GREENHOUSE GAS EMISSIONS OF FOOD WASTE: METHODOLOGY

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PROJECT INFORMATION	
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Commented [1]: To be updated when finalized

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Summary

ReFED is committed to maintaining a database of Greenhouse Gas (GHG) emission factors, which underpins the organization's modeling of the environmental impact of wasted food in the United States. By making emissions associated with food waste visible through Insights Engine tools including the Food Waste Monitor, Solutions Database, and the Impact Calculator, as well as food business-facing products, ReFED supports users in making informed and targeted decisions about food waste reduction strategies that achieve the most impactful emissions reductions.

Quantis supported the development of the first publication of emission factors on the Insights Engine in 2021 and has been commissioned again for a 2024 update. The goal is to produce an increasingly robust and precise tool to estimate impact through continual improvement, with a particular emphasis in 2024 on making methane emissions more visible. This document summarizes the methodology used to calculate the updated GHG emissions factors that ReFED will apply to food waste in the United States, documenting the approach, logic and assumptions.

Key changes include:

- Updated emission factors[1] and GWP factors[2] for modeling the upstream life cycle impacts as well as the end-of-life (EOL) destination impacts
- More granular parameters and modeling for the emissions associated with the EOL destinations
- Methane emissions accounted for and reported separately as kg CH_4, alongside total emissions as kg CO_2e
- A more representative food list for the US market (e.g., including several prepared food items)

The first chapter describes the objective of the project and its scope. Furthermore, it provides a definition of the concept of food waste and the Life Cycle Assessment (LCA) approach used. The second chapter describes the methodology used to estimate the GHG emissions for the food items throughout the supply chain (i.e., upstream life cycle impacts). The third chapter describes the methodology and sources used to estimate the GHG emissions downstream for various end-of-life destinations for food waste and food donation. And lastly, the fourth chapter summarizes conclusions from the upstream and end-of-life modeling.

[1] Emission factors quantify the amount of greenhouse gasses released by the specified activity. Commonly reported as carbon dioxide equivalents (CO2e) in a calculation that combines carbon dioxide, methane, and nitrous oxide gasses into a single measure using GWP on a 100-year timeframe.

[2] GWP or Global Warming Potential, a measure of how much heat trapping a greenhouse gas contributes relative to CO2 over a specified period of time. The IPCC publishes recommended values about every 6 years - see Table 9 for the latest update.

Main Concepts

Life Cycle Assessment

A leading tool for assessing environmental performance is life cycle assessment (LCA), a method defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 2006a; ISO 2006b). LCA is an internationally recognized approach that evaluates the relative potential environmental impact of products and services throughout their life cycle, beginning with raw material extraction and including all aspects of transportation, manufacturing, use, and end-of-life (EOL) treatment. LCA is composed of two main methodological steps, Life Cycle Inventory and Life Cycle Impact Assessment.

Life Cycle Inventory

Life Cycle Inventory (LCI) analysis involves creating an inventory of flows from and to nature for a product system. Inventory flows are mass and energy flows including (1) inputs of water, energy, and raw materials, and (2) releases to air, land, and water. The input and output data needed for the construction of the model are collected for all activities within the system boundary, including from the supply chain.

In this project, LCI datasets are taken from Quantis internal World Food LCA Database (WFLDB) 3.9[3] as well as ecoinvent 3.9[4] and Agribalyse 3.1.1. In addition, some inventory flows were calculated manually as there were no default database entries. The Food Commodity Intake Database (FCID)[5] was used to determine the recipes for prepared foods such as pizza, sandwiches, salads, and soup.

Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is a quantitative step that classifies and combines the LCI flows for the considered product system(s) to indicate the type of impact they have on the environment. In this project, GHG emissions and their relative impact on climate change is the indicator of environmental impact considered for the various food items and EOL destinations.

GHG potential is evaluated based on the International Panel on Climate Change's (IPCC) 100-year global warming potential (GWP) metric, as outlined in the IPCC's Sixth Assessment Report (AR6)[6], published in August 2021. This metric allows for the comparison of the ability of each greenhouse gas to trap heat in the Earth's atmosphere relative to carbon dioxide (CO_2), over a century, thereby standardizing emissions into kilograms of CO_2 equivalents (CO_2-eq). In this methodology, methane (CH_4), is included in CO_2 eq measures, but also reported separately as kg CH_4 due to its potent heat-trapping capacity and shorter atmospheric lifetime. This separate accounting is crucial to enable targeted reduction strategies that consider methane's significantly higher GWP compared to CO_2 over both 20- and 100-year timeframes.

[3] https://quantis.com/who-we-guide/our-impact/sustainability-initiatives/wfldb-food/
[4] https://support.ecoinvent.org/ecoinvent-version-3.9.1
[5] https://fcid.foodrisk.org/
[6] https://www.ipcc.ch/assessment-report/ar6/

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1 | Overview

In this methodology document, the term "food waste" is used as shorthand to cover any liquid or solid food or beverage that exits the originally intended value chain to ultimately provide nourishment for human consumption, even if it is rescued for people in need (i.e., donated) or routed to animal feed or industrial uses. Elsewhere, ReFED uses the term "food surplus" to refer to the same concept, and otherwise reserves "food waste" to refer to material that falls into the national (e.g. EPA) and international (e.g. Sustainable Development Goal 12.3) definitions of food waste.

1.1 Parameters used to calculate GHG emissions

The methodology developed here to model GHG emissions associated with food waste draws upon various external models and parameters, including (1) ecoinvent and WFLDB for upstream impacts and (2) the U.S EPA's WARM V16 database and (3) the waste module in The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (see Table 9) for the destination impacts. Quantis provided ReFED with a model based on this methodology, the outputs of which are intended to be made available through the ReFED Insights Engine. The main parameters that affect emissions related to food waste in this model are:

- **Type of Food**: Food items have different GHG emissions depending on how and where they are cultivated and processed.
- **Food Material Properties**: The physical characteristics of food, such as (1) water content, (2) nutrient values (e.g., fat and protein), and (3) energy content (i.e., caloric value) can influence the environmental impact (and benefits) of different EOL destinations. For some destinations, like landfill, emissions are generated from the dry matter content of a food item, so high water content items will emit less. For other destinations, such as animal feed or rendering for pet food, the amount of avoided emissions depends on the nutrient and energy content of the food material being used to replace standard feedstock.
- **Upstream Impacts**: Along the value chain of a food item, there are GHG emissions due to energy consumption and other processes related to logistics (transport) and storage, as well as processing and preparation. Upstream impacts embody all GHG emissions that were incurred all the way back to the farm prior to becoming waste. When such food items are prevented from becoming waste, these embodied upstream impacts become "avoided" or "saved" GHG emissions, as the recaptured food is assumed for this model to displace the production of the same type and amount of food.
- **End-of-life (EOL) Impacts**: Food material can be sent to different destinations (e.g.., landfill, animal feed) after it exits the intended value chain, where the activities and processes involved determine the associated net GHG emissions (e.g., gross emissions and avoided impacts).

The objective of this work is to model the global warming implications of food waste in a US context and to show the relative benefits of moving food through different end-of-life pathways. To achieve this goal, the modeling considers all GHG emissions along the life cycle stages of different food items, including avoided impacts from diverting food surplus to donation for human consumption and to other destinations where food waste is recovered and valorized. Note that the model calculates upstream and downstream GHG emissions of a selection of food items without differentiating between the various parts of the same food item. This means that, whether it is an apple peel or a whole apple, any wasted portion is quantified based on its weight as 'apple waste'. This assumption simplifies the model by considering that all parts of the food have an equivalent environmental impact, which is calculated based on the type of food, the stage of its life cycle as it moves through the supply chain, and its final destination.

1.2 Products and life cycle stages covered

A set of representative products was selected to portray common food items available on the US food market (see Table 1). This selection was based on data provided by ReFED and data from USDA Loss-Adjusted Food Availability (LAFA). Using retail sales (by weight) from Nielsen[7] as a proxy for domestic consumption, ReFED identified the top selling items within each department. Representative food items were then selected based on sales, while also trying to reflect the diversity of items available within a department. For example, cakes and other desserts are not in the top 5 sellers in Breads & Bakery but they do represent a significant percent of sales and are considered materially different from plain or savory bread items in terms of ingredients. Therefore, the representative food items in Breads & Bakery are Bread and Cake. This list of products was cross-referenced with USDA Food Availability and recipes used to model prepared food items were adapted from the Food Commodity Intake Database[8].

The GHG emissions for these food items are calculated across the following life cycle stages:

1. **Farm**
2. **Manufacturing**
3. **Consumer-facing businesses (retail and foodservice)**
4. **Residential**

Table 1 shows the individual food items used to represent a "food type", and whether emissions are recorded at the farm stage or not until the manufacturing stage. Certain food items, like prepared dishes, cannot be directly wasted at the farm stage because they do not exist in their final form there—for example, pizzas and pasta are not grown, but are assembled from multiple ingredients post-harvest. Consequently, for these food items, emissions at the farm stage are not reported, but any emissions related to raw materials that make up these food items are included in the manufacturing stage. Additionally, items such as fresh produce do not have a manufacturing life stage, as they are typically consumed in the same state as they are harvested, without undergoing any processing. Additional details about making adjustments to these assumptions is included in Section 2.2.4.

[7] NielsenIQ, nielseniq.com
[8] https://fcid.foodrisk.org/recipes/

Table 1: Overview of representative food items

Food Type	Representative Food Items	Waste at Farm Stage Modeled?[9]	Waste at Manufacturing Stage Modeled?[10]
Ready-to-drink Beverages	Orange juice		x
	Tea		x
Produce	Apples	x	
	Bananas	x	
	Carrots	x	
	Grapes	x	
	Lemons	x	
	Lettuce	x	
	Mandarins	x	
	Onion	x	
	Potatoes	x	
	Strawberries	x	
	Tomatoes	x	
	Watermelons	x	
Frozen	Ice cream		x
Fresh Meat & Seafood	Beef	x	x
	Chicken	x	x
	Meat alternatives (soy based)		x
	Pork	x	x
	Sausage		x
	Tilapia	x	
	Shrimp	x	
Dry Goods	Almonds	x	
	Beans (canned)	x	x
	Cereal		x
	Chocolate		x
	Coffee	x	x
	Flour		x
	Salty snacks		x
	Ketchup		x
	Olive oil		x
	Pasta		x
	Peanut butter		x
	Rice	x	
	Salt		x
	Sugar	x	x
	Vanilla	x	x
Dairy & Eggs	Almond drink		x
	Cheese		x
	Eggs	x	
	Milk	x	x
	Yogurt		x
Breads & Bakery	Bread		x
	Cake		x
Prepared Foods	Salad		x
	Sandwich		x
	Pizza		x
	Soup		x

[9] Prepared or processed food items do not exist in their final form and therefore cannot be 'wasted' at the farm stage. Farm stage emissions are included in the manufacturing emissions.
[10] Fresh produce that does not undergo processing cannot be 'wasted' at the manufacturing stage.

1.3 Destination (End-of-life) Modeling

A set of archetypal destinations were developed representing the common end-of-life destinations for food waste in the United States. These destinations were selected to align with the *Food Loss and Waste Accounting and Reporting Standard* (FLW Standard)[11], with some adaptation to fit the US context. Table 2 lists and defines the destinations used in ReFED's Impact Calculator.

A key deviation from the *FLW Standard* is the inclusion of a donation pathway. While rescued food remains within the human food chain and as such is not technically food waste, the goal of this methodology is to capture all emissions associated with food that exits the originally intended value chain - so donation is considered an option for surplus food management. On the other hand, the 'Refuse/Discard' destination, which is included in the *FLW Standard*, was removed in this model because open dumping is illegal in the U.S. and therefore not applicable as an end-of-life destination for ReFED's stakeholders.

Table 2: End-of-life destinations (adapted from *FLW Standard*)

Destinations	Description
Food Rescue (Donation)	The donation destination rescues or redistributes unsold food for human consumption via food banks or pantries, food distribution services, etc.
Animal Feed	The animal feed destination diverts food that was originally intended for human consumption or is a byproduct of human food production (e.g., corn husks) to livestock animals, either directly after harvesting or after processing.
Industrial Uses (Rendering)	The industrial uses destination is modeled here only for rendering animal products for pet food or cooking oil for biodiesel production. Of note, the *FLW Standard* was amended in 2021 to reflect that where the output is biodiesel, for reporting purposes, the FLW should not be included under "biochemical processing" (industrial uses) but instead under the "other" destination.
Composting	The composting destination breaks down food microbially in oxygen-rich environments to produce a stable, organic material that can be used as a soil amendment.
Anaerobic Digestion	The anaerobic digestion destination breaks down food microbially in the absence of oxygen, producing biogas and nutrient-rich digestate (or biosolids) that can be cured prior to their use as a soil amendment.
Land Application	The land application destination refers to spreading, spraying, injecting, or incorporating organic material onto or below the surface of the land to enhance soil quality. The model assumes direct application of food to agricultural land (in a controlled manner as an organic fertilizer) without composting, digestion, or other treatments.
Not Harvested	The unharvested destination signifies leaving crops ready for harvest in the field or tilling them into the soil.
Incineration (with Energy Recovery)	The incineration destination encompasses combustion of food in a controlled manner to reduce solid waste volumes and recover energy.
Landfill	The landfill destination sends food to an area of land, or an excavated site specifically designed and built to receive and contain waste. The landfills break down food waste in an anaerobic environment (without oxygen) and generate biogas (CO_2 + CH_4) that can be vented passively or captured to flare or to recover energy.
Sewer	The sewer destination sends food down sink drains (with or without prior treatment), followed by sewer collection and public treatment in a water resource recovery facility (WRRF) along with other sewage.

[11] https://flwprotocol.org/flw-standard/

2 | Upstream Life Cycle Impacts

Upstream life cycle impacts cover the GHG emissions arising along the value chain of a food item, from the farm to the final consumer. For each food item, life cycle impacts were calculated at each relevant stage of the value chain to allow for an understanding of the impact of food waste when discarded at various stages.

The upstream GHG emissions related to the food waste for each value chain stage were calculated for 1 kg of product leaving that stage (i.e., food waste at each stage incurs the full environmental impact of the previous value chain stages). The value chain stages, and the upstream emissions included for each stage considered are shown in Figure 1 below.

