculating average vehicle load (see *S.I. Transport*).

Table 4 Number of disposal sites for each disposal option

Disposal Option	Site Type	Number	Reference(s)
Donation	Food banks & redistribution centre	2085	(Guardian, 2017) (IFAN, 2017)
Animal feed	Animal feed Processing facility	50	Estimate
Anaerobic digestion	Anaerobic digestion facility	266	(WRAP, 2017)
Composting	Composting facility	330	(WRAP, 2015)
Incineration	Municipal solid waste incinerator	39	(UKWIN, 2017)
Landfill	Non-hazardous operational landfill	594	(HM Revenue & Customs, 2016) (SEPA, 2015)

2.2. Processing Facility/End of Life Destination Modelling

2.2.1. Donation

In the donation scenario, unsold ("waste") food is passed on to end consumers at the donation site, without incurring any further emissions except for those related to transport. We assume that refrigeration emissions are the same as would be incurred by households. The number of donation sites in the UK was taken as the combined total of independent food banks (712) identified by the Independent Food Aid Network food banks as of May 2017 (IFAN, 2017), and redistribution centres (1373) operating within the Trussell Trust network (Guardian, 2017). All donated food is assumed to be passed on to consumers, who are then assumed to waste the same proportion of each food type as do supermarket customers (i.e. donated and purchased food are treated the same in our analysis). Emissions mitigated by donation (M_D) are equal to the emissions embodied in the food at the supermarket store ($M_D = E_{store}$).

2.2.2. Animal Feed

In the animal feed scenario, food waste is converted to wet animal feed by being shredded, with addition of necessary substrates, incurring emissions (E_{AF}). The value used for E_{AF} was taken as the average of two previously reported values (Kim & Kim, 2010; Takata, et al., 2012). For the purposes of this study, the production of wet feed was deemed the end-point of the disposal option, so onward transport was not considered. We assume that food-waste derived animal feeds replace a mix of two selected conventional feeds (oats and soybean meal) (Eriksson, et al., 2015), mitigating the emissions that would otherwise have occurred from the production of these feeds (M_{AF}). The mass of oats and soybean meal replaced was based on the energy density (kcal/100 g) and protein density (g/100 g) of each food relative to those of oats and soybean meal. The embodied emissions in oats and soybean meal feeds were taken to be 380 kgCO_2e/t and 2700 kgCO_2e/t respectively, including emissions from production, transport and land-use change (Mogensen, et al., 2012). The energy and protein contents of Bread and Cheese were based on data for Wheat Bread (Item Code 18064) and Cheddar Cheese (Item Code 1009) taken from the United States Department of Agriculture (USDA) food composition database (USDA, 2017). Energy and protein contents of F&V, Fish, Meat, Oats and Soybean Meal were calculated from the USDA food composition data (USDA, 2017) for various relevant commodities listed in the Food and Agriculture Organisation (FAO) food balance sheets (FAO, 2016), weighted by FAO food balance sheet data on UK supply tonnage for each commodity (FAO, 2016). Methodology details are described in *S.I. Nutritional Profiles and S.I. Animal Feed.*

2.2.3. Anaerobic Digestion

In the anaerobic digestion scenario, food waste is converted to biogas and digestate at a digestion facility. Emissions incurred at the facility (E_{AD}) were taken to be those associated with the parasitic electricity and heat requirement of the digestion process, (183.7 kWh/t heterogeneous FW) (Banks, et al., 2011b), proportioned to the total solids (TS) content of the food (see *S.I Anaerobic Digestion*), plus the emissions from natural gas used during on-site electricity generation (0.96 kgCO_2e/t FW) (Banks, et al., 2011a). All biogas is assumed to be captured and the methane combusted to generate electricity, mitigating emissions which would otherwise have occurred in the generation of grid electricity ($M_{AD, GE}$), while the non-combustible CO_2 is simply released, without incurring further emissions, since it is of biogenic origin. Digestate substitutes for mineral fertilizers ($M_{AD, MF}$), mitigating the emissions that incur during the production of nitrogen (N), phosphorous (P) and potassium (K) fertilizers. Total nutrient contents of input food-materials are typically not significantly altered by the anaerobic digestion process (WRAP, 2016), thus we have assumed that no NPK losses occur during the digestion process.

