GREENHOUSE GAS EMISSIONS OF FOOD WASTE: METHODOLOGY

Prepared by:

Andrea Corona (Quantis) • **Alexi Ernstoff** (Quantis) • **Carolina Segato** (Quantis) • **Melissa Zgola** (Quantis)

For:

Contact:

Andrea Corona, PhD
Biomaterials expert
Andrea.Corona@quantis-intl.com

Alexi Ernstoff, PhD
Food systems expert
Alexi.Ernstoff@quantis-intl.com

Melissa Zgola
Senior sustainability consultant
Melissa.Zgola@quantis-intl.com

Quantis is a leading sustainability consulting firm specialized in supporting companies to measure, understand and manage the environmental impacts of their products, services and operations. Quantis is a global company with offices in the United States, Switzerland, Germany, France, and Italy. It employs 100 consultants, including internationally renowned experts in life cycle assessment and sustainability quantification.

Quantis offers cutting-edge services in environmental footprinting (multiple indicators including carbon, water and biodiversity), eco-design, sustainable supply chains and marketing claims and communication. Quantis also provides support for innovative and customized IT tools, which enable organizations to evaluate, analyze and manage their environmental footprint with ease. Fueled by its close ties with the scientific community and its strategic research collaborations, Quantis has a strong track record in applying its knowledge and expertise to accompany clients in transforming scientific results into decisions and action plans. More information can be found at www.quantis-intl.com.

PROJECT INFORMATION	
Project title	GREENHOUSE GAS EMISSIONS OF FOOD WASTE
Contracting organization	ReFED
Project team	Andrea Corona, PhD - Sustainability Consultant Alexi Ernstoff, PhD - Sustainability Consultant Carolina Segato - Sustainability Consultant Melissa Zgola - Senior Sustainability Consultant
Client contacts	David Brooks - david.brooks@refed.com Caroline Powell - caroline.powell@refed.com Dana Gunders - dana.gunders@refed.com

Table of Contents

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 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 treatment. LCA is principally 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 inputs of water, energy, and raw materials, and 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, LCIs dataset are taken from the Quantis internal databases. In addition, some inventory flows were calculated manually as there were no database entries.

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 are considered as the indicator of environmental impact of various foods and food losses and wastes. GHG potential is represented based on the International Panel on Climate Change's 100-year global warming potential (IPCC 2013). Substances known to lead to radiative forcing i.e. lead to a net gain of heat energy in the earth's atmosphere are weighted based on an identified global warming potential and expressed in grams of carbon dioxide equivalents ($CO_{2\text{-eq}}$).

1. Overview

ReFED is interested to support scientifically sound decision-making around food loss and waste by making a tool relating food loss and waste to associated greenhouse gas (GHG) emissions. In this methodology document, the term "food waste" is used for any liquid or solid food or beverage that exits the originally intended value chain which was to ultimately provide nourishment for human consumption.

The data available through this tool and described in this methodology document supplement and harmonize with data currently available in the U.S, EPA's WARM database and to be made available through the ReFED Insights Engine calculator for food waste impacts. The main aspects of this tool are that the impacts of food waste are sensitive to:

- **Food types**: Food items have different GHG emissions depending on how and where they are cultivated.
- **Upstream impacts**: Along the value chain of a food item, there are GHG emissions due to the energy consumptions and other processes related to logistics (transport) and storage, as well as processing and preparation. A food waste carries the GHG emissions that were incurred upstream (all the way to the farm) prior to becoming food waste.
- **Destinations**: Food wastes can end up at different destinations (e.g., landfill, animal feed) after they exit the intended value chain, and this influences the associated GHG emissions (or emission avoidance).

As the objective of this tool is to reduce impacts of food waste, the impacts of different material types have not been considered (e.g. if apple peel or apple are wasted) these material types are thereby assumed to carry the same impacts in relation to the food type, life cycle stage, and destination.

A set of representative products were selected to portray common food items available on the US food market (see Table 1).

Table 1: Overview of food categories and food items considered in this study

Food category	Food type
Ready-to-drink beverages	Orange juice
	Tea
Produce	Strawberries
	Mandarins
	Tomatoes
	Grapes
	Potatoes
	Lettuce
	Watermelons
	Mushrooms
	Apples
	Bananas
	Carrots
	Garlic

	Lemons
Frozen	Ice cream
Fresh meat & seafood	Chicken
	Beef
	Pork
	Sausage
	Meat alternatives (soy based)
	Tuna
	Tilapia
Dry goods	Candy (chocolate)
	Coffee
	Cereal
	Salt
	Peanuts
	Ketchup
	Olive oil
	Pasta
	Rice
	Beans
	Flour
	Sugar
	Almonds
	Vanilla
Dairy & eggs	Cheese
	Milk
	Eggs
	Almond drink
	Yogurt
Breads & bakery	Bread
	Cake

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

- Farm
- Manufacturing
- Consumer-facing businesses
- Residential

A set of archetypal destinations (i.e., end-of-life options) were developed representing the available end of life options for food waste in US. The destinations of food loss and waste were selected to align with Food Loss and Waste Accounting and Reporting Standard (https://flwprotocol.org/flw-standard/) and are listed in Table 2.

Table 2 Food waste destinations considered in the study

Destinations
Rescued food (Donations)
Animal feed
Industrial use
Composting
Anaerobic digestion
Not harvested
Sewer
Incineration
Landfill
Land application
Refuse/Discard

2. Upstream Life Cycle Impacts

Upstream life cycle impacts account for the key 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 the various stages of the value chain in order to permit flexibility within the tool to estimate the impact of food waste happening at various stages.