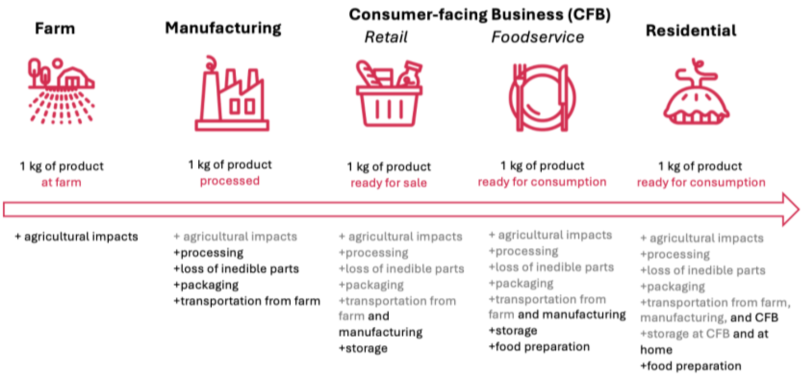

Figure 1: Life cycle stages of upstream food waste modeling. *This figure illustrates the life cycle stages considered in the study. For each stage depicted at the top, environmental impacts are assessed based on 1kg of product. The bullet points detail the specific activities evaluated at each stage, with impacts encompassing both direct effects (in black) and cumulative upstream effects (in grey). Note that food items are assumed to go to either retail or foodservice.*

2.1 Farm

Impacts of agricultural production were considered based on standard LCA-based methods which provide archetypal impacts for crop-country combinations. These datasets consider agricultural production processes such as fertilizers, fuels, materials and on-farm packaging as described elsewhere (Nemecek et al. 2015).

Food losses at the farm stage are assigned the same environmental impact as the product that leaves the farm system. For instance, the environmental impact of wasting 1 ton of strawberries on a farm is considered equivalent to the impact of producing 1 ton of strawberries that are suitable for sale. This implies that if 1 ton of strawberries is wasted at the farm level, and if consumer demand remains unchanged, an additional ton of strawberries must be produced to meet that demand. Consequently, reducing food loss at the farm stage can lead to what is known as "source reduction," effectively decreasing the total environmental impact (EPA 2019). Note that crop residue (leaves, stems, etc.) is not considered food waste.

GHG emissions were calculated using methods tailored to the unique attributes of the U.S. market, considering aspects such as domestic food market dynamics (see details below), energy mix for electricity (low voltage grid mix from ecoinvent 3.9.1), and transportation distances (950 miles by freight truck for local production; 5000 miles by container ship and 950 miles by freight truck for imported products). The results reflect market diversity due to varying origins of food items, recognizing that whether food is domestically produced, imported, or both, affects GHG emissions differently. By accounting for the different countries of origin for food production, this methodology accommodates the nuances in GHG emissions that arise from the geographical spread of the food supply chain.

To accurately represent the array of countries that contribute to the U.S. market mix, our analysis delineated the ratio of imports to domestic production (see Table 3). To determine the representation of countries for production in the U.S. market mix, we assessed the proportion of imports versus domestic production based on data from the FAOSTAT database[12] and identified the primary importing countries using statistics from USA Trade online statistics.[13] The analysis involved several steps:

1. **Domestic Consumption**: The domestic production intended for internal consumption was calculated by subtracting the 'Export' volume from the 'Domestic production' volume as listed in the FAOSTAT database, providing yearly totals in tons.
2. **Imports**: The 'Import' category in the FAOSTAT database reveals the annual total volume, in tons, of food items imported into the U.S.
3. **Total Market**: The sum of 'Domestic production consumed internally' and 'Import' gives the total U.S. market volume for food items.
4. **U.S. Domestic Market Share**: We derived the percentage of domestically consumed production by dividing it by the total market volume.
5. **U.S. Imported Market Share**: Similarly, the imported market share is calculated as the proportion of imports in the total market volume.
6. **Top Importing Countries**: Utilizing USA Trade Online statistics, we identified the main countries from which the U.S. imports, along with their respective market shares.
7. **Market Share for Each Food Item**: For individual food items, we selected either the top three producing countries or those accounting for at least 75% of the total U.S. market.

The countries making up the top three producers or comprising at least 75% of the market for each food item were then matched with the available data sets to contextualize their respective GHG emissions. This comprehensive approach ensures that the estimated GHG emissions reflect the intricate dynamics of the U.S. food market, encompassing both domestic production and diverse sources of importation. Emission factors were matched to the closest available representative data in WFLDB to best approximate the country or region specific GHG impacts from where the food is sourced.

[12] http://www.fao.org/faostat/en/
[13] https://usatrade.census.gov/

Table 3: Ratio of Imports to Domestic Production: Analysis of Contributing Countries to the U.S. Market Mix

Food Type	Country 1	% of the US market	Country 2	% of the US market	Country 3	%
Almond drink	US	79%				
Almonds	US	79%				
Apples	US	67%	CL	17%		
Bananas	GT	42%	CR	23%	CO	6%
Beans	US	76%				
Beef	US	87%				
Bread	US	64%	CA	36%		
Cake	US	100%				
Carrots	CA	64%	MX	31%		
Cheese	US	94%				
Chicken	US	99%				
Chocolate	CI	54%	GH	19%	EC	13%
Coffee	BR	45%	CO	39%		
Eggs	US	100%				
Flour	US	64%	CA	36%		
Grapes	US	75%				
Lemons	MX	76%	US	11%		
Lettuce	US	37%	MX	58%		
Mandarins	MX	63%	US	31%		
Milk	US	94%				
Olive oil	MX	97%				
Onion	US	81%				
Pork	US	93%				
Potatoes	US	75%				
Rice	US	77%	CN	16%		
Salty snacks	US	100%				
Shrimp	CN	91%				
Strawberries	MX	89%	US	11%		
Sugar	US	100%				
Tilapia	US	17%	CN	24%	TW	6%
Tomatoes	US	82%				
Vanilla	MG	71%	ID	20%		
Watermelons	MX	43%	GT	43%		
Yogurt	US	94%				
Cereal	CA	97%				
Ketchup	US	82%				
Pasta	US	64%	CA	36%		
Peanut butter	NA	NA				
Salt	GLO	100%				
Meat alternatives	US	100%				
Ice cream	US	94%				
Orange juice	NA	NA				
Tea	CN	23%	JA	12%	IN	11%

Commented [2]: Is there a typo for rice? There's no 2nd country listed. Also, I may not quite be following this but I thought that 75% or more of the market was represented in this table but seeing that for pasta there's just the US but it's 64% so under the 75% benchmark. Should there be a 2nd country?

Commented [MH3R2]: Both corrected

2.2 Manufacturing

Manufacturing refers to any kind of transformation or processing that occurs before a food item is ready for a consumer-facing business. Food waste *at* manufacturing is allocated the same impact as that of a product *leaving* manufacturing, which is equal to the carried upstream impact of agricultural production plus the accrued impact of manufacturing processes up until the product leaves the factory gate.

The accrued impacts considered in this life cycle stage cover:

- **Raw Material Conversion:** Loss of inedible parts and recipe adjustments (see 2.2.1)
- **Logistics:** Transportation from farm to manufacturing (see 2.2.3)
- **Manufacturing Process:** Energy and material consumption and processing losses (see 2.2.4)
- **Packaging:** Material used for packaging the product at the factory gate (see 2.2.5)

2.2.1 Raw Material Conversion

The manufacturing phase accounts for the (1) discarding of inedible parts and (2) recipes, both of which are reflected in the ratio of input to output of raw materials. The specified raw material conversion rates used in these calculations are adopted from databases such as WFLDB 3.9.1[14] (Table 4).

For instance, to obtain 1 kg of chicken at the manufacturing stage, 1.61 kg of chicken is assumed to be supplied at the farm gate to compensate for the removal of what are considered inedible parts. Similarly, the recipe used to produce a processed product may include ingredients like water that are assumed to have negligible GHG impact; for example, the recipe to produce 1 kg of bread calls for 0.8 kg of wheat and 0.2kg water which is embedded in the dataset that have been used for bread from WFLDB. For food items that do not have the farm stage in the model such as bread and orange juice, farm level emissions and associated conversions are included in the cumulative emissions at manufacturing stage (and are not listed in Table 4).

For other food items, in particular fresh food items such as bananas (and others that do not require manufacturing), the raw material conversion rate is 100% (i.e., not applicable).

Table 4: Raw material conversion rates

Food Item	Raw Material Conversion (% mass)
Beef	217%
Chicken	161%
Coffee	123%
Milk	106%
Pork	174%
Sugar	890%

2.2.2 Prepared food items

To quantify the greenhouse gas (GHG) emissions of prepared food including salad, sandwich, pizza, and soup recipes provided by the Food Commodity Intake Database (FCID)[15] from the EPA's What We Eat in America (WWEIA) dataset for the years 2005-2010 were utilized. The FCID recipes detail the ingredients and their respective quantities used in typical preparations of these food items, allowing for accurate assessment and comparison of GHG emissions based on the composition of each recipe. Each food item's recipe was broken down into its individual components with precise

[14] WFLDB includes both primary data sourced from industrial or research organizations and secondary data from publications and statistics.

[15] U.S. EPA. (2012). What We Eat in America - Food Commodity Intake Database, 2005-2010 (WWEIA-FCID 2005-10). Retrieved from https://fcid.foodrisk.org/

Commented [4]: Quantis to confirm. It's not a huge deal but does this mean ONLY conversion rates are applied to the items in Table 4? Seems strange that it would just be these items as bread (one of the examples isn't listed). If this is just a sampling, we should add that the title. Or.. list ALL the conversion rates.

Commented [MH5R4]: This is because bread does not have the farm stage in the model, thus farm level emissions and associated conversions are included in the cumulative emissions at the manufacturing stage. Text revised to better describe this quantities for each ingredient in grams. For instance, the salad recipe (FCID Code: 27446360) includes 40g of lettuce, 23.69g of chicken meat, and 13.21g of tomato. Emission factors sourced from the World Food LCA Database (WFLDB 3.9) provide the amount of GHG emissions per unit mass of each ingredient.

2.2.3 Logistics

To quantify emissions associated with logistics from the farm to the manufacturing site, the following default assumptions are applied to capture the transportation impact:

- **Domestic Goods:** For domestically produced items, it was assumed they travel 950 miles by truck from the farm to the distribution center and subsequently to the manufacturing site (Dettling et al. 2016).
- **Imported Goods:** For imported goods, it was assumed they travel an average of 5,000 miles by sea, followed by 950 miles by truck to reach their final manufacturing destination (Dettling et al. 2016).

2.2.4 Manufacturing Process

Emissions associated with the manufacturing process are calculated using Life Cycle Inventory (LCI) datasets for the specific manufactured product. The following assumptions were applied:

- **Loss Rate:** An average loss of 2% is included during the manufacturing phase. This presumed loss stems from inefficiencies inherent to the manufacturing process, as opposed to the exclusion of inedible components accounted for by the ratio of input to output. This loss rate can be adjusted based on primary or more accurate data per food type, which could potentially impact the emission factors used.[16] Note that a presumed level of farm-stage losses is already embedded in the farm-gate emission factors from WFLDB and ecoinvent.
- **Energy**: If a specific dataset for the United States was unavailable, the data has been adapted to better reflect U.S. conditions (i.e., used U.S. energy assumptions, which is a low voltage grid mix based on WFLDB 3.9 values).
- **Processing:** Food item specific manufacturing datasets have been drawn for the representative food items from ecoinvent. These processing factors are appropriate for the food items in their stated form.
  - However, food may exist in various states or change state as it moves along the supply chain. For example, strawberries are currently considered fresh produce in the model; to evaluate the impact of frozen strawberries, the freezing impact would need to be added.
  - A series of processing datasets are provided in Table 5 to provide flexibility to represent additional manufacturing processes as required. These datasets are taken from the Agribalyse database (Colomb et al. 2015) and adapted to U.S. conditions by modifying the electricity mix (Electricity, medium voltage, US Marker from ecoinvent 3.9). Please note that the values listed below are <u>not</u> utilized in the calculations provided to ReFED.

[16] ReFED reserves the right to adjust the loss rate based on primary data.

Table 5: Optional processing datasets for enhanced representation of manufacturing processes

Manufacturing	Assumptions
Freezing	0.18 kwh of energy using medium voltage electricity (Agribalyse, adjusted to US electricity mix)
Boiling	0.43 kwh of energy using medium voltage electricity (Agribalyse, adjusted to US electricity mix)
Baking	1.35 kwh of energy using medium voltage electricity (Agribalyse, adjusted to US electricity mix)
Canning	0.98 MJ/kg of heat from natural gas and 0.13 kWh of electricity (Agribalyse, adjusted to US electri
Generic	Manufacturing processes other than above, 1.47 MJ/kg of heat from natural gas and 1.27 kWh of electricity (Ladha-Sabur et al. 2019)

2.2.5 Packaging

Packaging emissions are quantified based on a broad assumption about all food items in a particular food type being either canned, frozen, chilled, or dry products (Table 6). Applying standard values ensures that emissions associated with the packaging of food items are accounted for, considering the typical physical state and preservation method of the products. Note the emissions associated with packaging made from other materials or with varying levels of recycled content would differ from these default assumptions. The assumptions used for packaging emissions are as follows:

- **Canned Products:** For canned products, the default assumption is 100 g of steel per kg of packaged food (Colomb et al. 2015).
- **Frozen Products:** The packaging for a frozen product is assumed to be 100 g of cardboard plus 40 g of high-density polyethylene (HDPE) per kg of packaged food (JRC, Zampori, and Pant 2019).
- **Chilled or Dry Products:** For chilled or dry products, the default assumption is 40 g of polyethylene (PE) per kg of packaged food (JRC, Zampori, and Pant 2019).

Table 6: Archetypes assumed for packaging

Food Type	Archetype Assumed
Ready-to-drink Beverages	Dry product
Produce	Chilled product
Frozen	Frozen product
Fresh Meat & Seafood	Chilled product
Prepared Food Items	Chilled product
Dry Goods	Dry / Canned product
Dairy & Eggs	Chilled product
Breads & Bakery	Dry product

2.3 Consumer-facing business (retail and foodservice)

Food ready for consumption can follow two primary pathways: it can either be directed towards grocery or other retail businesses and then to residential consumers, or alternatively, it can be supplied to foodservice providers. Food waste at the consumer-facing business stage is allocated the same impact as if that food were to be sold from said business, which is equal to the carried upstream impact of agricultural production, manufacturing, as well as the accrued impact after manufacturing (see details below).

The accrued impacts for consumer-facing businesses includes the following steps. It is assumed that the impact of food waste in foodservice also includes the additional step (and associated GHG emissions) of food preparation.

- **Logistics**: transportation from manufacturing to consumer-facing business (see 2.3.1)
- **Storage:** at the distribution center and at the consumer-facing business (see 2.3.2)
- **Food Preparation:** only for foodservice (see 2.3.3)

Three different datasets were developed to cover the various impacts related to logistics and storage at the consumer-facing business level:

- **Dry Products:** Covers food items with long shelf life and storage at ambient temperature.
- **Chilled Products:** Covers food items with short shelf life and chilled storage.
- **Frozen Products:** Covers food items with long shelf life and frozen storage.

Table 7 presents which archetype was applied to all food items in a particular food type (i.e., dry, chilled or frozen storage).

Table 7: Archetypes logistics and storage assumed for the consumer-facing business stage

Food Type	Archetype Assumed
Ready-to-drink Beverages	Dry product
Produce	Chilled product
Frozen	Frozen product
Fresh Meat & Seafood	Chilled product
Prepared Food Items	Chilled product
Dry Goods	Dry product
Dairy & Eggs	Chilled product
Breads & Bakery	Dry product

2.3.1 Logistics

The following assumptions were used to quantify the logistics impact for all businesses within this sector. For chilled and frozen items, calculations assume the use of a truck with refrigeration; for dry goods, a truck without refrigeration is used (this refrigeration assumption applies also to the transportation of items from farm to manufacturing or directly to distribution center).