Methane generation potentials (m^3 CH_4/t FW) were calculated using Equation 1 (Eriksson, et al., 2015), where VS is the percentage volatile solids and Specific Production Factor (m^3 CH_4/t VS) is the average volume of methane generated per tonne of volatile solids of a given food type. VS values were calculated from USDA total solids (TS) data (Table 2) and VS/TS ratios (Carlsson & Uldal, 2009).

Equation 1: $$CH_4\ generated = VS \times Specific\ Production\ Factor$$

The thermal energy content of methane (39,820 kJ/m^3) was converted to electrical units (11.07 kWh/m^3) using a 35% conversion efficiency factor (Banks, 2009). The average emission factor for UK grid electricity was then applied (BEIS, 2017b).

Emissions mitigated by use of the digestate produced ($M_{AD,\ MF}$) were based on the nitrogen (N), phosphorous (P) and potassium (K) content of the undigested food. Nitrogen contents were approximated from protein contents by the Kjedahl method, where nitrogen mass is taken to be 4/25 that of protein (AOAC, 2000). Phosphorous and potassium contents were taken directly from the USDA food composition database (USDA, 2017) for Wheat Bread (Item Code 18064) and Cheddar Cheese (Item Code 1009), and weighted by UK supply tonnage of relevant commodities listed in the FAO food balance sheets for F&V, Fish and Meat, using identical methods to those used in the calculation of M_{AF} (see *S.I Feed and Fertilizer Replacement).* Phosphorous and potassium contents were then converted to phosphate (P_2O_5) and potassium oxide (K_2O) contents, based on relative molecular masses, to quantify mineral fertilizer replacement. Individual embodied emissions in nitrogen, phosphorous and potassium fertilizers were taken from FAO data for Western Europe (FAO, 2015; Kool, et al., 2012). We assume that food-based digestates contain very little lignin and thus do not make a significant contribution to long term soil carbon sequestration.

2.2.4. Composting

In our composting scenario, we assume composting takes place at a commercial facility in an open-windrow system, with optimal temperature and concentrations of carbon, nitrogen and oxygen maintained throughout, ensuring complete aerobic composting, with the process meeting EU regulations. Some non-biogenic emissions are incurred in the composting process (E_C), because diesel and electricity are used at the facility and additives are used for maintaining the aerobic conditions of the compost. Our E_C value was taken as the average of those from three sources (Kim & Kim, 2010; Nilsson, 2013; Takata, et al., 2012). Compost has value as both a fertilizer and soil conditioner (WRAP, 2016). Here we assume it is used as a mineral fertilizer replacement and hence emissions mitigated by its use to replace mineral fertilizer (M_C) were calculated in the same way as for digestate in the anaerobic digestion scenario. As shown in Table 1, we assume that 6% of the nitrogen is lost during composting (Pardo, et al., 2015). The same assumption concerning soil carbon sequestration used in the Anaerobic Digestion scenario is applied to food-based composts.

2.2.5. Incineration (with electricity generation)

In the incineration scenario, it is assumed that food waste is combusted completely in a municipal solid waste (MSW) incinerator, without incurring any non-biogenic emissions. Volumes of ash were assumed to be negligible and hence emissions arising from disposal of the ash were not considered. Net thermal energy from combustion was used to generate electricity on site, mitigating emissions that would otherwise have occurred from grid electricity generation (M_I).

