FOOD WASTE MANAGEMENT

October 2023

Quantifying Methane Emissions from Landfilled Food Waste

U.S. Environmental Protection Agency
Office of Research and Development

EPA-600-R-23-064

Disclaimer

This document has been reviewed in accordance with U.S. Environmental Protection Agency (EPA) policy and approved for publication.

Authors

Max Krause, U.S. EPA Office of Research and Development, Center for Environmental Solutions and Emergency Response

Shannon Kenny, U.S. EPA Office of Research and Development, Office of Science Advisor, Policy and Engagement

Jenny Stephenson, U.S. EPA Region 9

Amanda Singleton, Eastern Research Group, Inc. (ERG)

Reviewers

EPA would like to thank the following people for their independent peer review of the report:

Debra Reinhart, University of Central Florida
Nickolas Themelis, Columbia University
Nazli Yeşiller, California Polytechnic State University

Acknowledgements

The authors would like to thank Lauren Aepli, Claudia Fabiano, Elizabeth Goodiel, and Susan Thorneloe from EPA, Kameron King and Alexandra Stern from Oak Ridge Institute for Science and Education, Natalie Detwiler from Oak Ridge Associated Universities, and Gordon Coates, Ben Morelli, Sarah Cashman, Andrew Henderson, and John Carter from ERG for their contributions to the report.

This report was prepared with support from ERG under GSA Contract GS-00F-079CA.The external peer review of the report was coordinated by Versar, Inc. under U.S. EPA Contract No. EP-C-17-23.

Cover Photo by Max Krause, with artistic affects applied.

ABBREVIATIONS AND ACRONYMS

Abbreviation or Acronym	Definition
C&D (Debris)	construction and demolition (debris)
CFR	U.S. Code of Federal Regulations
CH_4	methane
CO_2	carbon dioxide
GCCS	gas collection and control system
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
k	methane generation rate constant or waste decay rate
L_0	methane generation potential
LandGEM	Landfill Gas Emission Model
LMOP	Landfill Methane Outreach Program
MSW	municipal solid waste
MMTCO	million metric tons of CO_2-equivalents
$MTCO_2e$	metric tons of CO_2-equivalents
WARM	Waste Reduction Model

EXECUTIVE SUMMARY

Methane emitted from landfills results from the decaying of organic waste over time under anaerobic conditions. Methane is a greenhouse gas (GHG) that affects the earth's temperature and climate system. Because methane is both a powerful GHG and short-lived compared to carbon dioxide, achieving significant reductions would have a rapid and significant effect on reducing GHG emissions.

Most estimates of methane emissions from landfills are calculated based on the biodegradation of municipal solid waste (MSW) as a whole. National estimates of methane emissions from particular components of the organic fraction of MSW, such as food waste, have not been previously quantified by EPA. In the United States, a significant fraction of food waste generated is sent to landfills (U.S. EPA, 2020a). In this analysis, EPA has quantified the methane emissions released into the atmosphere from degrading food waste in MSW landfills in the United States from 1990 to 2020. There is no other peer-reviewed national reference point for the amount of methane emissions attributable to food waste in U.S. MSW landfills.

The analysis relies predominantly on existing, widely-used EPA models and data sources. It models landfill methane emissions based on the following key parameters:

- Total tonnage of landfilled food waste;
- Characteristics of the landfill, such as its operational phase (closed or open), size, cover material, and the climate in which its located;
- Rate at which food waste and other organic materials break down or decay;
- Schedule for installing, expanding, and maintaining operation of landfill gas collection systems after waste is deposited and the portion of methane that is captured through landfill gas collection systems; and
- Portion of methane that oxidizes as it passes through the landfill cover material and is converted into carbon dioxide before going into the atmosphere.

While there is uncertainty in any modeling approach, the results of the analysis indicate:

- In 2020, food waste was responsible for approximately 55 million metric tons of CO_2 equivalents (mmt CO_2e) emissions from U.S. MSW landfills.
- An estimated 58 percent of the fugitive methane emissions (i.e., those released to the atmosphere) from MSW landfills are from landfilled food waste.
- An estimated 61 percent of methane generated by landfilled food waste is not captured by landfill gas collection systems and is released to the atmosphere. Because food waste decays relatively quickly, its emissions often occur before landfill gas collection systems are installed or expanded.
- While total methane emissions from MSW landfills are decreasing due to improvements in landfill gas collection systems, methane emissions from landfilled food waste are increasing.
- For every 1,000 tons (907 metric tons) of food waste landfilled, an estimated 34 metric tons of fugitive methane emissions (838 mmt CO_2e) are released.
- Reducing landfilled food waste by 50 percent in 2015 could have decreased cumulative fugitive landfill methane emissions by approximately 77 million metric tons of CO_2 equivalents (mmt CO_2e) by 2020, compared to business as usual.