- From manufacturing center to distribution center, 293 miles by truck (Dettling et al. 2016).

- From distribution center to consumer-facing business, 450 miles by truck (Dettling et al. 2016).

2.3.2 Storage

The following assumptions were used to quantify storage impact. Emissions were quantified using WFLDB and ecoinvent 3.9.1 EFs for storage in refrigerators and freezers.

- At the distribution center: 4 weeks for dry and frozen products, 1 day for the chilled products in closed refrigeration/freezer storage (Dettling et al. 2016).
- At the consumer-facing business: 4 weeks for dry and frozen products, 2 weeks for the chilled products in open refrigeration/freezer storage (Dettling et al. 2016).

2.3.3 Preparation

The following assumptions were used to quantify preparation impact for foodservice. Table 8 presents which food items were assumed to be cooked or kept fresh/uncooked.

- Cooked products (e.g., grains, legumes, meats) are assumed to require 2.3 kWh/kg (Zampori and Pant 2019).
- Fresh products are assumed to have no preparation energy and consumed as is (Zampori and Pant 2019).

Table 8: Assumptions about preparation used for food products

Cooked Products	Beef, Chicken, Eggs, Flour, Meat alternatives (soy-based), Pasta, Pork, Potatoes, Rice, Sausage, Shrimp, Tea, Tilapia, Pizza, Soup
Fresh Products	Almonds, Apples, Bananas, Beans, Bread, Cake, Carrots, Cereal, Cheese, Chocolate, Coffee, Eggs, Grapes, Ice cream, Ketchup, Lemons, Lettuce, Mandarins, Milk, Onion, Olive oil, Orange juice, Peanut butter, Potatoes, Rice, Salad, Salt, Salty snacks, Sandwich, Strawberries, Sugar, Tomatoes, Vanilla, Watermelons, Yogurt

2.4 Residential

Food waste generated at residences is allocated the full impact of upstream agricultural production, manufacturing, and distribution via consumer-facing businesses plus in-home storage and preparation. The accrued impacts considered in this life cycle stage cover:

- **Logistics:** from consumer-facing business to home (see 2.4.1)
- **Storage**: at home (see 2.4.2)
- **Preparation:** at home (see 2.4.3)

2.4.1 Logistics

The following assumption is used to quantify the logistics impact:

- Residence to consumer-facing business, trip done by car, 13 miles round trip and car is used for shopping 15 items; therefore, each item accounts for 1/15 of the impact (Khan et al. 2019).

2.4.2 Storage

The following assumptions are used to quantify the storage impact:

- For dry products, no impact is assumed.
- For chilled products, 1 week at residence in closed refrigeration (Zampori and Pant 2019).
- For frozen products, 4 weeks at residence in closed freezer (Khan et al. 2019).

2.4.3 Preparation

The following assumptions are used to quantify the preparation impact:

- Fresh products are assumed to have no preparation energy (Zampori and Pant 2019).
- Cooked products (e.g., grains, legumes, meats) are assumed to require 2.3 kWh/kg (Zampori and Pant 2019).

3 | End-of-Life Impacts

In addition to the food life cycle (upstream) stages described above, the emissions impact associated with surplus food at end-of-life (EOL) to various destinations (including donation) were modeled (see Table 2). EOL impacts are calculated based on all GHG emissions arising *after* a food item departs from the originally intended value chain. The archetypal destinations were developed to represent EOL pathways in the U.S. following the guidance of the EPA's Wasted Food Scale (EPA 2023) and aligning with the *FLW Standard*.

The following guiding principles were used in this methodology:

- The transport of food waste to the destination is included in the impact.
- The processing of food waste related to the destination is included in the impact (e.g., fugitive emissions during anaerobic digestion, emissions from energy consumption).
- Avoided emissions from process outputs are included in the impact, where relevant. This represents avoided products that would otherwise be utilized in the wider economy if the food management pathway was not pursued (e.g., electricity avoided from energy recovery at landfills or biogas generated from anaerobic digestion, chemical fertilizer production avoided if using organic soil amendments generated through composting or anaerobic digestion).
- Food specific water content is considered when calculating EOL impacts and benefits because EOL GHG emissions, especially associated with anaerobic decomposition (e.g., landfill, anaerobic digestion, and sewer), are sensitive to methane yield which is a function of the food's water content.[17] The water content values for each food item were taken from the USDA Food Data Central database. This is a key granularity improvement from the 2021 methodology.
- Where relevant, food specific fat and energy content is taken into account when calculating GHG emissions produced or avoided.
- Food specific nitrogen and phosphorous content is used when calculating the N/P fertilizer offset (e.g., for land application) and calculating fugitive N_2O emissions for the sewer and unharvested pathways. Nitrogen content will have a large influence on emissions from land application and the amount of avoided fertilizer. While this methodology is focused on global warming potential, food specific phosphorous and nitrogen content could be used for future quantification of acidification and eutrophication impacts.

For the landfill, incineration, composting and anaerobic digestion destinations, Quantis selected GREET (Wang et al. 2023) as a guiding reference for the emission factor methodology development. While EPA's WARM model is commonly referenced in similar estimations of destination GHG impacts, two key aspects differentiated the models and justified the use of GREET 2023 for this work: 1) up-to-date assumptions and 2) customizability.

[17] The DM content (inverse of water content) of discarded food is a critical parameter that determines the amount of GHG (CH4 in particular) emissions from waste treatment facilities, especially landfills. The DM content varies greatly across different types of food (e.g., from 100 percent DM of oils to 5 percent DM of some vegetables). In anaerobic conditions like a landfill, most of the dry matter becomes CH4 hence the emission factors from landfill for drier food products (with a higher DM content) are greater than those of wetter food products (with a lower DM content).

1. **Assumptions:**
    - **GWP values**: WARM v16 uses AR4 values (2007) for GHG accounting while GREET uses AR6 (2021); use of AR4 values may lead to underestimated GHG emissions.
    - **Landfill regulations:** GREET reflects the rule amendment made by EPA in 2016 that lowered the threshold for non-methane organic compounds (NMOC) emissions, which triggers requirement of landfill gas collection and control systems to be installed and operating. This stricter regulation can lead to up to a 7% reduction in landfill CH4 for every 1 metric ton of municipal solid waste disposed in US landfills (Wang et al. 2021).
    - **GHG split**: Since ReFED is particularly interested in allowing users to isolate the methane-specific contribution to overall GHG emissions, splitting out emissions by the different types of GHG (e.g., CH4, N2O) is essential. At the time this methodology development began, WARM v15 was the most current version available and only reported the aggregate emissions in CO_2 equivalent units (i.e., without a gas split). The CH_4 split has since been made available in the most recent WARM v16 model.
2. **Customizability:** GREET 2023 Waste Module implements a bottom-up approach following the majority of WARM v16 *guidelines* for background food waste biodegradability (i.e., decay rate, carbon content, conversion rate to carbon emission, methane yield, and storage factors), electricity and fuel consumptions and subsequently assessing GHG emissions associated with landfill, incineration, composting and anaerobic digestion. However, GREET 2023 allows the user to adjust activity data to reflect food type granularity, or adjust the assumptions around how the destination operates. GREET 2023 also adds granularity regarding soil carbon storage and decomposition processes and emissions during the curing of final compost/digestate.

Table 9 summarizes the key aspects that differentiate and justify the use of the GREET 2023 model.

Table 9: Comparison of WARM v16 and GREET 2023

Parameter	WARM v16 (2023)	GREET 2023
GWP values	Uses IPCC AR4 (2007) e.g., 1 kg of CH_4 released to air has a GWP of 25 kg CO_2e over 100 yr time horizon	Uses IPCC AR6 (2021) e.g., 1 kg of CH_4 released to air has a GWP of 29.8 kg CO_2e over 100 yr time horizon
Landfill | Gas collection regulatory compliance threshold	50 metric tons per year = minimum threshold concentration for non-methane organic compounds (NMOC) (2006 regulation)	34 metric tons per year threshold (which requires landfills to turn on gas collection and control system earlier). This change leads to the changes in the proportion of CH_4 emitted and oxidized.

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Commented [WW9R7]: Confirmed!

Incineration | Carbon intensity of electricity	WARM has a much higher carbon intensity of electricity (0.73 kg CO2e/kWh) based on EIA 2018.	GREET has a lower carbon intensity 0.44 kg CO2e/kWh to represent more recent US grid mix (eGRID 2022)
AD | Electricity Recovery of AD Biogas	Wet AD typically has higher GHG emissions than dry AD due to additional electricity required to de-water/dry in wet AD. WARM shows the flipped trend because WARM applies different electricity recovery pathways between dry AD (electricity only) and wet AD (combined heat and power).	GREET assumes both wet AD and dry AD have a consistent energy offtake pathway from biogas combustion, i.e., electricity generation.
Activity Customizability	N/A	• Possible to update activity data (e.g., electricity consumption, carbon content, waste properties). • Possible to update market change in practice (e.g., fractions of landfill gas collected to flare vs. converted for energy recovery).

For the other destinations (i.e., donation, animal feed, industrial uses (rendering), land application, not harvested, and sewer), data and assumptions were pulled from other available literature which are detailed and cited in the following sections.

3.1 Carbon and Global Warming Potential Accounting

Differences in global warming potential (GWP) factors of different GHGs were also taken into account, discriminating between biogenic and fossil origin for methane (CH_4) and carbon dioxide (CO_2), and by considering the length of the C cycle of biogenic CO_2 (see Table 10). Differences in the origin of the CO_2 (fossil vs. biogenic, short-term vs. long-term) embodied in food items are considered by using the Neutral biogenic CO2 (CO_2b) accounting method (IPCC 2006[18]).

In the Neutral CO_2b method, biogenic CO_2 emissions from short-term carbon cycles have a GWP of zero because it has no effect on the climate. Released CO_2 molecules from the decomposition or incineration of food biomass are assumed to be taken up by plants via photosynthesis during their growth in the agricultural stage a few months or years back and released shortly after. On the contrary, biogenic CO_2 emissions from long-term C pools like soil or trees are considered as fossil CO_2 (GWP of 1) and included in the upstream life cycle emissions of food items generating land use change (LUC) emissions.

Carbon sequestration is considered for those food destinations where a fraction of the biogenic C from the assessed food items ends up stored in the soil for a long term, e.g., upon landfill disposal,

[18] IPCC Guidelines for National GHG inventories, Vol 4: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

application of compost/digestate, or directly applied back to land. This C storage is modeled by taking a GWP of -1. Latest GWP values from IPCC AR6 were taken for this assessment and are presented in Table 10. Time horizon GWP estimates are calculated using the equation below, following the Neutral CO_2b method.

$$GWP_{TH=100\ or\ 20\ yr} = biogenic\ CH_{4,TH} \times GWP_{biogenic\ CH_4,TH} + fossil\ CH_{4,TH} \times GWP_{fossil\ CH_4,TH} + N_2O \times GWP_{N_2O,TH} + fossil\ CO_2 \times 1 - stored\ biogenic\ CO_2$$

Table 10: IPCC AR6 GWP values based on 100-yr and 20-yr time horizons

Time Horizon	CH_4, fossil	CH_4, biogenic	CO_2 fossil and long-term C pools	CO_2, biogenic	CO_2 stored	N_2O
100-yr	29.8	27.05	1	0	-1	273
20-yr	82.5	79.75	1	0	-1	273

GHG factors modeled here refer to 1 metric ton (t) of food moving through each EOL destination in the U.S. A summary of activities included in each EOL destination is provided in Table 10 and each model is described in detail in the sections below.

To calculate a scenario that combines several destinations (e.g., 25% of food waste sent to animal feed and the rest is composted), this split in destinations should be separately calculated by the user. This choice was made to avoid ambiguity and accidental double counting when a user enters their food waste destinations into the Impact Calculator tool.

For all the destinations included in this model (except sewer), the impact results capture not only GHG emissions released (e.g., transportation of the waste to the treatment site, emissions of methane (CH_4) or dinitrogen monoxide (N_2O) due to food degradation) but also avoided emissions that reduce the overall GHG impact (see Table 11). Examples of avoided emissions include energy substitution from biogas combustion or waste burning, land application of final compost/digestate as a substitute of synthetic fertilizer, or source product replacement for animal feeds and rendered products.

Table 11: Activities/Processes modeled in end-of-life destinations

Destination	GHG Emissions Sources	Avoided Emissions
Food Rescue (Donation)	• Transportation (collection and redistribution)	• Avoided food production for the recovered food (discounting the loss rate at food banks)
Animal Feed	• Transportation • Processing for dry and wet feed production (heat treatment, dewatering, pelletizing)	• Protein-rich food items avoid (i.e., replace) feed-quality soy production • Low-protein food items avoid (i.e., replace) feed-quality corn production
Rendering for Pet Food	• Transportation • Rendering process energy (electricity and natural gas)	• Avoided emissions from displacement of low-grade slaughter by-products

Rendering for Biodiesel	• Transportation • Cleaning and esterification process (modeled as biodiesel production from used cooking oil)	• Avoided GHG emissions from fossil diesel production and combustion
Composting	• Transportation • Composting operation (electricity) • N_2O and CH_4 emissions from compost production and land application (any CO_2 emissions considered biogenic - no impact)	• Avoided NPK fertilizer in proportion to the N-P content of composted food waste • 20% of carbon stored in soil
Anaerobic Digestion	• Transportation • Equipment use and biogas leakage at anaerobic digester • CH_4 and N_2O emissions during composting of digestate solids • N_2O emissions from land application of liquid digestate	• Avoided energy production from biogas to energy • Avoided NPK fertilizer in proportion to the N-P content of digestate • 10% of carbon in land-applied digestate stored in soil
Land Application	• Transportation to farms • Aerobic decomposition when applied to land so any CO_2 emissions considered biogenic - no impact	• Avoided NPK fertilizer in proportion to the N-P content of applied food waste • 20% of carbon stored in soil
Not Harvested	• Aerobic decomposition on fields so any CO_2 emissions considered biogenic - no impact	• 20% of carbon stored in soil
Incineration with Energy Recovery	• Transport to waste to energy (WtE) plant • Combustion-related fossil CO_2 and N_2O emissions	• Avoided energy production from energy recovery
Landfill	• Transportation • Energy and fuel consumption for flare and combustion of gas • Fugitive emissions of CH_4 (any CO_2 emissions considered biogenic - no impact)	• Avoided emission due to landfill gas recovered for energy • Landfill's ultimate biogenic carbon storage 20% (Barlaz 1998), also varying with the selected time horizon
Sewer	• Grinding electricity required for in-home garbage disposal • CH_4 produced from sewer collection network and conveyance (methane production from wet pipe surfaces) • CH_4 and N_2O emissions during wastewater treatment including biogas leakage and incomplete flaring from AD	• None (see Section 3.12).