M_I values were calculated using Equation 2, where N.E.R is net energy released, η_{el} is electrical conversion efficiency and $Grid_{el}$ is the emissions intensity of grid electricity. A value of 22% was used for η_{el} (Baddeley, et al., 2011). N.E.R was calculated using Equation 3, where E_C is the energy content in the food, W_C is the water content, and W_B is the energy required to heat a unit of water to boiling point and then to boil it. E_C was calculated from USDA and FAO data as previously described (FAO, 2016; USDA, 2017). W_C data for Wheat Bread (Item Code 18064) and Cheddar Cheese (Item Code 1009) taken from the USDA food composition database (USDA, 2017) were applied to Bread and Cheese respectively. The W_C of Meat was taken as the average water content of typical common raw meats (USDA, 2013). The W_C of F&V and Fish were approximated from USDA data (USDA, 2017) on the water contents of representative foods commonly consumed in the UK (for F&V: apples, bananas, grapes, oranges, tomatoes, carrots, peas and lettuce; for Fish: tuna, salmon, cod and prawns). W_B was calculated using Equation 4, where T_1 is the boiling temperature of water (373K), T_2 is the starting temperature of the water (taken as 298K), $W_{Sp.H.C}$ is the specific heat capacity of water (4.19 KJ/kg/K) and $W_{L.H.C}$ is the latent heat of vaporisation of water (2257 kJ/kg).

Equation 2: $$M_I = N.E.R \text{ x } \eta_{el} \text{ x } Grid_{el}$$

Equation 3: $$N.E.R = E_C - (W_C \text{ x } W_B)$$

Equation 4: $$W_B = \left[(T_1 - T_2) \text{ x } W_{Sp.H.C}\right] + W_{L.H.C}$$

In place of a process emissions factor, gross thermal energy outputs were reduced by 15.5% to mimic the parasitic heat loss to the walls of the incinerator (Nixon, et al., 2013). In cases where net energy output was negative, i.e. thermal energy had to be inputted into the incinerator to achieve complete combustion, the thermal energy was increased by 15.5%.

2.2.6. Landfilling (with and without gas collection)

When food is deposited in landfill, it decomposes over time under anoxic conditions producing landfill gas (LFG), mainly methane (CH_4) and CO_2. Over time some of the methane is oxidised to CO_2 in covering soils. The majority of methane generated within UK landfills is flared or utilised (Gregory, et al., 2003). We investigate three landfill scenarios. In the first we assume best practice in which 70% of gases are collected and used for electricity generation. In the second we assume, allowing for some leakage, that 70% of gases are collected and flared (i.e. converted to CO_2 and water). In the third scenario it is assumed that produced gases are simply vented to the atmosphere. For all three scenarios it is assumed that food is immediately buried on arrival, then left undisturbed, without incurring onsite transport-related emissions. The number of landfills in the UK was taken as the sum of non-hazardous operationally active sites in England, Wales and Northern Ireland (HM

Revenue & Customs, 2016b) and Scotland (SEPA, 2015). Methane emissions (E_{LF}) where calculated by Equation 5 (IPCC, 2006), where *CH_4 generated* is calculated in the same way as described in section 2.2.3. Anaerobic Digestion *CH_4 oxidised* is the proportion of generated methane oxidised to CO_2 in covering soils. Oxidation rates of 20% and 10% were applied for landfills with and without gas collection systems respectively (EPA, 2015). Where gas is flared we assume 100% destruction efficiency of CH_4 to CO_2. Where electricity is generated, mitigation is calculated in the same way as for the Anaerobic Digestion scenario.

Equation 5:

$$CH_4\ emitted\ =\ (CH_4\ generated\ -\ CH_4\ collected)\ \times\ (1 - \%\ CH_4\ oxidised)$$