The upstream GHG emissions related to the food waste for each stage the impacts were calculated for 1 kg of product leaving the stage. The value chain stages and the upstream emissions included for each stage considered are shown in Figure 1.

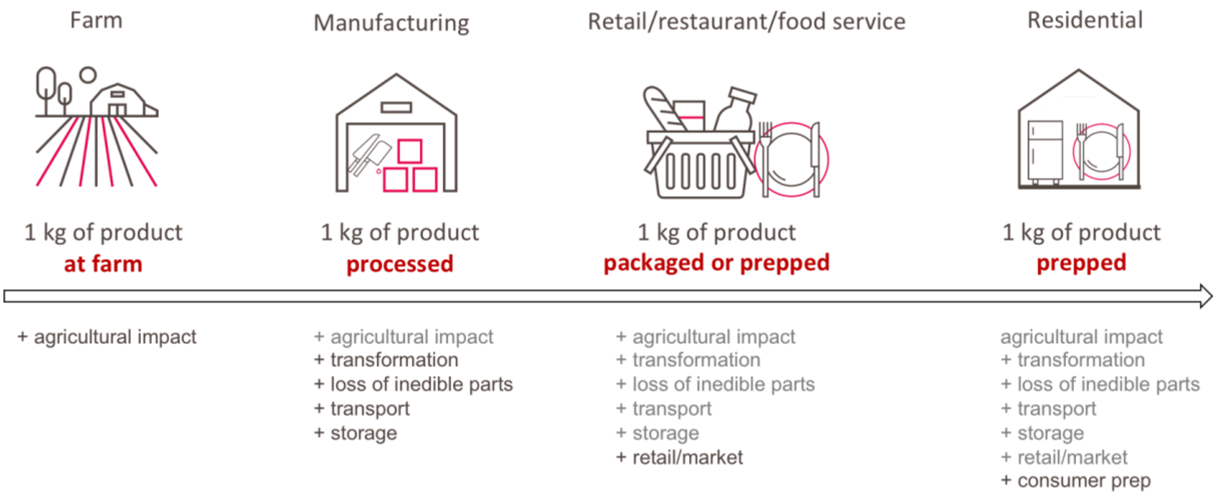

Figure 1: Life cycle stages included in the study. At each life cycle stage (top) the impacts are calculated for a certain mass unit (center). The bottom part of the figure shows the activities whose impacts are calculated at each life cycle stage. Impacts include the cumulative impacts of the upstream stages (in grey) plus the impacts arising at the specific life cycle stage (in black)

2.1. Farm

GHG emissions were calculated based on a series of rules and expert assumptions to best represent US conditions (e.g., food market representation, electricity mix, transport distance). Results represent market mixes sensitive to the country of origin.

Food losses occurring at the farm are allocated the same impact as the product exiting the farm system.

As an example, wasting 1 tonne of strawberries at the farm has equal impact to producing 1 tonne of commercially viable strawberries to be purchased from a farm. The interpretation of this is that if 1 tonne of strawberries is lost at the farm, and demand remains constant, there is 1 tonne of extra strawberries that needs to be produced. Thereby avoiding food losses on the farm would lead to what is referred to as a "source reduction" (US-EPA 2019).

Impacts of agricultural production were considered given 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. 2014).

In order to select which countries of production represent the US market mix, market proportions of imports and domestic production were estimated using the FAO Stat database[1] and the main importing countries were derived from USA Trade online statistics[2]. Specifically, the analysis consisted of the following steps:

1. Domestic production consumed internally: in the FAO Stat, the "Export" category is subtracted from "Domestic production" category. The two categories present the total volumes, in tonnes, per year.
2. Imported: in the FAO Stat the "import" category presents the total volumes, in tonnes, of imported food items per year.
3. Total market: sum of "Domestic production consumed internally" and "import".
4. The US Domestic market share is calculated dividing "Domestic production consumed internally" by Total market" (%).
5. The US Imported market share is calculated dividing "Imported" by Total market" (%).
6. Top import countries: from USA trade online statistics the top import countries and their market share were selected.
7. Market share: for each food item the top three producing countries or those covering at least 75% of the total market were selected.

The list of top three producing countries or those covering at least 75% of the market, were then matched to available data.

1 http://www.fao.org/faostat/en/

2 https://usatrade.census.gov/

2.2. Manufacturing

Food losses at manufacturing are allocated the same impact as that of the product leaving manufacturing, which is equal to the carried upstream impact of agricultural production and the accrued impact up until factory gate.

Manufacturing refers to any kind of transformation or processing that occurs before a food item is ready for a consumer-facing business. The accrued impacts considered in this life cycle stages covers:

- Logistics: transportation from farm to manufacturing (see 2.2.1)
- Manufacturing process: energy and material consumption, processing losses and variation of the water content (see 2.2.2)
- Packaging: material used for packaging the product at the factory gate (see 2.2.3)

2.2.1. Logistics

- If produced domestically, apply a default assumption of 950 miles by truck from farm to distribution center and distribution center to manufacturing site (Dettling et al. 2016).
- If imported, apply a default assumption of 5000 miles by sea and 950 miles by truck (Dettling et al. 2016).

2.2.2. Manufacturing process

When LCI datasets for a manufactured product (e.g., bread) are available in the LCA databases this dataset is applied. The dataset is then adapted to better represent the US conditions in terms of electricity mix (using the US low voltage grid mix) and transportation distances of the food items.

Additionally, a series of processing datasets were included to allow the user to have a higher flexibility in representing the manufacturing process. The manufacturing dataset made available are:

- Freezing
- Canning
- Boiling
- Baking

These dataset are taken from the Agribalyse database (Colomb et al. 2015) and adapted to US conditions (by modifying the electricity mix and transportation distances).