3.2 Properties of Food Items

The properties assumed for food items when wasted are presented in Table 12 and were used to estimate the food-item-specific CH_4 emissions and GHG emission results (including gross emissions and avoided impacts in the different destinations).

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Table 12: Properties assumed for each food item; 'ww' = wet weight (sources in Table 13)

Food Type	Food Item	Water Content	Biogenic C Content	Fossil C Content	Energy Content	Nitro-gen	Phos-phorus	Total Lipid (fat)	Protein
		% ww	kg bio-C/kg dry matter	kg fossil-C/kg dry matter	MJ/kg ww	kg/kg ww	kg/kg ww	kg/kg ww	kg/kg ww
Breads & Bakery	Bread	36%	0.50	0.01	11.0	0.017	0.0016	0.036	0.109
	Cake	36%	0.50	0.01	11.0	0.017	0.0016	0.036	0.109
Dairy & Eggs	Almond drink	84%	0.50	0.01	2.0	0.001	0.0003	0.013	0.006
	Cheese	37%	0.50	0.01	12.9	0.029	0.0040	0.234	0.209
	Eggs	75%	0.50	0.01	7.5	0.021	0.0018	0.129	0.131
	Milk	90%	0.50	0.01	2.0	0.005	0.0010	0.015	0.034
	Yogurt	81%	0.50	0.01	3.0	0.009	0.0012	0.028	0.070
Dry Goods	Almonds	5%	0.50	0.01	25.0	0.039	0.0046	0.577	0.214
	Beans	71.50%	0.50	0.01	6.5	0.014	0.0047	0.014	0.239
	Cereal	4%	0.50	0.01	10.0	0.022	0.0040	0.058	0.130
	Chocolate	9.50%	0.50	0.01	20.0	0.04	0.00	0.30	0.04
	Coffee	1.41%	0.50	0.01	18.3	0.030	0.001	0.11	0.02
	Flour	11.50%	0.50	0.01	15.5	0.024	0.0025	0.061	0.133
	Salty Snacks	2%	0.50	0.01	6.0	0.011	0.0000	0.004	0.080
	Ketchup	67%	0.50	0.01	4.9	0.002	0.0002	0.005	0.011
	Olive oil	0%	0.50	0.01	37.0	0.000	0.0000	1.000	0.000
	Pasta	87%	0.50	0.01	6.6	0.01	0.00	0.01	0.06
	Peanut butter	1%	0.50	0.01	25.0	0.04	0.00	0.50	0.23
	Rice	74%	0.50	0.01	7.3	0.01	0.000	0.03	0.04
	Salt	0%			0.0	0.00	0.00	0.00	0.00
	Sugar	1%	0.50	0.01	16.1	0.00	0.00	0.00	0.00
	Vanilla	11.00%	0.50	0.01	15.4	0.04	0.01	0.06	0.00
Fresh Meat & Seafood	Beef	54.50%	0.50	0.01	6.6	0.03	0.00	0.13	0.23
	Chicken	62%	0.50	0.01	6.7	0.03	0.00	0.06	0.23
	Meat alternatives (soy-based)	7%	0.50	0.01	0.9	0.01	0.00	0.01	0.24
	Pork	40%	0.50	0.01	20.9	0.03	0.00	0.11	0.25
	Sausage	49.50%	0.50	0.01	12.2	0.03	0.00	0.23	0.17
	Tilapia	76%	0.50	0.01	10.0	0.03	0.00	0.01	0.16
	Shrimp	60.50%	0.50	0.01	11.9	0.01	0.00	0.18	0.18
Frozen	Ice cream	62%	0.50	0.01	8.7	0.00	0.00	0.27	0.03
Produce	Apples	84%	0.50	0.01	2.6	0.00	0.00	0.00	0.00
	Bananas	74%	0.50	0.01	3.8	0.00	0.00	0.00	0.01
	Carrots	91%	0.50	0.01	1.5	0.00	0.00	0.00	0.01
	Grapes	81%	0.50	0.01	2.4	0.00	0.00	0.00	0.01
	Lemons	89%	0.50	0.01	1.2	0.01	0.00	0.00	0.01
	Lettuce	96%	0.50	0.01	0.7	0.00	0.00	0.00	0.01

	Mandarins	87%	0.50	0.01	2.0	0.00	0.00	0.00	0.01
	Onion	89%	0.50	0.01	1.6	0.00	0.00	0.00	0.01
	Potatoes	62%	0.50	0.01	2.4	0.00	0.00	0.00	0.02
	Strawberries	92%	0.50	0.01	1.3	0.00	0.00	0.00	0.01
	Tomatoes	94%	0.50	0.01	0.9	0.00	0.00	0.01	0.01
	Watermelons	92%	0.50	0.01	1.4	0.00	0.00	0.00	0.01
Ready-to-drink Beverages	Orange juice	88%	0.50	0.01	1.8	0.00	0.00	0.00	0.01
	Tea	96%	0.50	0.01	0.0	0.00	0.00	0.00	0.00
Prepared Food	Salad	85.12%	0.50	0.01	2.6	0.01	0.00	0.02	0.08
	Sandwich	47%	0.50	0.01	9.9	0.01	0.00	0.12	0.13
	Pizza	47.50%	0.50	0.01	12.6	0.02	0.00	0.16	0.16
	Soup	86.50%	0.50	0.01	2.8	0.02	0.00	0.03	0.04

These properties were not relevant across every destination. For example, fat and protein content is only taken into account in modeling the GHG emissions associated with the animal feed destination. Table 13 summarizes for which destinations the various food properties have been included.

The dry matter (DM) content of discarded food is the inverse of the water content and a critical parameter that determines the amount of GHG emissions (CH_4 in particular) from waste treatment facilities, especially landfills. The DM content varies greatly across different types of food (e.g., from 100% DM for oils to 5% DM for some vegetables). In anaerobic conditions like a landfill, most of the dry matter becomes CH_4 hence the emission factors from landfill for drier food products (with a higher DM content) are greater than those of wetter food products (with a lower DM content).

Biogenic carbon content is assumed to be a constant percent of DM content for all food items because it typically does not vary greatly on a dry weight basis. The assumption of a constant 50% carbon content ratio on a dry weight basis for all food items may underestimate or overestimate the GHG emissions (and GHG savings) on some food destinations.

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Commented [15]: is 3-8% variation true for both carrots and tomatoes? Also wondering if this is reversed? Carrots should have higher C content than tomatoes I think?

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Table 13: Food item properties and data sources

Food Item Property	Property Type	Bulk Constant or Food-specific	Source	EOL Destination for which Property is Relevant
Water Content	Wet weight basis	Food-specific	USDA (2002) - Nutritive Value of Foods	• Animal Feed • Landfill • Incineration • Composting • Anaerobic digestion • Sewer • Not harvested

Biogenic C Content	Dry weight basis and need water correction	Constant from bulk food waste	GREET 2023: EPA WARM v16 2023	• Landfill • Composting • Anaerobic digestion • Land Application • Not harvested
Fossil C Content	Dry weight basis and need water correction	Constant from bulk food waste	GREET 2023	• Incineration with energy recovery
Energy Content	Wet weight basis	Food-specific	USDA FoodData Central (2023)	• Animal Feed • Incineration with energy recovery
Nitrogen	Wet weight basis	Food-specific	USDA FoodData Central (2023)	• Land Application
Phosphorus	Wet weight basis	Food-specific	USDA FoodData Central (2023)	• Land Application
Total lipid (fat)	Wet weight basis	Food-specific	USDA FoodData Central (2023)	• Rendering for pet food
Protein	Wet weight basis	Food-specific	USDA FoodData Central (2023)	• Animal Feed

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3.3 Food Rescue (Donation)

This model estimates the GHG impacts of food rescue by only including the GHG-related emissions from the transportation of food for donation as well as the benefits of avoided upstream GHG emissions (see system boundaries in Figure 2). The GHG emissions from sorting and storage at the donation center are excluded (as well as further processing that may take place, depending on the specific food rescue destination or activity) as these can vary greatly and should be assessed on a case-by-case basis. Note that the values provided to ReFED assume food is rescued from the retail sector and ReFED will re-calculate the avoided emissions within its own models based on the generating sector.

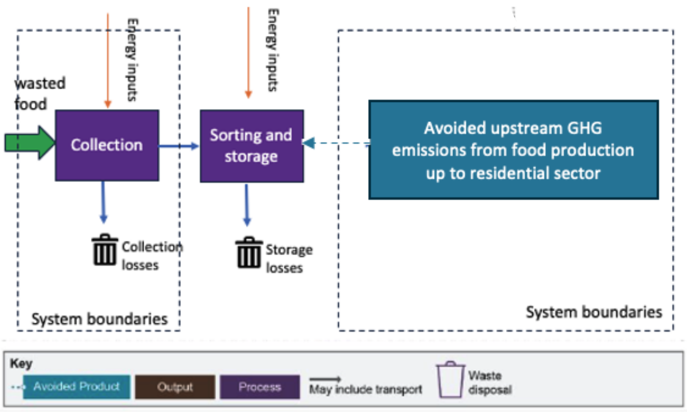

Figure 2: *Considered system boundaries for calculated food rescue (donation) GHG emissions and savings*

- **GHG emissions from food transportation (collection and redistribution)**:
    - For food collection, it is assumed that 66% of rescued food is transported 15 miles with private cars, while the rest (34%) is transported 60 miles with cargo vans.
    - The redistribution to final consumers was modeled as the same distance for collection but with different vehicle types, considering 15 miles with cooled reefer trucks for dry goods, dairy products, and meat or seafood, and 60 miles with frozen reefer trucks for prepared foods and ice cream.
    - Any further GHG emissions from cold/frozen storage at the collection and distribution center, eventual processing, and losses at the final consumer stage of donated food, have not been included.
- **Avoided GHG emissions**: Given the lack of precise data, the donated food is assumed to avoid demand for the same food (category) that would have been purchased by those receiving the food donation. It is thereby assumed that food donation leads to source reduction of the same food item in the same quantities, as well as reduction of the other life cycle impacts (e.g., transport).
    - However, it is assumed that some rescued items will spoil, get damaged, or otherwise be discarded during the donation process. To represent this eventual food waste, an average 6.5% loss rate of organic[19] food items is assumed (based on data from ReFED's partners) and subtracted from the source reduction amount. Note that emissions associated with end-of-life management for that loss are not included.
    - This may still overestimate avoided emissions as there may be additional losses in the new life cycle of the rescued food items along the value chain. Moreover, different rebound effects may arise that could negate the presumed avoided GHG impacts (Meshulam et al. 2023).

The avoided downstream impacts, e.g., avoiding landfill by donating food, can be calculated by users of ReFED's Impact Calculator selecting the baseline food waste destination as an alternative scenario.

3.4 Animal Feed

This destination considers food that is being sent to companies that produce animal feed using dry feed or wet feed technology. GHG emissions associated with this destination include the transportation of collected food items to the animal feed site, the emissions from processing the rescued food (energy use at the site) and the avoided impacts of the displaced animal feed.

- **GHG emissions from food collection and processing**:
    - Transportation emissions were modeled assuming a 100 km trip (i.e., 0.1 t*km/kg food) carried with 16-32 t lorries.
    - Energy use values for the treatment and processing of food waste into pig feed were taken from Table 5 in Salemdeeb et al. 2017.
    - Animal feed can be produced as wet material or dry material, with the processing technology for each style requiring a different amount of energy. An industry survey (Meticulous Research, 2024) on market share of the global animal feed shows that in

[19] For inorganic food items (i.e., salt), no food loss is assumed

2024, the dry feed is expected to account for 92.7% of the global market due to convenience of storage, less cost, higher nutrient density, and stability. These figures were used - 92.7% (dry feed) and 7.3% (wet feed) - to create a U.S. national average.

- **Avoided GHG emissions**: As protein and energy content are key aspects of determining animal feed quality, the protein and energy (and water) content of food items were taken into account using the US Food Data Central database[20]. Table 14 summarizes the food specific feed substitution and replacement ratios assumed which are based on the following factors:
  - Soy was assumed to have a protein content of 39 g per 100 grams of soy (wet weight), and corn was assumed to have an energy content of 19 MJ/kg (wet weight).
  - Food items with high protein content (>100 g of protein per kg food) are assumed to replace soy in proportion to their protein content, e.g., bread (109 g protein/kg) substitutes 28% of soy feed (386 g protein/kg).
  - Food items with low protein (≤100 g of protein per kg food) are assumed to replace corn in proportion to their energy content, e.g., rice (3600 kcal/kg) substitutes 78% maize feed (4600 kcal/kg).

For food safety reasons, meat waste is commonly prohibited from inclusion in animal feed feedstock and therefore fresh meat and seafood items are not considered for this destination.

Note that food items with low protein and energy content, e.g., lettuce, may result in positive GHG values as the emissions required for processing these items as animal feed are greater than the GHG emissions avoided by replacing the nutrient-equivalent amount of corn or soy as the traditional ingredients.

Table 14: Feed replacement parameters

Food Item	Protein (kg protein/kg wet food)	Energy (MJ/kg wet food)	Feed Ingredient Replaced	Replacement Ratio	Water Content
Bread	0.109	11	soy	28%	36%
Cake	0.109	11	soy	28%	36%
Almond drink	0.000	2	NA	0%	84%
Cheese	0.209	13	soy	54%	37%
Eggs	0.131	7	soy	34%	75%
Milk	0.034	2	maize	10%	90%
Yogurt	0.070	3	maize	16%	81%
Almonds	0.262	25	soy	68%	5%
Beans	0.239	6.5	soy	62%	71.50%
Cereal	0.130	10	soy	32%	4%
Chocolate	0.04	20	maize	58%	9.50%
Coffee	0.000	0	NA	0%	98.50%
Flour	0.133	16	soy	34%	11.50%
Salty Snacks	0.133	6	soy	34%	2%
Ketchup	0.011	5	maize	25%	67%
Olive oil	0.000	37	maize	191%	0%

[20] https://fdc.nal.usda.gov/index.html

Pasta	0.133	16	soy	34%	12%
Peanut Butter	0.232	25	soy	60%	1%
Rice	0.071	15	maize	78%	11%
Salt	Considered in this methodology ineligible to serve as animal feeds				
Sugar	0.000	17	maize	87%	1%
Vanilla	0.000	15	NA	0%	11.00%
Beef	Considered in this methodology ineligible to serve as animal feeds				
Chicken					
Meat alternatives (soy-based)					
Pork					
Sausage					
Tilapia					
Shrimp					
Ice cream	0.000	9	NA	0%	62%
Apples	0.002	3	maize	13%	84%
Bananas	0.007	4	maize	20%	74%
Carrots	0.008	2	maize	8%	91%
Grapes	0.009	3	maize	16%	81%
Lemons	0.000	1	maize	16%	89%
Lettuce	0.010	1	maize	4%	96%
Mandarins	0.000	2	maize	16%	87%
Onion	0.000	2	maize	5%	89%
Potatoes	0.020	2	maize	16%	62%
Strawberries	0.006	1	maize	7%	92%
Tomatoes	0.008	1	maize	5%	94%
Watermelons	0.000	1	maize	5%	92%
Orange juice	0.008	2	NA	0%	88%
Tea	0.000	0	NA	0%	96%
Salad	0.230	3	soy	60%	53.50%
Sandwich	0.230	10	soy	60%	47%
Pizza	0.109	13	soy	28%	47.50%

3.5 Rendering

For the rendering destination, two archetypes have been considered: pet food and biodiesel. This is largely due to poor data availability for modeling the GHG impacts of rendering as a destination overall since there are multiple outputs produced through rendering. This EOL destination was assumed to only be valid for activities occurring in the upstream farm and manufacturing stages.