2.3. Out of Scope Emissions and Uncertainties

Several activities are outside of the system boundaries shown in Figure 2 and thus any emissions associated with these activities are excluded from evaluation. Specifically, for all scenarios, the following activities were excluded from the evaluation: energy consumed at facilities that is not directly used for food waste conversion; trace gas emissions other than carbon dioxide, methane and nitrous oxide; facility construction and maintenance; local heating; employee activities at sites; and transport vehicle manufacture. For anaerobic digestion, composting and landfill scenarios, onsite vehicular diesel emissions, emissions from transport and land application of digestate and compost, and emissions mitigated though carbon sequestration were excluded from the analysis. Transport and treatment of wastewater and other wastes were also excluded, as it was assumed for simplification that no wastes were generated in any scenarios. Similarly, it was assumed that volumes of fly and bottom ash from incineration of food waste were negligible, since it was assumed that food waste did not include packaging and therefore was 100% organic matter. All life cycle analyses contain uncertainties that are difficult to quantify. Values used here for the embodied emissions in foods are derived from a number of secondary sources, selected on the basis of fit to the specific supply chains used by the case study retailer and credibility of the sources. Emissions factors quotes by different sources generally agree to within a factor of two. Uncertainty around transport emissions arises from both the emissions factors used and the assumptions relating to average distances. Both are also estimated to be accurate to within a factor of two. Overall transport emissions are a small component of all of our scenarios, making their uncertainty less important. Uncertainty also exists as to emissions and other outputs arising from the different disposal processes of composting, anaerobic digestion, incineration and landfill, although less so than for the upstream emissions, since they can be directly measured. The core findings in this paper are sufficiently clear cut as to be resilient to the uncertainties listed above.

3. Results and Discussion

Table 5 shows the emissions (arising or mitigated) through every term considered in each disposal option. Transport emissions occur in each disposal option, and are most influenced by the number of disposal sites, and consequently the distance that must be travelled. Refrigeration increases transportation emissions by a third relative to non-refrigerated transportation. Further emissions are incurred from processing of food waste in feed conversion, anaerobic digestion, composting and all landfilling options. Conversion of food waste to wet animal feed requires minimal inputs, incurring less emissions than does transportation. The processes of anaerobic digestion and composting are more energy intensive in our evaluation, however incurred emissions are still a fraction of those resulting from all landfill scenarios. Water (and thus volatile solids) content and specific methane production potential are the controlling factors in methane production. Relatively watery plant-derived foods (F&V) incur least methane emissions, whilst energy-rich animal-derived foods (Cheese, Fish and Meat) incur the most.

Table 5. GHG emissions occurring at each step of food waste disposal pathways, for five food types.

Term	Symbol	Emissions (kg CO2e / tonne of food)					
		Bread	Cheese	F&V	Fish	Meat	Weighted Average
Incurred Emissions							
Transport, donation	T_D	6	8	6	8	8	7
Transport, animal feed	T_{AF}	14	14	14	14	14	14
Transport, anaerobic digestion	T_{AD}	6	6	6	6	6	6
Transport, composting	T_C	5	5	5	5	5	5
Transport, incineration	T_I	16	16	16	16	16	16
Transport, landfill	T_{LF}	4	4	4	4	4	4
Feed conversion process	E_{AF}	7	7	7	7	7	7
Anaerobic digestion process	E_{AD}	163	159	43	67	89	89
Composting process	E_C	44	44	44	44	44	44
CH_4 release, 70% CH_4 capture landfill	E_{LF70}	848	1339	408	980	1333	791
CH_4 release, 0% CH_4 capture landfill	E_{LF0}	3181	5021	1531	3676	4999	2965
Mitigated Emissions							
Consumption of donated food	M_D	1400	13700	2500	2700	13800	5590
Crop-based animal feed replacement	M_{AF}	364	1005	36	1121	735	369
Grid electricity replacement, anaerobic digestion	$M_{AD, GE}$	340	537	164	393	535	317
Mineral fertilizer replacement, anaerobic digestion	$M_{AD, MF}$	103	222	17	187	147	85
Mineral fertilizer replacement, composting	$M_{C, MF}$	97	210	16	176	139	80
Grid electricity replacement, incineration	$M_{I, GE}$	177	283	-36	47	130	74
Grid electricity replacement, 70% CH_4 capture landfill with gas utilisation	$M_{LF70, GE}$	238	376	115	275	375	222

Mitigated emissions are greatest through donation of waste food, with consumption of the food by people negating all embodied emissions at the supermarket checkout. Significant emissions can be mitigated through replacement of crop-based feeds (especially soybean meal) though food-to-feed conversion. Appreciable emissions are also mitigated by electricity generation in anaerobic digestion and, for some foods, by incineration, although the degree of this mitigation will fall if grid electricity becomes less carbon intensive in the future. Some emissions are also mitigated by mineral fertilizer replacement with digestate and compost. In the case of landfill, there is an important benefit to gas utilisation rather than flaring off.