When there is no dataset available for a specific manufacturing process the user can select a “generic” dataset developed with the following assumptions:

- Energy consumption: 1.47 MJ/kg of heat from natural gas and 1.27 kWh of electricity. Estimation based on (Ladha-Sabur et al. 2019).
- Losses: it is assumed a 2%wt losses due to the manufacturing process.
- Water content: it is assumed that the resulting food has 15%wt water content.

2.2.3. Packaging

- Default assumption for canned product: 100 g of steel per kg of packaged food (Colomb et al. 2015).

- Default assumption for frozen product: 100 g of cardboard + 40 g of HDPE per kg of packaged food (JRC, Zampori, and Pant 2019).
- Default assumption for chilled or dry product: 40 g of PE per kg of packaged food (JRC, Zampori, and Pant 2019).

2.3. Consumer-facing business

Food wastes at consumer-facing business are allocated the same impact as that of the food if it were to be sold from the business, which is equal to the carried upstream impact of agricultural production, and manufacturing, as well as the accrued impact after manufacturing.

The accrued impacts considered in this life cycle stage cover:

- 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).

Three datasets are to be developed to cover the various impacts related to distribution and logistics at the consumer-facing business level:

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

The dataset are to be adapted to better represent US conditions in terms of electricity mix (using the US low voltage grid mix). Table 3 presents the grouped food items considered in the study under the three archetypes developed.

Table 3 : Archetypes for the consumer-facing business stage

Food category	Archetype
Ready-to-drink beverages	Dry good
Produce	Chilled good
Frozen	Frozen good
Fresh meat & seafood	Chilled good
Dry goods	Dry good
Dairy & eggs	Chilled good
Candy	Dry good
Breads & bakery	Dry good

2.3.1. Logistics

- 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

- At the distribution center: 4 weeks for dry and frozen goods, 1 day for the chilled goods. Closed refrigeration/freezer storage (Dettling et al. 2016).

- At the consumer-facing business: 4 weeks for dry and frozen goods, 2 weeks for the chilled goods. Open refrigeration/freezer storage (Dettling et al. 2016).

2.4. Residential

Food wastes at residences are allocated the same impact as that of the product when it reaches the home and after preparation, which is equal to the carried upstream impact of agricultural production, manufacturing, consumer-facing business, and the accrued impact up until 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

- Residence to consumer-facing business. Trip done by car, 13 miles round trip (Khan et al. 2019).

2.4.2. Storage

- For dry goods: no impact is assumed (negligible impacts).
- 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

- 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. Destination Impacts

The archetypal destinations were developed to represents as much as possible US conditions. The U.S. EPA WARM tool (US-EPA 2016) was used as a guiding reference to develop the emission factors for destinations. The difference between this tool and the U.S. EPA WARM tool are documented below.

The guiding principles considered here were that the

- transport of food waste to the destination was included in the impact
- the processing of food waste and the infrastructure related to the destination was included in the impact (e.g. fugitive emissions during anaerobic digestion) and the energy and infrastructure
- substitution of another product on the market was included in the impact when relevant
- when relevant, water weight was considered in calculating the destination impact or benefit assuming that the water content in a food waste is the same as the original food item according to the USDA.

Destination impacts consider all GHG emissions arising after a food departs from the originally intended value chain. As an example, if a food is being produced with the intention to sell as a food at a retail center, but leaves the supply chain during manufacturing due to spoilage or any other reason, the "destination" impacts occur with respect to whatever happens after the food leaves the manufacturing stage.

The destinations modeled in this tool were assumed for 100% of the food mass, e.g. if in reality 25% of a food waste intended to go for animal feed is in the end composted, this split in destinations should be calculated by the user. This choice was to avoid ambiguity and accidental double counting when a user enters their food waste destinations.

Depending on the destination there can be impacts due to GHG emission (e.g., transportation of the waste to the treatment site, emissions of methane (CH_4) or dinitrogen monoxide (N_2O) due to the food degradation) and there can also be impact "offsets" due to the waste stream providing some kind of product that can be used to replace another product (e.g. biogas).

Table 4 presents an overview of the considered destinations. The models are described in the paragraphs below.

Table 4 Overview of the destinations included in the project.

Destinations	Source	Impacts	Offset
Food rescue (Donation)	WARM[34]	• Transportation • Storage	• Avoided food production for the recovered food
Animal feed	Custom	• Transportation	• Assumption that protein-rich food wastes can avoid (i.e. replace) feed-quality soy production.

[3] https://www.epa.gov/sites/production/files/2019-06/documents/warm_v15_background.pdf

[4] For this destination a factor has been included when accounting the avoided feed production. The factor takes into account for the percentage of food donated that is suitable for human consumption. The remaining, not suited for human consumption is assumed to be landfilled