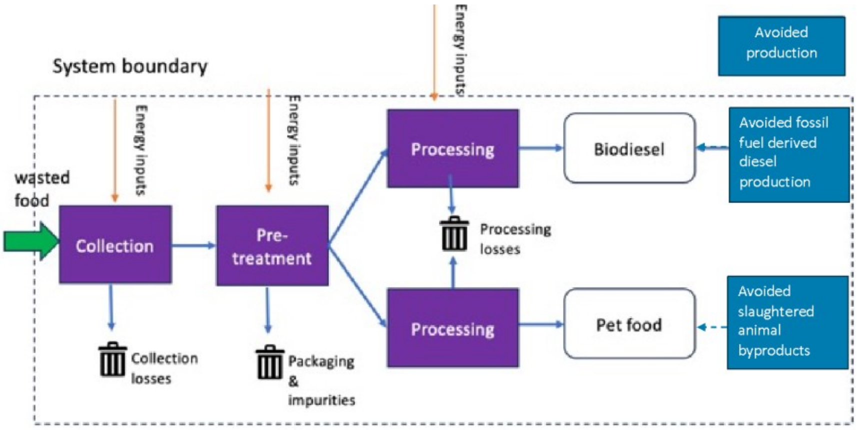

Figure 3: *Considered system boundaries for calculated rendering GHG emissions and savings*

3.5.1 Pet Food

The pet food rendering destination has been considered for all food items. A food's fat content is the key parameter used to characterize the potential for substituting slaughtering by-products typically used for the production of pet food.

- **GHG emissions from transportation and processing**:
    - A 100 km trip (i.e. 0.1 t*km/kg food) carried with 16-32 t lorries, i.e. 0.1 t*km per kg pet food produced, has been taken from Avadi et al. 2020.
    - Energy inputs for pet food production processes have been included based on the same study and amount to 0.16 kWh of electricity and 4.37 MJ of natural gas per kg pet food produced.
- **Avoided GHG emissions:** The amount of pet food produced from valorized food waste is based on the fat content of each food item, assuming a 10% fat content (the average of beef, pork and chicken[21]) for the produced pet food.
    - The rendering process of such food items produces pet food, substituting for low-grade animal slaughtering by-products like bones, skins and offal. It is assumed that 0.4 kg of by-products like offal from chicken, beef and pork slaughtering are displaced per kg pet food.

3.5.2 Biodiesel

For this methodology, the assumption was made that biodiesel is produced only from fats, grease and used oils. Of the representative food items included in this model, only olive oil fulfills the characteristics needed to produce biodiesel.

- **GHG emissions from transportation and processing:**

[21] USDA Food Data Central is used as reference database for the characterization of all food items.

  - A 100 km trip (i.e. 0.1 t*km/kg food) carried with 16-32 t lorries, i.e. 0.1 t*km per kg pet food produced, has been included (this is the assumption for the pet food pathway, applied to rendering due to lack of data).
  - The biodiesel yield from rendered vegetable oil is 18.77 MJ/kg vegetable oil (Chen et al. 2023). The calorific or low heating value of olive oil was used to calculate the amount of diesel that would be eventually displaced.
  - The rendering process considered is esterification and the energy inputs considered for its production are based on the Ecoinvent 3.9 dataset "Fatty acid methyl ester {RoW}| treatment of waste cooking oil, purified, esterification | Cut-off, U".
- **Avoided GHG emissions:** Avoided emissions are calculated as the difference between biodiesel and diesel production and combustion emissions. It is assumed that 1 kg of biodiesel replaces 1 kg of fossil diesel. Ecoinvent 3.9 datasets "Diesel {GLO}| market group for diesel | Cut-off, U" and "Diesel, burned in diesel-electric generating set, 10MW {GLO} | Cut-off, U" were used for this calculation. The non-CO_2 GHG emissions considered for the combustion process of biodiesel are based on the previous diesel combustion dataset (removing CO_2 emissions since these are climate neutral).

3.6 Compost

The compost destination is considered valid for all supply chain stages and all food items. The compost operation modeled in this methodology is the windrows method. Windrows are the most commonly used technology for composting yard trimmings and municipal solid waste (MSW), and they are considered to be the most cost-effective composting technology, particularly suitable for high-volume organic waste (Coker 2006; EPA WARM v16). Approximately 63% of organic waste composted in the United States is composted in windrows, while the remainder is treated in in-vessel or static piles (BioCycle 2019).

We acknowledge that aerated static piles (ASP) is a method that is growing in prevalence – ASP tends to be more space-efficient and enables faster decomposition and therefore better suited to jurisdictions such as California that have limited space and high demand. Due to limited data availability, we are not including ASP in this methodology but are noting high-level insights based on literature. An ASP system typically uses a positive pressure system to control aeration based on pile temperature. ASP systems may lead to higher GHG emissions than windrows due to a shorter active composting process and higher energy use (Levis and Barlaz 2011).

GHG emissions for the compost destination in this methodology include transportation of food waste of 25 miles by diesel truck (EPA WARM v16), fugitive CH_4 and N_2O emissions from composting facility, energy consumption in the facility, avoided fertilizer production equivalent to the nitrogen/phosphorus (N/P) content of the final compost product applied to soil, and stored carbon in soils from applied compost.

- **GHG emissions from transportation and process energy:**
  - GHG emissions associated with collection and transportation of the food waste to composting facilities were also estimated based on WARM v16 Section 4-Composting. The food waste was assumed to be transported by a diesel short-haul truck over 25 miles.

    - 0.24 kWh/wet tonnage of food waste is required to turn the windrows (Levis and Barlaz 2021).
- **Fugitive GHG emissions**: During the process of turned windrows composting, food waste is formed into rows of piles, and releases fugitive CO_2 (neutral), CH_4, and N_2O emissions during aerated composting. This methodology assumes:
    - Approximately 57% and 1% of the initial carbon content is emitted as CO_2 and CH_4, respectively (Beck-Friis et al., 2000; Levis and Barlaz, 2011) during the composting process.
        - 1.7% of the emitted C (58% of total carbon) is assumed to be emitted as CH_4, which equals 0.99% (i.e. 1%) of the initial carbon.
    - During the curing or stabilization process, and after compost is applied to land, 52% of C in compost will be released as CO_2.
        - (1-58%) = 42% remaining C after CO_2 and CH_4 emissions.
        - 52% of 42% = 21.84% of initial carbon content is released as CO_2 during curing (compost stabilization).
        - 42%-21.84% = 20.16% remaining in the cured compost to be stored in soil.
    - The remaining carbon (approximately 20% of initial carbon content) is assumed to ultimately be stored in soil after being applied to land. This is the same assumption used in EPA WARM v16.
    - About 0.4% of the initial nitrogen is emitted as N_2O and the remaining nitrogen stays in compost (Levis and Barlaz, 2011).
- **Avoided GHG emissions**: Compost includes nitrogen, phosphate, and potash, which is beneficially used for soil amendment and assumed to offset the use of synthetic fertilizers.
    - GREET (2023) was used to estimate the avoided emissions by displacing synthetic N/P fertilizer production with compost for soil amendment.
    - 4.09 kg N fertilizer and 1.38 kg P fertilizer per composted wet tonnage of food waste have been avoided, respectively (GREET 2023).

As an inorganic compound, sending salt to the compost destination was assumed to carry the impacts of composting but none of the fugitive gas emissions and benefits of avoided fertilizer.

3.7 Anaerobic Digestion

The destination of anaerobic digestion (AD) is considered valid for all supply chain stages and all food items. The AD operation modeled in this methodology to estimate GHG emissions from anaerobically digesting food waste is a stand-alone centralized facility, with a national average generated to capture the use of both wet and dry systems for digestion, and the beneficial use or flaring of biogas produced.

- **GHG emissions from transportation and process energy:**
    - GHG emissions associated with transportation of food waste was assumed to be 200 miles via a diesel haul truck (EPA WARM v16).
    - The underlying process energy required for the wet and dry AD configurations is based on the WARM v16 model but calculated in the GREET 2023 tool. Both wet and dry AD consume electricity and diesel for preprocessing (e.g., grinding, screening, and mixing the waste feedstock).

        - Wet AD reactors contain more water and require higher electricity consumption for pumping and stirring waste feedstock than dry AD. In wet AD, digestate requires dewatering prior to being applied to soil.
        - Dry AD involves more solids than wet AD and requires higher diesel fuel consumption in front-end loaders for stacking materials (EPA WARM v16).
    - Field data indicates a split of 89% and 11% between wet and dry AD systems in the United States for stand-alone food waste AD facilities (EPA, 2019).
- **Fugitive GHG emissions:**
    - The CH_4 concentration in AD biogas (which is a combination of $CH_4 + CO_2$) is assumed to be 50%. In both wet and dry AD systems, it was assumed that 90% of the ultimate CH_4 yield of food waste (72 kg CH_4/wet metric ton of food waste with a 73% moisture content) could be reached under AD (EPA WARM v16).
    - The EPA's food waste AD facilities survey in 2023 (2019 data) reported that 86% of standalone AD facilities beneficially used the biogas produced, and 14% flared it (EPA, 2023).
        - In AD with biogas flared, a 5% CH_4 leakage and 95% to flare was assumed.
        - In AD with biogas beneficially used, EPA estimated a 2% CH_4 leakage, 15% to flare, and 83% converted for electricity recovery (EPA WARM v16).
        - The methane leakage rate is higher in the flare system than the energy recovery (beneficially used) system because there is lower CH_4 destruction efficiency. Internal combustion engines equipped for energy recovery systems generally provide more consistent and slightly higher efficiencies due to their controlled combustion processes.
    - N_2O emissions were calculated based on the assumptions that 1% of initial nitrogen content that is lost as N2O emissions during digestate curing process. During the land application stage, an additional 2.3% of N applied as fertilizer is lost as N_2O.
- **Avoided GHG emissions:**
    - It was assumed that all beneficially used AD biogas is used to generate electricity and avoids the impact of US national average electricity consumption (calculated in GREET 2023). Expert opinion and anecdotal evidence indicate that dry AD may result in lower biogas yields, but without concrete data in the literature to quantify the difference, this methodology assumes the same biogas yield for both wet and dry AD systems.
    - In both wet and dry AD systems, solid digestate is assumed to be aerobically cured and applied to land. It was estimated that 10% of the initial carbon is eventually sequestered. Nutrients in digestate were assumed to displace synthetic fertilizer, generating avoided emissions based on GREET (2023).

As an inorganic compound, salt was assumed to carry the impacts of AD, but not any fugitive gas emissions or energy production via biogas.

It is important to note that impacts from AD are highly dependent on system credits – the difference in grid energy mix that is replaced - and system boundary (i.e., scope of energy demand and operation, inclusion or exclusion of curing and land application). Assuming that biogas is displacing or avoiding the production of energy from a low carbon intensity grid (based partially on renewable solar or wind) leads to lower GHG "savings" from the beneficial use of AD biogas. Curing

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and composting of final digestate prior to land application for fertilizer offset can also add extra energy demand and fugitive N2O emissions to the final GHG figure.

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3.8 Land Application

The land application destination is considered valid for all supply chain stages and all food items. The biochemical process and carbon storage due to land application was modeled in the same way as composting. The only non-biogenic emissions contribution is from the use of machinery.

- **GHG emissions from transportation:**
  - 6.25 L of diesel per metric ton of dry matter was considered to transport food waste to milling sites (Batuecas et al., 2019)
- **Fugitive GHG emissions:**
  - Food waste applied to land is assumed to degrade aerobically, and only N_2O emissions and carbon storage are included in GHG emissions accounting.
  - As assumed in the composting destination, 0.4% of nitrogen is released as fugitive N_2O emissions.
- **Avoided GHG emissions:**
  - 20% of biogenic carbon is assumed to remain sequestrated in soil (see detailed explanation in Section 3.6 Compost)
  - For avoided emissions associated with fertilizer production, the N and P nutrients in applied food waste were assumed to replace N/P fertilizer production in proportion to their N and P content.
- The emission factors for fertilizer production were based on agricultural chemical pathways in GREET (2023).

3.9 Not Harvested

This destination is assumed to only be valid at the farming stage and only for the produce category as well as almonds (under dry goods) that are directly produced on farms. Reported GHG emissions and offsets are calculated compared to the reference situation where all food items are harvested for human consumption. It is assumed that unharvested nuts, fruits and vegetables are left to decompose aerobically (scattered, not piled) on fields, so no CH_4 emissions are considered. The only GHG considered is N_2O, considering 0.4% of N content in unharvested food released as fugitive emissions (like for Land Application and Composting). As with those other two destinations, fertilizer offsetting (based on N-P content of unharvested food) and soil carbon storage has been assumed, considering that 20% of the total carbon content in the organic matter will stay in the soil (see detailed explanation in Section 3.6 Composting) . The rest of the carbon in unharvested food is released as biogenic CO_2 (with a neutral climate change impact).

3.10 Incineration | Combustion with Energy Recovery

The incineration destination was considered valid for all supply chain stages and for all organic food types and is based on mass burn and refuse-derived fuel (RDF) facilities. According to a U.S.

industry survey, 79% of incinerated waste is sent to mass-burn and the remaining 21% sent to RDF facilities (Energy Recovery Council, 2018).

- Net GHG emissions:
  - In total, including avoided emissions from produced energy and the energy required to evaporate the water content of food waste sent to incineration, mass-burn incinerators emit 140.44 kg CO_2e/dry ton food waste while RDF incinerators emit 174.78 kg CO_2e/dry ton food waste.

- **GHG emissions from transportation and process energy:**
  - The waste is transported 75 miles by diesel truck to the incineration destinations (EPA WARM v16).
  - Energy required to evaporate water weight in food items is included. The latent heat of vaporization of water is 2.257 MJ/kg water, which is equal to 0.63 kWh of kg water required for evaporation during the incineration.
- **Fugitive GHG emissions:**
  - A 2% downtime was assumed for the internal combustion engines used for MSW incineration, and 98% of carbon converted to CO_2, according to WARM (EPA, 2023).
  - 0.52 kg N2O emissions/dry t food waste was assumed as measurable from direct combustion. This value is based on EPA WARM v16 which refers to an average value from a range of six municipal solid waste incinerators given reported in IPCC complication.
- **Avoided GHG emissions:**
  - Both incinerator types are assumed to generate electricity. A U.S. mix grid was assumed as the offset for electricity substitution to calculate avoided emissions. For the two types of facilities:
    - Electricity generation through mass-burn incineration was estimated using a weighted average generation efficiency of 21.4% for MSW-fired power plants based on 2020 operational data (EIA Survey Forms).
    - Electricity generation through RDF was estimated given an industry report generation efficiency of 16.3% (EPA WARM v16).
    - An improvement was made on previous modeling to account for food type-specific energy content, since the energy content or calorific value of a material determines the amount of energy released during combustion. Standard expected electricity generation, which as noted above varies by facility type, is redefined as a function of energy content using an estimate of energy content for bulk food waste (expressed as Lower Heating Value or LHV of 5513 MJ/ dry tonne food waste) (EPA WARM v16), and then scaled to the item-level using food item-specific energy content values from USDA's FoodData Central database. Therefore, items with a higher energy content are assumed to generate greater GHG "savings" if incinerated.