Table 6 shows the net emissions resulting from disposal of waste food through each disposal option, along with the mass-weighted average across the five food types and the disposal option priority order, based on the weighted average emissions. With the least incurred emissions and most emissions mitigated, donation unsurprisingly has the most negative net emissions of all disposal options regardless of food type. Conversely landfilling leads to the greatest net emissions, increasing proportional to the volume of uncaptured methane released. Reasonable weighted average net negative emissions are achieved by conversion of waste food to animal feed and anaerobic digestion, with superior net emissions mitigation through conversion to animal feed than anaerobic digestion for all food types considered with the exception of F&V. We find composting and incineration to have similar weighted average net emissions, and both are preferable to landfill, for which weighted average net emissions are highly positive even for a modern landfill with efficient gas collection and utilisation. Figure 3 shows the order of disposal options for each food type from least to most GHG emissions. Interestingly, the priority orders for all five foods (with the exception of Fish) and the mass weighted average order deviate slightly from hierarchies published by both US and European government agencies (Figure 3), which place animal feed, anaerobic digestion, composting and incineration in places 2, 3, 4 and 5 respectively (EPA, 2017; Commission Directive 2008/98/EC).

Table 6. Net emissions from each disposal option

Disposal Option	Formula	Emissions (kg CO_2e/t FW)						Weighted Disposal Priority
		Bread	Cheese	F&V	Fish	Meat	Weighted Average	
Donation	$T_D - M_D$	-1394	-13692	-2494	-2692	-13792	-5583	1
Animal feed	$T_{AF} + E_{AF} - M_{AF}$	-342	-983	-15	-1100	-714	-347	2
Anaerobic digestion	$T_{AD} + E_{AD} - (M_{AD, GE} + M_{AD, MF})$	-280	-601	-137	-513	-593	-314	3
Composting	$T_C + E_C - M_{C, MF}$	-48	-161	33	-127	-89	-31	5
Incineration	$T_I - M_{I, GE}$	-161	-266	52	-31	-114	-58	4
Landfill, 70% CH_4 capture with gas utilisation	$T_L + E_{LF70} - M_{LF70,GE}$	614	967	298	709	963	573	6
Landfill, 70% CH_4 capture with flaring	$T_L + E_{LF70} - M_{LF20, NG}$	852	1343	412	984	1337	795	7
Landfill, 0% CH_4 capture	$T_L + E_{LF0}$	3185	5025	1535	3680	5003	2969	8