			• Assumption that low-protein food wastes can avoid (replace) feed-quality corn production.
Industrial Uses (meat)	Custom	• Transportation • Rendering process energy and infrastructure	• Avoided production of feed (from meat and bone meal production) • Avoided production of biodiesel (from tallow oil) • Avoided production of glycerin (from tallow oil)
Industrial use (plant-based)	Custom	• Transportation • Biomaterials process energy and infrastructure •	• Assumption that protein-rich food wastes can avoid (i.e. replace) soy production. • Assumption that low-protein food wastes can avoid (replace) corn production.
Compost	Adapted WARM[3]	• Infrastructure & operation	• Assumption that application of compost avoids NPK fertilizers • Long-term productivity through prevention of soil degradation
Anaerobic Digestion	WARM[3]	• Transportation to anaerobic digester • Equipment use and biogas leakage at anaerobic digester • CH_4 and N_2O emissions during digestate curing • N_2O emissions from land application of digestate	• Avoided energy production from biogas to energy • Assumption that digestate avoids NPK fertilizers
Not Harvested	Custom	• Full impact of cultivation minus the impact of harvesting.	• Potential fertilizer offset in the following crop cycle.
Sewer	Custom	• At home grinding (sink garbage disposal) • Wastewater treatment	• None
Incineration (Combustion)	Adapted WARM[3]	• Transport to waste to energy (WtE) plant • Combustion-related N_2O emission	• Avoided energy production from energy recovery
Landfill	WARM[3]	• Transportation • Equipment use • Fugitive emissions of CH_4	• Avoided emission due to landfill gas recovered to energy • Landfill carbon storage
Land Application	Custom	• Transportation • Fugitive emissions of CH_4 and N_2O (same as composting)	• Soil carbon storage

3.1. Food rescue (Donation)

The destination of food donation is assumed to be most relevant for food postproduction (e.g. after manufacturing or at retail). This tool estimates the GHG impacts of food waste going to food donation by including impacts of logistical handling of food donation (transport and storage) and avoided upstream impacts assuming to include up to retail.

With a lack of more precise information, the donated food is assumed to avoid demand for the same food (category) that would have been purchased by people receiving the food donation. It is thereby assumed that food donation leads to source reduction of the same food item as well as reduction of the other life cycle impacts (e.g. transport). As a simplifying assumption the impacts of logistics (transport, packaging etc.) of food donation are assumed to be the same as for retail center.

Any avoided downstream impacts, e.g., avoiding landfill or other destinations would have to be compared by the tool user, for example to compare a scenario of food surplus going to donation versus food waste going to landfill.

3.2. Animal feed

The destination of animal feed is assumed only to be possible if the waste occurs along the value chain prior to consumer-facing business. Ready-to-drink beverages, frozen foods, and candies are thereby not valid for the animal feed destination. This tool estimates the GHG impacts of food waste going to animal feed by including the impacts of transportation to the animal feed site and the avoided of impacts of producing animal feed (100 miles by truck).

As protein and energy content are key aspects of determining animal feed proportions, protein and energy content of categories were approximated per food category to determine substitutions. Food waste categories with high protein (>10% by weight, or 10 g of protein per 100 grams of food waste) are assumed to replace soy in proportion to protein, whereas food waste categories with low protein are assumed to replace or corn in proportion to energy (kilocalories). Soy was assumed to have a protein content of 40% or 40 g of protein per 100 grams of soy (wet weight), and corn was assumed to have an energy content of 350 kilocalories per 100 grams of corn (wet weight). The same assumption of feed replacement is applied to all the food items in the same category with the exception of salt which was assumed to replace salt 1:1.

All supporting data for the calculation of the final adjustment factor is in Table 5.

Table 5 Feed replacement for the food categories

Food category	Protein (g protein/ 100 g)	Energy (kcal/ 100 g)	Feed	Replacement ratio food waste: feed	Final adjustment factor
RtD beverages	n/a				
Produce	1	50	Corn	7:1	14%
Frozen	n/a				
Fresh meat & seafood	20	200	Soybean	2:1	50%
Dry goods	10	200	Corn	2:1	50%
Dairy & eggs	20	200	Soybean	2:1	50%
Candy	n/a				
Breads & bakery	10	250	Corn	1:1.5	67%

3.3. Industrial use – meat

The destination of Industrial use - rendering is assumed to only be valid as a possibility before consumer-facing business and only for the food items belonging to the "fresh meat & seafood" category. The same assumptions are to be applied to all the food items in this category

The rendering process produces a protein-rich solid (meat and bone meal) and a fat-rich liquid (tallow oil). Tallow oil is subsequently converted to biodiesel and glycerin in a biodiesel plant.

Modelling details are taken from the GREET model (Han, Elgowainy, and Wang 2013).

The rendering process generates GHG emissions due to:

- Transportation of the food waste to the rendering facilities
- Transportation of the tallow oil to the biodiesel facility
- Rendering and biodiesel processes

The rendering process generates avoided impacts due to:

- Avoided protein-rich feed production. It is assumed that 1 kg of meat and bone meal replaces 1.02 kg of soybean.
- Avoided diesel production and fossil emission for diesel combustion. It is assumed that for 1 kg of biodiesel replaces 1 kg of fossil diesel.
- Avoided glycerin production. 1 kg glycerin by-product of the biodiesel process is assumed to replace 1 kg of conventional glycerin.

3.4. Industrial use – plant-based

The destination of Industrial use – plant-based materials is assumed to only be valid as a possibility before consumer-facing business and only for produce and dry goods. Because there is a variety of industrial options for using food waste there are no assumptions about type of product being created. Market substitution was therefore done at the level of the feedstock where the assumptions were the same as animal feed (see section) with respect to the replacement crop (corn or soy). Salt was an exception, where it was assumed to replace salt with a ration 1:1.

3.1. Compost

The destination of composting was assumed to only be valid as a possibility before consumer-facing business. Ready-to-drink beverages, frozen foods, and candies are thereby not valid for the compost destination. Compost impacts were taken from the WARM tool as **0.022 kgCO2eq/kg of food waste due to compost facility operation and transport** (see Exhibit 1-44 of Version 15 and adjusted to units of kg per kg).

The calculation of fugitive emissions of CH4 and N2O were taken from IPCC 2006 Tier I method from Chapter 1, table 4.1.[5] Specifically, where 10 g CH4/kg dry matter, and 0.6 gN2O/kg dry matter were assumed to be emitted through compost production. The

[5] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

characterization factors from IPCC 2013 AR5 report of 28 kg CO2eq/kg CH4, and 298 kg CO2eq/kg N2O were used, leading to a total of **0.5 CO2eq/kg dry matter food waste due to fugitive emissions**.