As the findings indicate, food waste has an outsized impact on landfill methane emissions due to its relatively quick decay rate. Since fifty percent of the carbon in food waste is degraded to landfill gas within 3.6 years, improving gas collection system efficiency in later years cannot substantially reduce these emissions. Diverting food waste from landfills would be an effective way to reduce methane emissions from MSW landfills.

TABLE OF CONTENTS

Abbreviations and Acronyms ii

Executive Summary iii

List of Figures v

List of Tables v

Introduction 1

Methodology 1

Results & Discussion 9

Implications of Findings 13

Works Cited 14

Appendix A. Percentage of Food Waste in Lanfilled MSW Stream 16

Appendix B. Archetype Landfill Parameters Based on LMOP Database Query 19

Appendix C. Portioning National Tonnage of Landfilled Food Waste amongst the 10 Landfill Archetypes 20

Appendix D. Gas Collection Efficiency Installation and Operation Schedule 23

Appendix E. Modeled Landfilled Food Waste Emission Results 24

LIST OF FIGURES

Figure 1. Factors that influence landfill methane emissions........ 2
Figure 2. Fate of methane generated from landfilled food waste........ 10
Figure 3. Contributions of food waste to methane emissions at MSW landfills........ 11
Figure 4. Amount of landfilled food waste and the methane generated from it........ 12

LIST OF TABLES

Table 1. Decay rates of various organic materials........ 5
Table 2. Landfill gas collection efficiency schedule........ 6
Table 3. 2020 Snapshot: Estimated MSW landfill methane emissions........ 9

INTRODUCTION

Municipal solid waste (MSW), commonly referred to as garbage or trash, is composed of the common materials discarded from residential and commercial sources. Each year, roughly half of the MSW generated in the United States is disposed in landfills (U.S. EPA, 2020a). When organic waste (including food waste) breaks down in anaerobic (i.e., without oxygen) conditions in landfills, methane is produced. MSW landfills are the third-largest source of methane emissions from human activities in the United States, contributing methane emissions equivalent to 94 million metric tons of carbon dioxide (CO_2) in 2020 (U.S. EPA, 2023a).[1] Methane is a greenhouse gas (GHG), which affects the earth's temperature and climate system. Because methane is both a powerful greenhouse gas and short-lived compared to carbon dioxide, achieving significant reductions would have a rapid and significant effect on global warming potential (U.S. EPA, 2022b).

Food waste comprises about 20 percent of MSW disposed of in U.S. landfills. In 2020, approximately 62.5 million tons (56.7 million metric tons) of food waste was disposed of in MSW landfills. To understand the impact food waste has on U.S. landfill GHG emissions, this analysis quantifies the estimated amount of methane emissions released into the atmosphere from degrading food waste in MSW landfills from 1990 to 2020. This is the first time EPA has published modeled estimates of annual methane emissions from landfilled food waste. There is no other known national reference point for the national amount of methane emissions attributable to food waste in MSW landfills. This analysis relied predominantly on existing, widely-used EPA models and data sources.

METHODOLOGY

This analysis begins with the annual national methane emissions from landfills from the Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. EPA, 2022c). These emissions are not directly measured. Instead, the emissions are based on the landfill operators' reported methane generation, collection rates, and oxidized methane, as shown in Equation 1.

$$\text{Emitted} = \text{Generated} - \text{Collected} - \text{Oxidized} \quad \text{(Eq.1)}$$

Modeled methane emissions from landfills are subject to interpretation due to the various parameters that can influence the calculated estimates. The data sources, approaches, and limitations for each of the key parameters are discussed within this document. However, since national estimates of methane emissions are currently based on modeled emissions, this analysis compares the estimates of modeled methane emissions for MSW landfills as a whole with the estimates of modeled methane emissions for landfilled food waste. This provides a basis of comparison to food waste's contributions to emissions from this source category as shown in Equation 2.

$$E_{GHGI} - E_{food} = E_{non\text{-}food} \quad \text{(Eq. 2)}$$

Where E_{GHGi} is the MSW landfill emissions as reported in the Greenhouse Gas Inventory, E_{food} is the landfilled food emissions calculated here, $E_{non\text{-}food}$ is the difference which is attributed to all other biodegradable sources in the landfill.

[1] In 2020, emissions from MSW landfills accounted for approximately 86 percent of total landfill emissions (94.2 MMT CO2 Eq.), while industrial waste landfills accounted for the remainder (15.1 MMT CO2 Eq.). Nationally, there are significantly fewer industrial waste landfills (hundreds) compared to MSW landfills (thousands), which contributes to the lower national estimate of methane emissions for industrial waste landfills. Additionally, the average organic content of waste streams disposed in industrial waste landfills is lower than MSW landfills (U.S. EPA, 2022a).