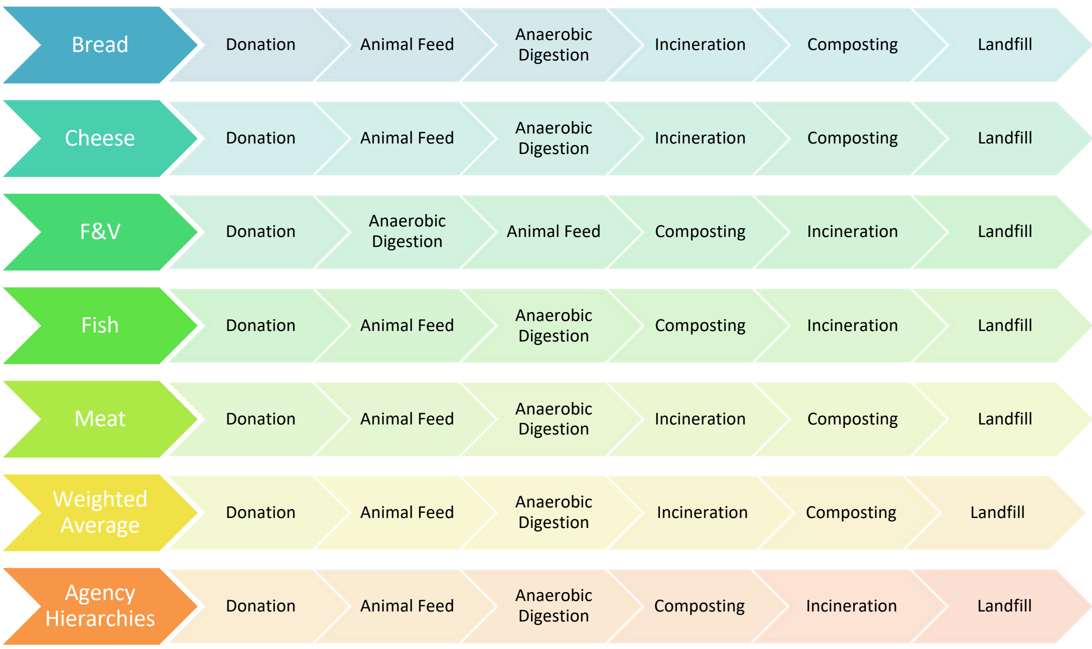

Figure 3 *Disposal priority orders, in terms of GHG emissions, for all individual food types and the mass weighted average, are distinct from those reported by government agencies.*

By setting absolute net emissions as a proportion of the embodied emissions of each food at the supermarket checkout, we can quantify the extent to which the embodied emissions in each food type can be mitigated (or otherwise) by each disposal option (Table 7).

Table 7. Net mitigation as a percentage of embodied food emissions

Disposal Option	Food Type					
	Bread	Cheese	F&V	Fish	Meat	Weighted Avg.
Donation	100%	100%	100%	100%	100%	100%
Animal feed	24%	7%	1%	41%	5%	6%
Anaerobic digestion	20%	4%	5%	19%	4%	6%
Composting	3%	1%	-1%	5%	1%	1%
Incineration	11%	2%	-2%	1%	1%	1%
Landfill, 70% CH_4 capture with gas utilisation	-44%	-7%	-12%	-26%	-7%	-10%
Landfill, 70% CH_4 capture with flaring	-61%	-10%	-16%	-36%	-10%	-14%
Landfill, 0% CH_4 capture	-227%	-37%	-61%	-136%	-36%	-53%

4. Conclusions

Under all circumstances insuring food that cannot be sold is eaten by humans is the best disposal option available to a retailer, with respect to GHG emissions. In this option, additional emissions, incurred through transport, <1% of those embodied in the food at the supermarket store. From a GHG perspective this is the only option which can be considered comparable to selling the food. Even if half of donated food is wasted and disposed of to a landfill with no gas collection infrastructure, this is still better than the next best option, conversion to animal feed.

Our analysis also clearly shows that disposal to landfill is the worst available option for all foods. Landfill emissions are particularly high for energy dense foods and hence diversion of these foods from landfill is particularly important.

If food is unfit for human consumption, conversion to animal feed is the best available option, followed by anaerobic digestion, for all five food types except F&V, for which anaerobic digestion is preferable over conversion to animal feed. However, mitigation of the emissions embodied in the waste food is never higher than 41% for conversion to animal feed and 20% for anaerobic digestion, compared with >99% for food donation. Our results indicate that incineration with energy recovery is preferable to composting for bread, cheese and meat, but not for F&V or fish. In this respect our food waste hierarchy differs from the US EPA and European Union published food waste hierarchies (see Figure 3), though the EU hierarchy is based on a range of environmental criteria, not just GHG emissions, and the US EPA hierarchy includes environmental, social and economic considerations.

Policy Implications

Our results show the importance of channelling all edible food waste from retail outlets to food banks, redistribution charities and other such organisations to ensure that as much unsold “waste” food as possible is eaten by people. To that end, our study supports the development of policies encouraging the donation of all edible unsold food from food retail stores. Our data also shows that, for food unsuitable for human consumption, conversion to animal feed is the best option in terms of net GHG emissions, followed by anaerobic digestion, for all food types except F&V. Landfill, even at a modern site capturing and utilising 70% of generated methane, is the worst option for all food types by a clear margin. Our findings indicate that, from a GHG perspective, landfill should not be used for the disposal of waste food by retailers.

Supplementary Information

The supplementary information is contained in the Excel workbook: ‘SI Greenhouse Gas Emissions of Food Waste Disposal Options for UK Retailers.xlsb’.

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