To calculate the benefit of replacing fertilizers, the NPK in compost was assumed to directly avoid the production of NPK from ammonium nitrate, diammonium phosphate, and potassium chloride. It was assumed compost from food waste had a composition of 2% N, 1% P205, and 1% K2O per dry matter unit, leading to **the avoided impact of fertilizer with a benefit of -0.2 kgCO2eq/kg dry matter food waste.**

As an additional benefit, applying composts on agricultural lands is one strategy to maintain soil health and prevent land degradation. Degraded land can lead to long term yield reduction. Here we provide an assumption that there is a 25% efficiency loss due to insufficient compost addition over a 100 year period, given 3.5 t of crop/ha/year and 5 t compost/ha/year application this would result in 500 tonnes of crop productivity benefit over 100 years, or 0.175 tonnes of improved productivity /tonne of compost. Given a compost wet weight of 60%, this would lead to a 0.3 kg crop savings/kg of dry weight applied. If one assumes the yield benefit is for a crop like soybean, the end benefit in CO2 savings would be **-0.15 kg CO2eq/kg dry matter benefit due to applying compost.**

The consideration of operation and transport, fugitive emissions, avoided fertilizer emissions, and benefits for degraded land leads to a range of impacts and benefits of compost depending on the water content of the food waste. The total value generally ranges from 0.03 to 0.14 kg CO2eq / kg of food waste that is used as compost. This number is far higher the final number of the WARM tool of -0.2 kg CO2eq/kg compost which is completely dominated by the assumption of -0.27 kg CO2eq/kg compost benefit related to soil carbon storage, however well aligned with the average GHG emission in WARM of -0.07 kg CO2eq/kg compost. Although there is evidence that applying compost combined with other farm management practices (e.g. reduced tillage) can lead to soil carbon storage, this should be calculated on a case-by-case basis, and adjusted for CO2-equivalency (using GWP100) and it is not recommended to add this value to the total carbon footprint by the GHG Protocol or ISO 14040. Thereby, the calculation performed here suggests that there is a GHG emission associated with sending food waste to compost which is consistent with other work (Heller et al. 2019), however we acknowledge that there may be other benefits of compost not captured in relation to nutrient cycling and pest management for example.

As an inorganic food type, sending salt to the compost destination was assumed to carry the impacts of infrastructure, but not any fugitive gas emission, benefits of avoided fertilizer emissions, or long-term yield.

3.1. Anaerobic digestion with energy recovery

The destination of anaerobic digestion was assumed to only be valid as a possibility before consumer-facing business. Ready-to-drink beverages, frozen foods, and candies are thereby not valid for the anaerobic digestion destination. Process energy, avoided utility emissions due to energy production, and avoided fertilizer application due to digestate were taken from the WARM tool as **0.022 kg CO2eq/kg food waste for process energy**. Transport was added as another **0.02 kg CO2eq/kg food waste.**

Adjusting energy production by dry weight (as energy production is correlated to biogas production, which is correlated to carbon content, which is correlated to dry weight) we estimate **-0.26 kg CO2eq/kg dry matter food waste** for avoided utility emissions (assuming 60% dry weight). To calculate the benefit of replacing fertilizers, the NPK in the resulting compost and digestate from anaerobic digestion, was assumed to be conserved from the food waste input and directly avoid production of NPK from ammonium nitrate, diammonium phosphate, and potassium chloride. It was assumed compost from food waste had a composition of 2% N, 1% P205, and 1% K2O per dry matter unit, leading to **the avoided impact of fertilizer with a benefit of -0.2 kgCO2eq/kg dry matter food waste.**

The calculation of fugitive emissions of CH4 and N2O were taken from IPCC 2006 Tier I method from Chapter 1, table 4.1.[6] Specifically, where 2 g CH4/kg dry matter, and 0 (negligible) g N2O/kg dry matter were assumed to be emitted through anaerobic digestion. This leads to a total of **0.056 kg CO2eq/kg dry matter food waste due to fugitive emissions**.

As an inorganic food type, anaerobically digesting salt was assumed to carry the impacts of infrastructure, but not any fugitive gas emission or energy production via CH4.

3.2. Not harvested

The destination of "not harvested" is assumed to only be valid as a possibility at the farming stage and refers to crops that have been cultivated but are not finally harvested (e.g. for market reasons) and are left on the field. The same assumptions are to be applied to all the food categories. With the current data availabilities, it is not feasible within this project to develop a robust approach to calculate the impact of "not harvested" per food categories. Specifically, there are uncertainties related to when in the cultivation process the decision to not-harvest is made (and thus no further agrochemical inputs), what fraction of fields are typically not harvested (e.g. if this is a scaling of yield, or if this is an entire hectare not harvested and thus zero yield), what is the fate of the final crop and residues (e.g. if removed or kept-on-field), and what are the impacts on the application fertilizer and agrochemicals for the next crop cycle. Given these uncertainties – a generic assumption is applied here. The purpose of this generic assumption is not to provide an exact carbon footprint value, but to indicate that not-harvesting can lead to environmental impacts similar to harvested crops – yet without any value added. It is suggested that not-harvesting could likely be equal to the impact of the harvested food item - (minus) the impact of harvesting (fuel and equipment) - (minus) the impact of some fertilizer use for the next year, if resides are kept on field. Given this assumption and the uncertainties previously mentioned, **a simple adjustment is applied such that the impact of not harvested is 75% of the impact of harvested crop.** This factor acknowledges that not harvesting is nearly equal to the impact of harvesting, with some savings.