The activity breakout of combustion-related emissions and energy production is shown in Table 15.

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Table 15: Activity breakout of combustion emissions and energy production

Activity Type	Activity and Emissions Breakdown	Incinerator Type	
		Mass-burn	RDF
Fugitive Emissions from Direct Combustion	Fossil CO_2 from combusting fossil C (kg/dry t food waste)*	88.89	88.89
	N_2O emissions (kg/dry t food waste)	0.52	0.52
Energy Benefits	Electricity production (kWh/dry t food waste)	325.93	248.15
	Electricity production (kWh/MJ)	0.06	0.05

*Note: (1) Food waste may contain a trace amount of fossil C (0.01 kg fossil-C/kg dry matter) from food additives (2) Biogenic CO_2 emissions from burning food waste are not accounted for as the Neutral CO_2b method is being applied and biogenic carbon emissions carry zero impact on global warming.

3.11 Landfill

The landfill destination is considered valid for all supply chain stages and all food types. Food waste disposed in landfill contains carbon that will be anaerobically decomposed by microbes, producing landfill gas (LFG). LFG is about 50% CO_2 and 50% CH_4. If any LFG escapes to the atmosphere without being oxidized in the soil, the CO_2 portion is considered biogenic and to have no impact. LFG can be captured and used as a feedstock for generating electricity, heat, and renewable natural gas (RNG).

GHG emissions modeled include transportation of food waste, energy consumption for landfill operation, fugitive LFG (i.e., CO_2 and CH_4 emissions), avoided utility emissions, and sequestered carbon from landfilled food waste.

The impacts of landfills were calculated and extracted from GREET 2023 for multiple archetypes that are classified by (1) U.S. climate regions (arid, moderate, wet), which influences the waste decay rate, and (2) according to treatment of LFG (passive venting, flare, energy recovery), which influences the fugitive emissions type and rate.

Landfilling of salt, as an inorganic compound, was assumed to carry the impacts of the destination and transport, but not any fugitive gas emissions due to zero carbon content.

3.11.1 National Average Landfill Assumptions

- GHG emissions include transportation of food waste over 150 miles to landfills via diesel haul truck (EPA WARM v16).
- Three climate regions were used to represent the range of mean annual precipitation (cm/yr) that a U.S. landfill might experience. Corresponding bulk MSW decay rate constants are used to define the speed of decomposition in each region (see Table 16). Higher precipitation accelerates decomposition, leading to a higher waste decay rate and therefore a faster release of CH_4.
- Bulk MSW decay rate is the speed of MSW mixture which is composite of different waste components. The bulk decay rate is a function of moisture conditions and influences the longevity of gas collection and control system.
- Different components degrade at different rates relative to bulk MSW decay rate (De la Cruz and Barlaz 2010)

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2. Text has been reorganized and divided above.
3. Missing gap is the first half sentence: "In total, including avoided emissions from produced energy and the energy required to evaporate the water content of food waste sent to incineration, mass-burn incinerators emit 140.44 kg CO2e/dry ton food waste while RDF incinerators emit 174.78 kg CO2e/dry ton food waste. "

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- De la Cruz and Barlaz (2010) scaled experiment-measured component-specific decay rate to field-scale values, assuming that the weighted average decay rate for a waste mixture of the same composition as MSW would be equal to the bulk MSW decay rate.
- The field decay rate was adopted from WARM v16 (EPA, 2023) and De la Cruz and Barlaz (2010). Rate of decay influences the amount of fugitive landfill methane emissions based on the selected time horizon (i.e., 20-yr vs. 100-yr) since LFG emissions are released over decades.
  - For example, food waste disposed in a landfill located in an arid region only produces 64% of the total CH_4 by year 20, but over 99% by year 100 (Wang et al. 2021).
  - Tables 18a and 18b summarize the proportion of CH_4 emitted and oxidized considering the CH_4 generated from food waste decay on 100- and 20-year time horizons. The estimates are provided for each climate region and gas treatment. Table 18a and Table 18b show the estimates for EPA Typical and NSPS Minimum collection schedules and efficiencies, respectively.
- Three landfill gas (LFG) treatment scenarios are considered to represent common gas treatment practices in the US: passive vent, flare, and conversion to energy. The treatment scenario determines the timing and the form of the gas release (methane emissions without collection, burning off to CO_2, and beneficial use of methane, respectively).
- An average U.S. landfill is modeled using the distribution across climate and gas treatment scenarios shown in Table 16 (USGHGI 2022; LMOP 2022).

Table 16: US average shares of MSW disposed in each climate under each gas treatment scenario

Climate Regions (annual precipitation)	Bulk MSW Decay Rate	Field Decay Rate of food[a]	Three Gas Treatment Scenarios		
			Passive Venting	Flare	Energy Recovery
Arid (<51 cm/yr)	0.02 yr^{-1}	0.07 yr^{-1}	1%	5%	8%
Moderate (51-102 cm/yr)	0.04 yr^{-1}	0.14 yr^{-1}	1%	7%	18%
Wet (>102 cm/yr)	0.06 yr^{-1}	0.29 yr^{-1}	5%	18%	36%

[a]Values are adopted from WARM v16 (EPA, 2023) and De la Cruz and Barlaz (2010).

- Carbon not released in the chosen time horizon is considered as sequestered carbon. Twenty percent of initial biogenic carbon content is assumed to ultimately be stored (i.e., after 100 years for food waste) (EPA WARM v16). Note there will be more carbon stored temporarily if the time horizon is cut shorter (e.g., 20 years) for analysis.

3.11.2 Landfill Gas Generation, Collection, Oxidation, and Emissions Assumptions

- The carbon in LFG is from anaerobic biodegradation of biomass in landfill and is thus all biogenic. This carbon can be assumed to be 50% CH_4, with the rest being CO_2, prior to oxidation in the topsoil.
- Similar to EPA's WARM model v16, LFG generation is estimated using methane yield (267 kg CH_4/dry metric ton food waste) and the carbon storage factor (100 kg carbon/dry metric ton) from Barlaz (1998). This methane yield is the maximum CH_4 generation potential given optimized conditions and across the entire life MSW as disposed in landfill.
- The lifetime gas collection efficiency is the proportion of gas collected over the total gas generated. The efficiency rate for an average sized US landfill was adopted from Wang et al.

Commented [39]: I think we're now missing the difference between the bulk MSW decay rate and field decay rate, since the table footnote has been edited

Commented [CA40R39]: I believe the extra detail of the calculation in the footnote was taken out for clarity; it was very technical/in the weeds and might be causing more confusion than necessary…. But it might be helpful to include simple definitions of each type of decay rate? @Wang, Wendy

Commented [41]: Minnie: I presume this is literally ALL types of waste (otherwise we'd need to alter title to say 'food waste). Also presume that if this is all waste, the assumption is that food wasting nationally mirrors the waste so that we can say it's 36% of waste (OR food waste) that goes to a landfill located in a wet region using energy recovery. I'm pulling that 36% from the bottom right hand corner. If you're understanding is different, let's check with Quantis.

Commented [CA42R41]: @Wang, Wendy all comments on this page are related - is this ALL waste or food waste specifically?

Commented [WW43R41]: It is all MSW but it does not matter because it is percentage which should remain the same as long as the composition of food waste in MSW in each climate region is assumed the same.

Commented [44]: same understanding, but let's check anyway!

(2021). Gas collection involves phased-in collection with an improved cover. Two scenarios are considered in the methodology. EPA's typical collection scenario represents the average US landfill and the New Source Performance Standards (NSPS) minimum requirement represents a more conservative scenario with a longer time until gas collection (see Table 17).

Table 17: EPA Typical and the most conservative New Source Performance Standards (NSPS) gas collection schedule and efficiencies (adopted from Table S11 from Wang et al. 2021)

Underlying Parameters	EPA Typical Collection	NSPS Minimum
Time until initial gas collection (yr)	2	5
Initial gas collection efficiency (%)	50	50
Time to increased gas collection efficiency (yr)	5	10
Increased gas collection efficiency (%)	75	75
Time from initial waste placement to long term cover (yr)	15	15
Gas collection efficiency under long term cover (%)	82.5	82.5
Time from final waste placement to final cover (yr)	1	1
Gas collection efficiency under final cover (%)	90	90
Gas to Flare Inputs		
Non-methane organic compounds emission rate at which gas collection is turned off (metric ton/yr) (NSPS, 2016)	34	34
Flare turn-on time (yr)	2	5
Flare turn-off time (yr) by decay rate		
Arid (food decay rate = 0.07 yr^{-1})	113	113
Moderate (food decay rate = 0.14 yr^{-1})	100	100
Wet (food decay rate = 0.29 yr^{-1})	95	95
Gas to Energy Inputs		
Minimum landfill gas collection required for an energy recovery project (m^3/min)	10	10
Energy recovery engine downtime (%)	3	3
Energy system turn-on time to turn-off time (yr to yr) by decay rate		
Arid (food decay rate = 0.07 yr^{-1})	10-170	12-170
Moderate (food decay rate = 0.14 yr^{-1})	6-128	8-128
Wet (food decay rate = 0.29 yr^{-1})	5-112	7-112

- **Methane Emissions:**
  - Total landfill methane emissions subtract the LFG collected and oxidized from the LFG generation rate by the chosen time horizon: CH_4 emissions = CH_4 generation – CH_4 collection (flared or converted to energy) – CH_4 oxidation.
    - A fraction of the uncollected CH_4 is oxidized to CO_2 in the landfill topsoil, and the remaining fraction is fugitive emissions.

- The fraction of CH_4 oxidized is varied from 10% to 35%, based on U.S. EPA guidance (EPA WARM v16). When no gas collection is in place, the landfill has a relatively high CH_4 flux and 10% oxidation efficiency. Twenty percent and 35% oxidation rates are assumed for landfills with gas collection prior to landfill closure and after the final cover is placed, respectively.

Tables 18a and 18b show for the two scenarios (EPA Typical versus NSPS, respectively) the end results of CH_4 generated, which are applied with CH_4 yield and time horizon adjustment percentages to calculate the shares of CH_4 flared, recovered for energy, oxidized and emitted. E.g., CH_4 emissions$_{food,arid,\ flare}$ = CH_4 yield$_{food}$ * % adjustment by year 100$_{food,arid}$* %CH_4 emitted$_{food,arid,flare}$.

Table 18a: Results of CH_4 generated that is flared, converted to energy, oxidized, and emitted across two time horizons, three climate regions, and three gas treatment scenarios under the EPA Typical gas collection schedule (Wang et al. 2021)

Time Horizon	% CH_4 generated	Climate Region	Gas Treatment Scenario	Gas Collection Schedule	% CH_4 Flared	% CH_4 Converted to Energy	% CH_4 Oxidized	% CH_4 Emitted
100-yr	99%	Arid	Passive Venting				10%	90%
	100%	Moderate	Passive Venting				10%	90%
	100%	Wet	Passive Venting				10%	90%
	99%	Arid	Energy Recovery	EPA Typical	4%	72%	5%	19%
	100%	Moderate	Energy Recovery	EPA Typical	3%	66%	6%	24%
	100%	Wet	Energy Recovery	EPA Typical	3%	62%	7%	29%
	99%	Arid	Flare	EPA Typical	72%	0%	6%	21%
	100%	Moderate	Flare	EPA Typical	68%	0%	7%	26%
	100%	Wet	Flare	EPA Typical	64%	0%	7%	29%
20-yr	64%	Arid	Passive Venting				10%	90%
	87%	Moderate	Passive Venting				10%	90%
	95%	Wet	Passive Venting				10%	90%
	64%	Arid	Energy Recovery	EPA Typical	5%	66%	6%	23%
	87%	Moderate	Energy Recovery	EPA Typical	3%	64%	6%	26%
	95%	Wet	Energy Recovery	EPA Typical	3%	61%	7%	29%
	64%	Arid	Flare	EPA Typical	71%	0%	6%	23%
	87%	Moderate	Flare	EPA Typical	67%	0%	6%	26%
	95%	Wet	Flare	EPA Typical	64%	0%	7%	30%

Table 18b: Results of CH_4 generated that is flared, converted to energy, oxidized, and emitted across two time horizons, three climate regions, and three gas treatment scenarios under the NSPS Minimum gas collection schedule (Wang et al. 2021)

Time Horizon	% CH_4 generated	Climate Region	Gas Treatment Scenario	Gas Collection Schedule	% CH_4 Flared	% CH_4 Converted to Energy	% CH_4 Oxidized	% CH_4 Emitted
	99%	Arid	Passive Venting				10%	90%
	100%	Moderate	Passive Venting				10%	90%
	100%	Wet	Passive Venting				10%	90%
	99%	Arid	Energy Recovery	NSPS Minimum	4%	67%	5%	24%
100-yr	100%	Moderate	Energy Recovery	NSPS Minimum	3%	57%	6%	34%
	100%	Wet	Energy Recovery	NSPS Minimum	3%	49%	7%	41%
	99%	Arid	Flare	NSPS Minimum	67%	0%	7%	27%
	100%	Moderate	Flare	NSPS Minimum	58%	0%	7%	35%
	100%	Wet	Flare	NSPS Minimum	51%	0%	7%	42%
	64%	Arid	Passive Venting				10%	90%
	87%	Moderate	Passive Venting				10%	90%
	95%	Wet	Passive Venting				10%	90%
	64%	Arid	Energy Recovery	NSPS Minimum	5%	58%	6%	31%
20-yr	87%	Moderate	Energy Recovery	NSPS Minimum	3%	53%	7%	37%
	95%	Wet	Energy Recovery	NSPS Minimum	3%	48%	7%	43%
	64%	Arid	Flare	NSPS Minimum	63%	0%	6%	31%
	87%	Moderate	Flare	NSPS Minimum	56%	0%	7%	37%
	95%	Wet	Flare	NSPS Minimum	50%	0%	7%	43%

- **Avoided GHG emissions**:
  - EPA's LMOP landfill and LFG energy projects database estimated that 69%, 8%, and 23% of the total CH_4 generated from energy projects in the U.S. are beneficially used to produce electricity, heat, and RNG, respectively (LMOP, 2022).
    - LFG to electricity: 4.2 kWh of electricity produced per kg of CH4 combusted in internal combustion engine is estimated in GREET 2023 based on an electricity conversion efficiency of 30% (i.e., weighted average electricity conversion efficiency from LFG-powered electric plants reported in EIA-923 form) and an average lower heating value of landfill methane (962.2 Btu/ft^3 CH4).
    - LFG to direct thermal heat: 37,913 Btu of heat produced per kg of CH4 combusted in boiler is estimated in GREET 2023 based on a thermal

Commented [45]: is it easy to model what % of the total lifetime CH4 emitted escapes in the first year/before gas collection begins, based on the decay rate? (not asking Quantis to do so, just checking feasibility)

Commented [WW46R45]: It is feasible via a dynamic (i.e., time varying yearly landfill carbon emissions and GWP) landfill LCA which has been published in my previous academic article Wang et al. 2019 "An Assessment of the Dynamic Global Warming Impact Associated with Long-Term Emissions from Landfills" https://pubs.acs.org/doi/10.1021/acs.est.9b04066 conversion efficiency of 80% and an average lower heating value of landfill methane (962.2 Btu/ft^3 CH4).