3.3. Sewer

The destination of Sewer is considered valid for all the supply chain stages. The sewer climate change impact considers the impact of grinding the food waste with an at-home sink garbage disposal. Impacts of grinding were included at any life cycle stage for simplicity. The energy consumption of grinding is assumed to be as 0.2 kWh/kg of dry weight grinded (Bolzonella

[6] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

et al. 2003). Wastewater treatment was estimated to have a total impact of 0.5 kgCO_2-eq per cubic meter of wastewater treated which includes infrastructure and fugitive emissions. No anaerobic digestion or energy recovery was assumed. Each cubic meter of wastewater was assumed to have 0.35 kg of dry mater. No offsets are assumed for this destination. As an inorganic food type, sending salt to the sewer destination was assumed to carry the impacts of infrastructure, but not any fugitive gas emission.

3.1. Incineration / combustion with energy recovery

The destination Incinerated is assumed to be valid for all the supply chain stages and for all organic food types. In order to estimate the impacts or benefits of incineration, the following assumptions were taken into account. Following US EPA WARM tool assumptions, incinerators were assumed to generate energy in the form of heat and electricity (which is not be the case for all incinerators in the US). Emissions from transportation, and fugitive emissions e.g. of N2O were assumed to be 0.055 kg CO2eq/kg food waste as wet weight as from US EPA WARM. Food waste was assumed like other organic wastes to have an intrinsic heat of 15 MJ/kg dry weight, and water requires 2.6 MJ/kg to evaporate. The amount of MJ created for each food item was estimated by the water weight content, where the dry matter multiplied 15 MJ/kg dry weight created, and the water weight multiplied by 2.6 MJ/kg consumed. An efficiency was assumed to be 10% of the energy (MJ) created would go for electricity to the grid, and 20% for thermal energy. As an inorganic food type, combustion of salt was assumed to carry the impacts of the transport, but not the emission or energy production.

3.1. Landfill

The impacts of landfilling were adjusted from US EPA WARM using an assumed dry weight factor. The landfill impacts in US EPA WARM are equal to 0.6 kgCO2eq/kg of food landfilled as wet weight. Adjusting for an assumed water content of 65% for average organic waste sent to landfill, the impacts are 0.9 kgCO2eq/kg of food landfilled as dry weight. This value was then scaled for each food item’s wet weight. As an inorganic food type, landfilling of salt was assumed to carry the impacts of infrastructure and transport, but not any but not any fugitive gas emission.

3.2. Land application

The destination of Land Application is considered valid for all the supply chain stages. Land Application was modeled the same way as composting (it is assumed the same biogeochemical processes occur for both composting and land application), however without the composting infrastructural impacts. (See Compost section).

4. Main findings

The cumulation of this work results in several main findings. First being the greenhouse gas emissions associated with food items across the supply chain as demonstrated in Figure 2. The general trends for these climate impacts are aligned with existing scientific literature showing large emissions related to enteric emissions from cattle, and large emissions for items with associated with land use change (animal feeds, coffee, chocolate). Furthermore, the upstream agricultural production impacts (i.e. listed as farm impacts) are generally dominating the impact of food items, except in cases where the agricultural impact is very small (e.g. due to high yield) and thus the rest of the life cycle becomes important. For some items that cannot be wasted at the farm, e.g. cake, the upstream impacts are embedded in the manufacturing stage.

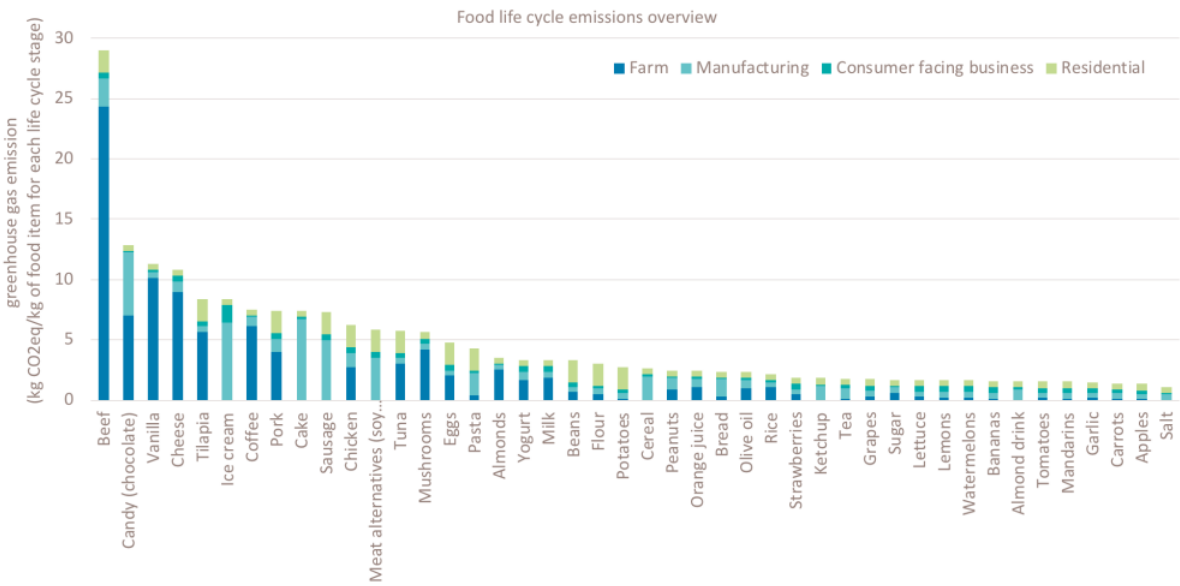

Figure 2. Greenhouse gas emissions overview for food items across the life cycle (not including end-of-life destinations)

Another set of findings is related to the destinations of food wastes. First, when excluding food rescue (donation) generally, for many of the destinations and food items the greenhouse gas emissions and avoided emissions are a function of the percent water weight in a food waste (assumed to be equal to the water weight in the original food). Thereby, food wastes like sugars, cereals, and nuts are particularly interesting to avoid landfill and to valorize through destinations such as industrial use, and incineration and anaerobic digestion with energy recovery. This is because the water content is inversely proportional to the dry matter content in a food item, and the dry matter content for most food items (e.g. apart from salt) contains carbon and nutrients. Water content has generally no value for recovery (given the considered destinations) and leads to impacts related to its transport and processing infrastructure, yet does not lead to increased fugitive emissions e.g. of CH_4 and N_2O. Furthermore, when incinerated, food items with high water content (e.g. beverages, and produce) actually require energy and thereby are less interesting from an environmental perspective to incinerate. The carbon and the nutrients in the dry matter content of food wastes can offer benefits when valorized (e.g.

through incineration or anaerobic digestion with energy recovery). When not valorized, these same components can lead to fugitive emissions of CH4 and N2O when sent to a destination like landfill. This relationship between destinations and water content is visualized in Figure 3. Note that since salt is an inorganic compound, several of the destinations do not lead to impacts through fugitive emissions. Industrial uses offer an interesting option for valorization as well, for example when considering rendering of meat products, or substitution of feedstock for food wastes like cereals and sugars.

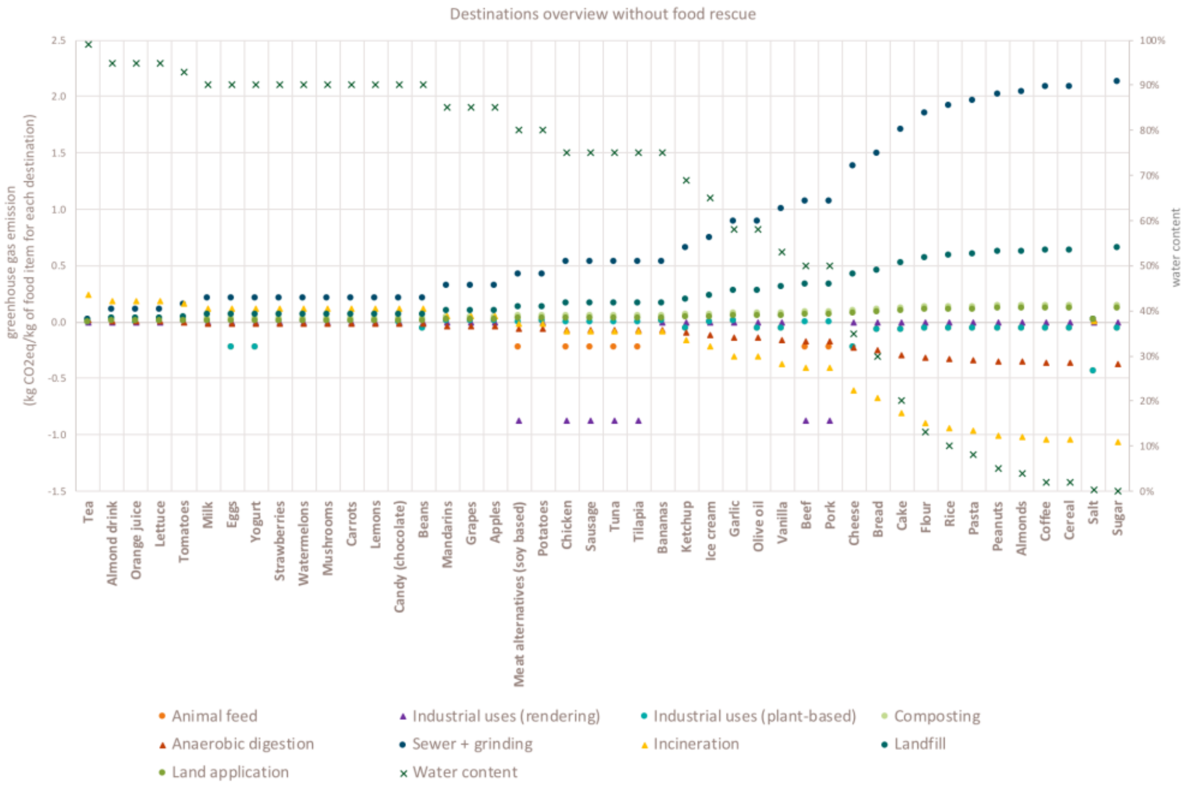

Figure 3 The relationship of the greenhouse gas emissions or avoided emissions (negative values) by various food wastes sent to different destinations, with respect to water content (right axis) of foods as indicated by the “x” symbol. Water content is ranked from greatest to least from left to right.

When considering food rescue as a destination, it offers for most food items by far a larger avoided emission benefit. This is assuming that rescuing food can reduce food source production of the same food item. The largest climate benefit is related to rescuing specialty items like beef, cheese, vanilla, chocolate, and coffee, whereas staples (e.g. cereals, sugar, flour) and then produce (e.g. apples, carrots) offer a smaller climate benefit if rescued (due to lower impacts per kilogram). This finding points to the need to consider multiple indicators when decision making (e.g. to guide what foods are best to rescue) because produce and staples can be more important for nutrition than specialty food items, although specialty items may have other benefits related to wellbeing.