- LFG upgraded to renewable natural gas (RNG): 47,392 Btu of RNG produced per kg of CH4 combusted is estimated in GREET 2023 based on an average lower heating value of landfill methane (962.2 Btu/ft^3 CH4).

- Avoided GHG impacts for food waste are estimated using these GREET-embedded emissions factor for electricity, heat, and RNG generation (Table 19). The final values that represent the net production of electricity, heat, and RNG per dry tonnage of food waste are presented in Table 20.

Commented [47]: just to confirm my own understanding - this is all captured in the Excel in the LFG to electricity section?

Commented [WW48R47]: Heat and RNG is not split out in excel. But results have embedded everything.

Commented [49]: Also seems like an edit would help to clarify. Is what I changed this too correct based on your read of the Excel?

Commented [CA50R49]: @Wang, Wendy confirm accuracy of sentence since Kai edited!

Table 19: Carbon intensity for electricity, heat, and renewable natural gas (RNG) production under 100-yr and 20-yr time horizons, which are estimated in GREET et al. 2023.

Carbon Intensity Category	Carbon Intensity Category	Value of Carbon Intensity	Unit
US mix electricity production	100-yr	0.44	kg CO2e/kWh
	20-yr	0.485	kg CO2e/kWh
Heat production	100-yr	0.086	kg CO2e/MJ
	20-yr	0.099	kg CO2e/MJ
RNG production and combustion	100-yr	0.013	kg CO2e/MJ
	20-yr	0.023	kg CO2e/MJ

Table 20: Results of generation rate per dry tonnage of bulk food waste of electricity, heat, and renewable natural gas (RNG) from landfill gas combustion across two time horizons, three climate regions, and US weighted average under the NSPS Minimum and EPA Typical gas collection schedule (Wang et al. 2021; GREET et al. 2023)

Climate Region	Gas Collection Scenario	Time Horizon (yr)	Electricity (kWh/dry t)	Heat (MJ/dry t)	RNG (MJ/dry t)
Arid	EPA Typical	100-yr	-551	-611	-2196
	NSPS minimum	100-yr	-513	-568	-2043
	EPA Typical	20-yr	-322	-357	-1285
	NSPS minimum	20-yr	-284	-315	-1131
Moderate	EPA Typical	100-yr	-510	-566	-2032
	NSPS minimum	100-yr	-440	-488	-1755
	EPA Typical	20-yr	-426	-473	-1700
	NSPS minimum	20-yr	-357	-396	-1422
Wet	EPA Typical	100-yr	-474	-526	-1889
	NSPS minimum	100-yr	-379	-420	-1510
	EPA Typical	20-yr	-444	-492	-1770
	NSPS minimum	20-yr	-349	-387	-1391
US Weighted Average	EPA Typical	100-yr	-305	-338	-1216
	NSPS minimum	100-yr	-256	-284	-1020
	EPA Typical	20-yr	-260	-289	-1038
	NSPS minimum	20-yr	-212	-235	-846

3.12 Sewer

The sewer destination is considered valid for all supply chain stages and all food types. The GHG impact of food discarded down the sewer includes the impact of operating the sewer collection network, as well as infrastructure impacts and fugitive CO_2, CH_4, and N_2O emissions of organic waste at wastewater treatment plants, i.e., a Water Resource Recovery Facility (WRRF).

3.12.1 Sewer Collection Network and Emissions Assumptions

- Emissions for the sewer pathway were estimated using data from Song et al. (2023). This article quantified average methane emissions per m^3 wastewater using monitoring campaigns from municipal wastewater collection and treatment and therefore included emissions from all materials present in sewage, not just food waste. To determine the emissions specifically from food waste the following information was used:
    - It was assumed that 15% of food waste from households ends up in garbage disposals which are connected to sewers[22], and 0.44 kg of food waste[23] and 0.69 m^3 of municipal wastewater[24] are generated per person per day, so 0.1 kg/m^3 of food waste is found in sewer wastewater on average.
        - Assuming food waste has a water content of 73%, then applying these assumptions in the following equation results in the estimate of 0.02 kg of dry t food waste present in each m^3 -of wastewater produced.
        - Calculation: 0.44 kg food waste/capita-day * 15% / (0.69 m^3 wastewater/capita-day) / (1-73%) = 0.02 kg of dry t of food waste per m^3 wastewater produced
    - Methane emission factors for all plausible archetypes were applied from Song et al. (2023) and allocated to food waste only using the calculated food waste mass that ended up in municipal sewer (i.e., 0.02 kg of dry food/m^3 wastewater). Although this is likely not the case, this assumes that all wastewater components contribute equally to methane emissions based on mass.
- **GHG emissions**:
    - **Emissions from grinding in home garbage disposal**
        - The energy required for daily grinding of food material in household sinks over the course of a year was taken from Bolzonella et al. 2003. Associated emissions were then calculated using a national average GHG intensity for the electricity grid mix.
    - **Emissions during sewer collection:**
        - Two sewer collection network systems (gravity and rising main) were considered. In the US, 92.5% of the public network uses gravity sewer while the rest 7.5% uses rising main sewer (Song et al. 2023).

[22] EPA 2020. Wasted food measurement methodology scoping memo. https://www.epa.gov/sites/default/files/2020-06/documents/food_measurement_methodology_scoping_memo-6-18-20.pdf

[23] EPA 2018. National overview: facts and figures on materials, wastes and recycling. EPA 2024, accessed https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#composting

[24] EPA. The use of reclaimed water and sludge in food crop production. https://www3.epa.gov/npdes/pubs/mstr-ch2.pdf

Commented [CA51]: @Stern, Alexandra tagging you here generally for any sewer updates/clarifications based on your work this past week and the handful of comments/questions from Kai and Minnie in this section

Commented [52]: In the Excel, it looks like the 0.1kg is the weight of food in wastewater, not sludge - and is calculated based on the previous 3 datapoints, not taken from the EPA report.

Commented [53]: This sounds like definitely a question for Quantis to check on.

Commented [54]: I think this means that we're assuming all those methane emissions come from the small volume of food waste. We're missing the scaling down factor: i.e. % of all sewer organic constituents that is food material - and that's probably why the sewer estimate is an entire order of magnitude greater than all other pathways.

Commented [55]: Added this: Quantis to check for accuracy

Commented [SA56R55]: Ok

        - Sewer collection networks, including gravity sewers and rising mains, collect and convey sewage to nearby WRRFs. Biological reactions which produce methane may occur in this collection and conveyance stage from biofilms that grow on wet pipe surfaces. Gravity sewers typically promote aerobic processes and lower methane production (0.7±0.2 mg/L), and rising mains promote anaerobic processes and higher methane production (5.6±1.8 mg/L) (Song et al. 2023).
    - **Emissions during sewer sludge treatment at WRRFs**: Food waste solids will be separated from wastewater at the WRRF through various treatment processes. Three archetypes for WRRF plant systems (no AD, AD in place, and stabilization ponds) -were included, with the respective shares of these archetypes in the U.S. market taken from a survey from Song et al. (2023).
        1. WRRF with AD (86% of the WRRF plants in the US)
        2. Other WRRF without AD, excluding stabilization ponds (81.6% of the WRRF plants in the US)
        3. WRRF with stabilization ponds (9.8% of the WRRF plants in the US)
            - Stabilization ponds are a subset of WRRF without AD but separated out as a stand-alone archetype because stabilization ponds were found to have significantly higher mean emissions at 49.5 (35.1–63.9) g CH_4/m^3, ~20 times and ~4 times larger than the emissions from the other WRRFs without AD and WRRF with AD, respectively.
            - A major driver of higher CH_4 emissions is that stabilization ponds generally enable open anaerobic organic degradation and they are commonly used in community-level wastewater treatment, which generally do not have accurate operational controls or sufficient and ubiquitous aeration.
    - The other key GHG contributor is N_2O emissions from wastewater treatment. N_2O emissions were estimated assuming that the 30% of nitrogen in food waste is present in soluble form (M. Kim et al. 2015) and 0.04 kg N_2O is released per kg of N-influent from activated sludge treatment (Ahn et al. 2010).
- **Avoided GHG emissions**: Avoided emissions from energy recovery, if under WRRF with AD, might have been embedded in the cited literature reported EFs but cannot be split out due to lack of visibility of raw data.
- End uses of biosolids and wastewater effluent (beneficial or otherwise) are not included.

The assumptions for salt differed from the other foods included in this methodology because it is inorganic. Sending salt to the sewer destination was assumed to carry the impacts of wastewater treatment but not any fugitive gas emissions.

Commented [57]: Is this what's considered "leaks from pipes"? are these included in the model? I think so - rows 27 and 28. But in that case, believe this should be included in the GHG emissions section as shown now

Commented [SA58R57]: Yes

Commented [59]: Reworded and moved some things around. Quantis to check for accuracy

Commented [SA60R59]: Ok

Commented [61]: Minnie added this. Quantis to confirm accuracy of the statement

Commented [SA62R61]: Yes

4 | Results & Conclusions

Upstream Life Cycle Impacts

The general trends for upstream climate impacts are aligned with existing scientific literature showing high production-level impact attributed to enteric emissions from cattle and land-use change (LUC) for certain food items - cheese, chocolate, coffee, as examples. Furthermore, the upstream agricultural production impacts (referred to in this methodology as farm-level impacts) generally dominate the total impact of food items except in cases of very high-yield items such as cereals. For these items, there is a larger share of impact generated in other life cycle stages.

The total GHG emissions by value chain stages are shown by food item in Figure 4 and methane-specific emissions by value chain stages are shown in Figure 5. Upstream methane emissions are mostly generated by the farming sector, with beef production being the largest contributor by a substantial margin. Note that for items not wasted at the farm stage (i.e., because they are multi-ingredient, processed, or otherwise manufactured items such as cake), these farm-stage impacts are included in the manufacturing stage (cradle to manufacturing gate) in Figures 4 and 5.

Commented [63]: Quantis to confirm:
1. I missed this before in reading this section and looking at Figure 4. Does this mean cheese has no emissions at the farm stage b/c it's a processed item?
2. Do we need to say 'cradle to manufacturing gate'? No harm in being repetitive if that means the same thing as the language before it

Commented [MH64R63]: 1. It means that the farm stage (milk) is included in the manufacturing stage and thus is cradle to manufacturing gate,
2. Thank you addition of a cradle to the manufacturing gate is helpful.

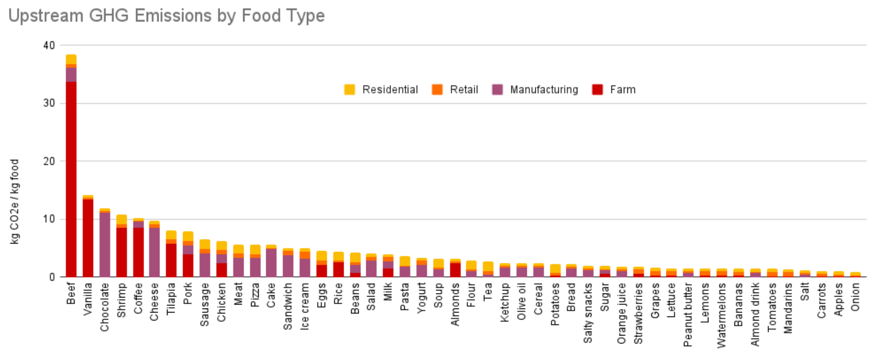

Figure 4: *Upstream GHG emissions if 1 kg of food is wasted across farm to residential stages, by food item.*

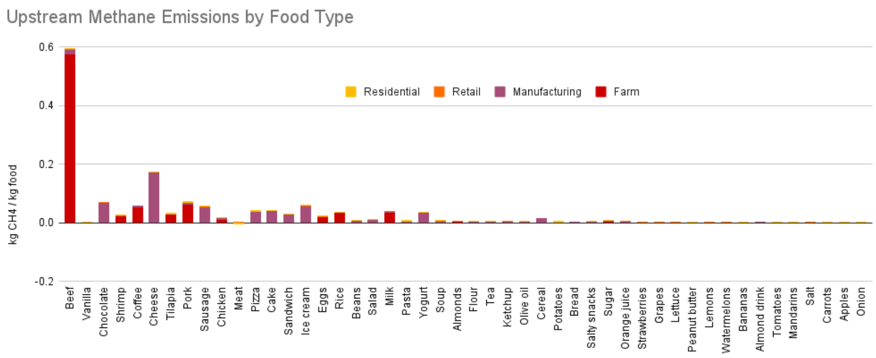

Figure 5: *Upstream CH4 emissions if kg of food is wasted loss across farm to residential stages, by food item.*

End-of Life (Destination) Impacts

Destinations can be roughly ranked according to GHG impact, regardless of food type. Note that negative GHG values represent net avoided GHG emissions, while positive values imply that more GHG emissions would be emitted during the processes at that destination than they would displace.

Figure 6 shows total GHG emissions by food item across destinations, where the most apparent trend is that sewer has a significantly higher impact than all other destinations. Figure 7 removes sewer, so the remaining destinations are more easily compared, revealing the following rough hierarchy, from least to most preferred, based on GHG emissions: Landfill, Incineration, Anaerobic Digestion, Not Harvested, Composting and Land Application, Animal Feed, Rendering/Industrial Uses, and Donation. These results generally mirror the preferences laid out by the EPA's Wasted Food Scale, although a few key areas of departure are apparent based on differences in underlying assumptions such as the avoided emissions modeled.

Figures 6 and 7 also illustrate that a food's properties (see Table 12) affect the GHG impact of different destinations, which is an important consideration if a material stream is composed of only a few food items.

- GHG impacts have an inverse relationship with water content for anaerobic digestion, landfill, and sewer destinations, where GHG impacts increase among higher dry matter food items. For composting, land application, and not harvested destinations, avoided emissions increase among higher dry matter food items.
- For incineration, GHG impact is driven by the energy content of the food item determining the level of avoided emissions (i.e., the higher the food's energy content, the higher the potential avoided GHG emissions).
- For animal feed and rendering pathways, the fat and protein content of the food item determines the type and amount of traditional feedstock that is substituted with food waste, thereby affecting GHG impact through avoided emissions.