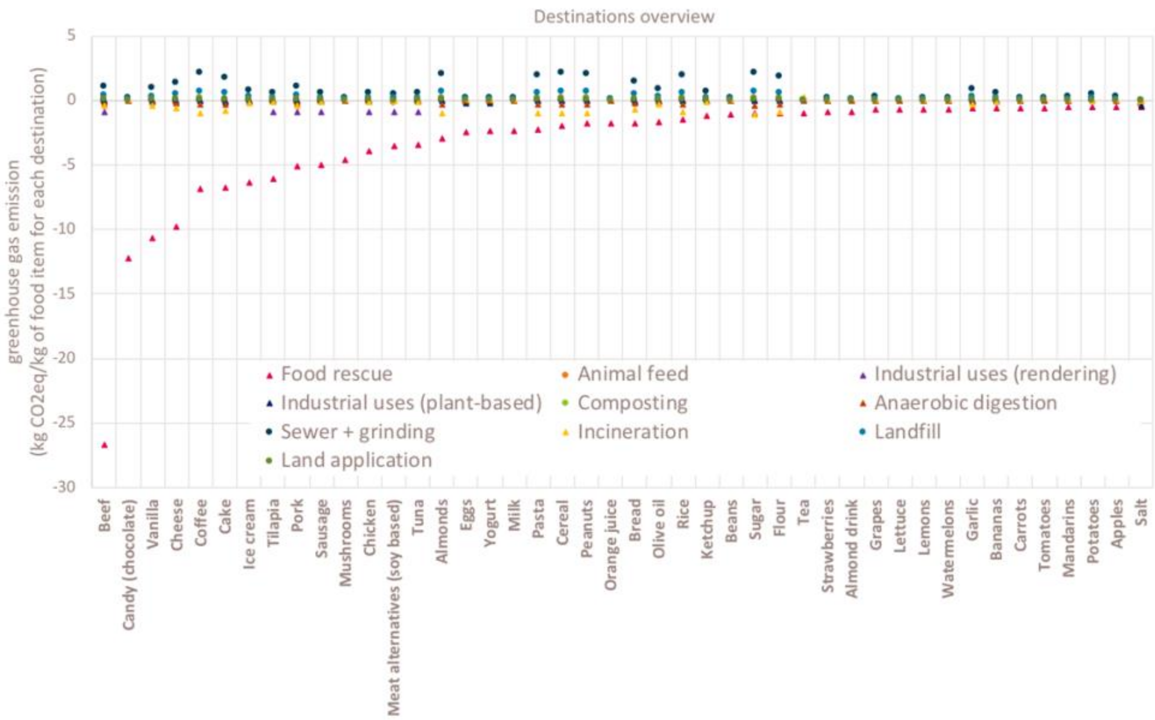

Figure 4. Greenhouse gas emissions or avoided emissions (negative values) caused by various food wastes sent to different destinations, including food rescue (donation).

5. References

Bolzonella, D., F. Cecchi, P. Pavan, and P. Battistoni. 2003. "The under Sink Garbage Grinder: A Friendly Technology for the Environment." Environmental Technology (United Kingdom) 24 (3): 349–59. https://doi.org/10.1080/09593330309385567.

Colomb, Vincent, Samy Amar Ait, Claudine Basset Mens, Armelle Gac, Gérard Gaillard, Peter Koch, Jerome Mousset, Thibault Salou, Aurélie Tailleur, and Hays M.G. Van Der Werf. 2015. "AGRIBALYSE®, the French LCI Database for Agricultural Products: High Quality Data for Producers and Environmental Labelling." OCL - Oilseeds and Fats 22 (1): 8–10. https://doi.org/10.1051/ocl/20140047.

Dettling, Jon, Qingshi Tu, Mireille Faist, Andrea DelDuce, and Sarah Mandlebaum. 2016. "A Comparative Life Cycle Assessment of Plant-Based Foods and Meat Foods. Quantis Report. Https://Www.Morningstarfarms.Com/Content/Dam/Morningstarfarms/Pdf/MSFPlantBasedLCAReport_2016-04-10_Final.Pdf," no. March.

Han, Jeongwoo, Amgad Elgowainy, and Michael Wang. 2013. "Development of Tallow-Based Biodiesel Pathway in GREET." Not Mentioned, no. October: 10.

IPCC. 2013. "Fifth Assessment Report (AR5)." Geneva, Switzerland. 2013. http://www.ipcc.ch/report/ar5/.

JRC, Luca Zampori, and Rana Pant. 2019. "Suggestions for Updating the Product Environmental Footprint (PEF) Method." Luxembourg. https://doi.org/10.2760/424613.

Khan, Sofia, Jon Dettling, Joshua Hester, and Rebekah Moses. 2019. "Comparative Environmental LCA of the Impossible Burger With Conventional Ground Beef Burger." Quantis, 1–64.

Ladha-Sabur, Alia, Serafim Bakalis, Peter J. Fryer, and Estefania Lopez-Quiroga. 2019. "Mapping Energy Consumption in Food Manufacturing." Trends in Food Science and Technology 86 (December 2018): 270–80. https://doi.org/10.1016/j.tifs.2019.02.034.

Nemecek, T., X. Bengoa, J. Lansche, P. Mouron, V. Rossi, and S. Humbert. 2014. "Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 2.0." World Food LCA Database.

US-EPA. 2016. "Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM) Management Practices," no. February.

———. 2019. "Modeling Food Donation Benefits in EPA's Waste Reduction Model (WARM)," 1–7.

Zampori, Luca, and Rana Pant. 2019. "Suggestions for Updating the Product Environmental Footprint (PEF) Method." Eur 29682 En. https://doi.org/10.2760/424613.