While the carbon and nutrients in a food item's dry matter can offer environmental benefits, this depends on the output being valorized - i.e., through energy recovery during incineration or anaerobic digestion, or nutrient recycling through compost or land application. However, if the dry matter content is not further valorized (i.e., AD digestate is sent to a landfill rather than applied to land as is assumed in this methodology), the GHG emissions associated with the destination would be higher since the benefits of carbon sequestration or fertilizer avoidance are not realized.

Commented [65]: need to check order based on updated modeling from Quantis AND errors corrected by ReFED

Commented [66]: Minnie: I'm thinking it would be useful to mention something about how this lines up with the EPA Scale. As I tried to resort the list based on the latest data, this statement doesn't fully hold true. We can also say "This differs somewhat from the preferences suggested by the EPA's Wasted Food Scale as the assumptions underlying some of the destinations differed???" Still TBD what to say...

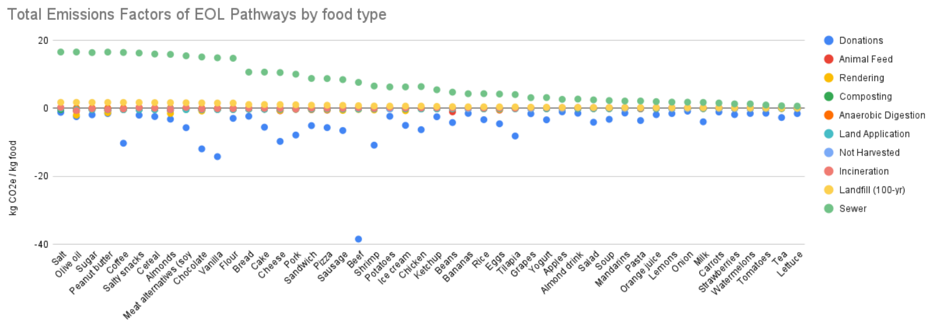

Figure 6: *Total GHG emissions (CO_2e) by food item for each end-of-life destination*

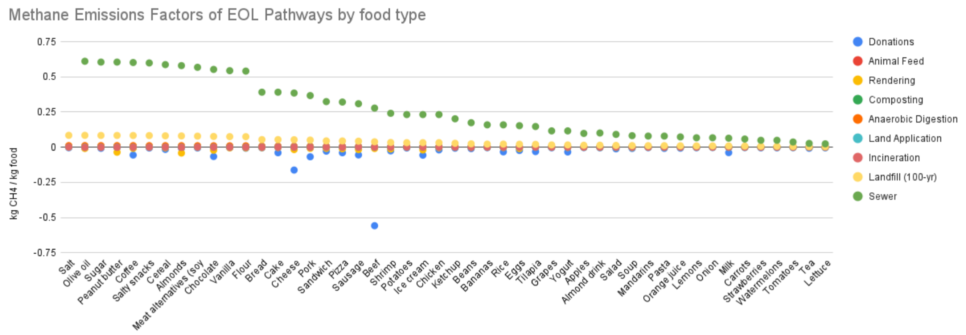

Figure 7: *Total GHG emissions (CO2e) by food item for each end-of-life destination (excluding sewer)*

Given that not all destinations produce methane, Figure 8 shows many destinations clustered at zero methane emissions. Of those that do, the sewer pathway produces the most methane, followed by landfill, then anaerobic digestion. The donation pathway is excluded from Figure 8 as methane emissions aren't generated from downstream activities.

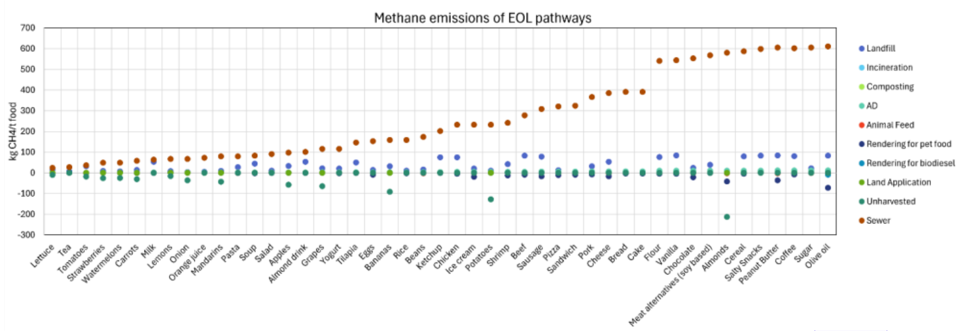

Figure 8: *Methane emissions (kg CH_4) by food item for each end-of-life destination (excluding donation)*

Commented [67]: ReFED to remove donation series from graph

Sewer may benefit from being considered separately from other destinations, since there is a lack of data specific to food waste treatment in the sewer system and this modeling indicates that in the U.S., the average impacts of sewer can be larger than the other pathways by over two orders of magnitude. It is important to note that GHG emissions vary substantially depending on which of the three treatment archetypes is being used: the adaptation from literature (Song et al. 2023) used in this methodology results in a range between 0.9-15.4 MT CO2e/t food waste across archetypes.

Additional Analysis of Landfill Impacts

Modeling the destination of landfill was a particular emphasis of this work, so a deeper level of analysis is provided.

1. **LFG capture for energy recovery often has lower emissions than flare scenarios.**

Energy recovery scenarios often lead to greater gas collection efficiencies (i.e., lower emissions, see Figures 9 and 10) than flare scenarios because energy systems collect LFG for longer than flares (see “turn-off times” in Table 17). Energy recovery systems are typically activated to generate revenue, while flare systems are required for minimum regulatory compliance once the federal emissions threshold is reached. Therefore, operators seeking to ensure that the revenue produced from the sold electricity is greater than the marginal costs required to operate the system are incentivized to allow the gas control system to run at a lower gas flow rate over a longer period of time. Gas collection for energy recovery is turned off when gas quality or quantity eventually declines past a cut-off, typically less than 10 m^3 LFG min^{-1}. Flare systems, on the other hand, can be turned off once NMOC generation is below 34 Mg yr^{-1}.

2. **Food decays faster in wet regions and will release more methane before control systems are in place. This has implications for the timing of installing gas control systems.**

Generally, landfills located in wetter climate regions have higher methane emissions compared to those in drier regions. This is because, typically, food waste degrades faster in wet regions and releases more CH_4 emissions before a gas collection and control system is even in place. In Figures 9 and 10, there is a more pronounced difference in emissions between NSPS Minimum and EPA Typical gas collection schedules in the wet climate region, since the NSPS Minimum schedule has initial gas collection beginning 3 years later than in the EPA Typical schedule.

3. **Because the majority of landfill emissions generated are methane, employment of a 20-year time horizon rather than the more conventional 100-year time horizon to calculate global warming potential (GWP) significantly influences the total emissions estimate.**

Figure 9 indicates that employing the shorter time horizon of 20 years to calculate GWP reduces the estimate of landfill methane emissions because not all carbon is emitted by year 20. This is irrespective of the gas treatment system, collection schedule or climate region. However, Figure 10 shows that the total GHG emissions for landfill are higher for the 20-yr time horizon than the 100-yr time horizon. While ostensibly less of the theoretical methane yield is captured in 20 years, the high GWP of methane in the shorter time horizon (82.5 kg CO_2e/kg CH_4 over 20-yr time horizon vs.

Commented [SA68]: this is not true -- delete.

Emissions with AD = 0.0125 kg ch4/m3 wastewater and w/o AD = 0.0025 kg ch4/m3 wastewater

Commented [69]: significant rewrite and reorder: Kai to see if you agree and Quantis to approve for accuracy

Commented [CA70R69]: @Wang, Wendy

Commented [71]: Quantis to provide its input on what the implication is for food waste management is meant to be based on points 1 and 2. See Minnie's note below about possibly combining 1 and 2?

Commented [SA72R71]: This is out of scope. This is a methodology document explaining the methods used to model impacts of EOL. Commentary on the model was not initially scoped.

Commented [73]: is there a way to compare these units?

Commented [SA74R73]: Out of scope

Commented [75]: can we calculate the %?

Commented [SA76R75]: out of scope

Commented [77]: Minnie: I reordered these points as I think this point is the more salient point here. Do you agree?

Either way, I think both the funder (GMH) and Dana may be particularly interested in how these conclusions are worded. So perhaps worth running by Dana or others?

Commented [78]: agree, let's keep this comment in as a reminder

29.8 kg CO_2e/kg CH_4 over 100-yr time horizon) outweighs the smaller amount of methane that is assumed to be emitted after year 20.

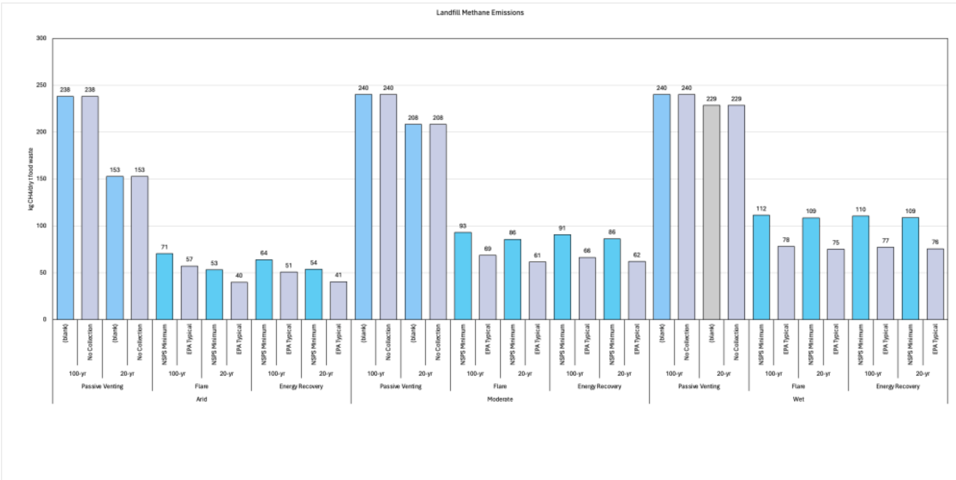

Figure 9: *For landfill, CH_4 emission factors (kg) based on 1 metric ton of dry matter in food waste across 100-yr and 20-yr time horizons, for three climate regions, and for three gas treatment scenarios under EPA Typical and NSPS Minimum gas collection schedules*

Commented [79]: Maybe later we can redo a figure to be more useful to the narrative. This has too much going on.

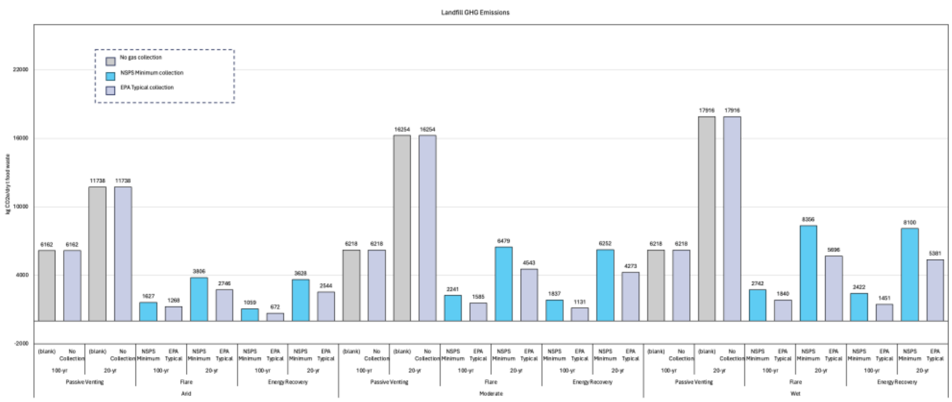

Figure 10: *For landfill, total GHG emission factors (CO2e) based on 1 metric ton of dry matter in food waste across 100-yr and 20-yr time horizons, three climate regions, and three gas treatment scenarios under EPA Typical and NSPS Minimum collection schedules*

No matter the time horizon used, the conservative gas collection schedule (i.e., NSPS minimum), results in 17% to 39% higher methane emissions compared to the EPA Typical scenario due to a longer period before gas collection and control begins, and the subsequent lower gas collection efficiency (see Figures 11 and 12).

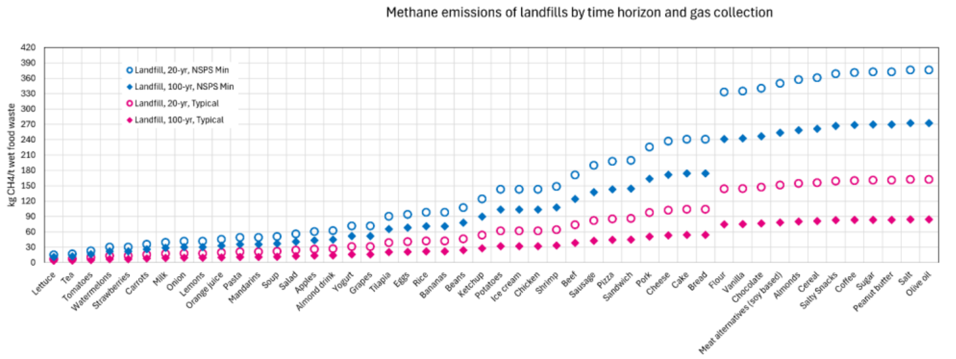

Figure 11: *For landfill, CH_4 emission factors based on unit mass of wet weight in food waste across 100-yr and 20-yr time horizons under EPA Typical and NSPS Minimum collection schedules (averaged across three climate regions and three gas treatment scenarios)*

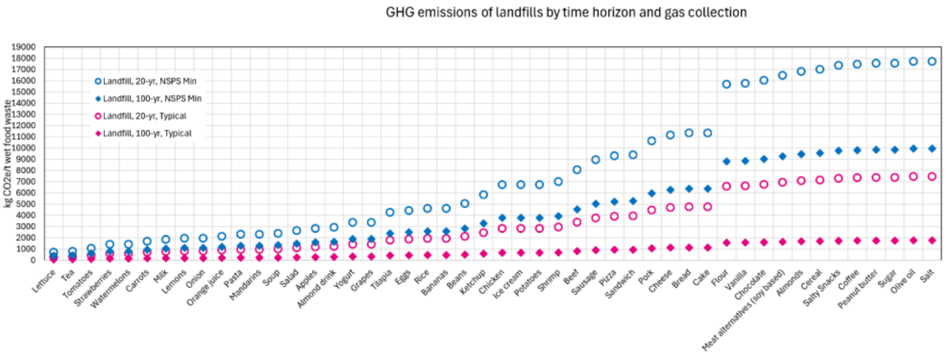

Figure 12: *For landfill, GHG emission factors based on unit mass of dry matter in food waste across 100-yr and 20-yr time horizons under EPA Typical and NSPS Minimum collection schedules (averaged across three climate regions and three gas treatment scenarios)*

Commented [80]: for ReFED at end: check that series are coded in a way that's intuitive and that units in axis and figure description are either all wet weight or all dry matter

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