Key EPA Data Source

Inventory of U.S. Greenhouse Gas (GHG) Emissions and Sinks (U.S. GHG Inventory)

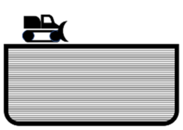
The U.S. GHG Inventory tracks GHG emissions and sinks by source, economic sector, and greenhouse gas, from 1990 to present, releases a report each year. Over time, the methodology for estimating annual landfill methane emissions has evolved. For 1990-2004, the U.S. GHG Inventory currently uses a U.S.-specific first-order decay model following the *2006 IPCC Guidelines* with the tonnages of landfilled estimated from a national total of waste generated (based on states' survey responses) and a national average disposal factor developed by BioCycle in collaboration with Columbia University for *The State of Garbage in America* reports.

With the introduction of EPA's Greenhouse Gas Reporting Program (GHGRP), the U.S. GHG Inventory began a transition, relying on net methane emissions reported by landfills between 2005-2009. Within the GHGRP, MSW landfill operators report modeled annual methane generation and emissions. From 2010 to present, the U.S. GHG Inventory uses net methane emissions as directly reported by landfill operators through the GHGRP, with a scale-up factor to account for emissions from landfills that aren't required to report to the GHGRP.

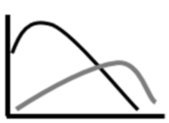
*For more details, refer to the U.S. EPA (2022) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 (EPA 430-R-22-003) and the EPA Greenhouse Gas Reporting Program Subpart HH Information Sheet (2018) https://www.epa.gov/ghgreporting/subpart-hh-information-sheet

Within a landfill, several factors influence the amount of methane that is generated and emitted. These parameters include the:

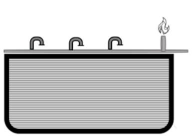
Total tonnage of landfilled material and its composition, particularly the portion that is degradable organic material such as food waste;



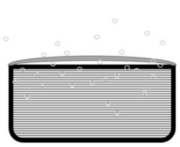
Characteristics of the landfill, such as its size, cover materials, use of system for leachate recirculation, and the climate in which it is located;



Rates at which food waste and other biodegradable (sometimes called organic) materials decompose (break down or decay);



The schedule for installing, expanding, and maintaining operation of the landfill gas collection system after waste is deposited, and the portion of methane that is captured through landfill gas collection systems; and



Portion of methane that oxidizes as it passes through the landfill cover material and is converted into carbon dioxide before going into the atmosphere.

Figure 1. Factors that influence landfill methane emissions.

Tonnage of Landfilled Food Waste

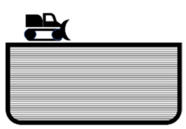
A substantial amount of the food waste generated in the United States is ultimately disposed of in MSW landfills. Because MSW landfills typically receive co-mingled wastes, landfills often do not have the ability to track the tonnage of incoming food waste specifically, and the annual estimates of food waste disposed at landfills vary depending on the method used (Kibler et al., 2018; Thyberg et al., 2015). The waste tonnage inputs into the modeling for methane generation significantly impact the results. *Appendix A* compares two approaches for estimating tonnages of landfilled food waste. The first is EPA's Advancing Sustainable Materials Management Facts and Figures reports. The second is EPA's Greenhouse Gas Reporting Program (GHGRP). Facts and Figures uses information from trade associations and economic data to estimate food production, use, loss, and waste. GHGRP is reporting program whereby landfill operators submit information regarding tons of landfilled waste disposed annually. Figure A1 displays the different estimates by year.

For the tonnage of landfilled food waste, this analysis uses data from the EPA Greenhouse Gas Reporting Program (GHGRP) since landfills are required to directly report bulk waste data annually, and these data are certified and confirmed using a multi-step verification process. Some landfills do not meet the threshold for GHGRP requirements and others phase out of reporting requirements over time. This analysis did not apply a scale-up adjustment factor to account for difference in the landfills that report to GHGRP and the total number of MSW landfills, since it is assumed to be minimal. EPA estimates that the landfills reporting to the GHGRP represent more than 91% of the total emissions from MSW landfills (U.S. EPA, 2023a).

Landfill owners may report detailed tonnages of specific waste categories, such as food waste, but the vast majority do not. Typically landfills track incoming wastes by the weight of trucks bringing in co-mingled wastes. Thus, most landfills report only total waste tonnages, or separate the total out into one of three broad categories – bulk waste (where food waste and other MSW would be categorized), inert waste (such as glass, plastics, metal and concrete), or construction and demolition (C&D) waste (40 CFR 98).

Where food waste reports were available from reporting facilities, they were used in this analysis. For operators reporting in three broad categories, inert and C&D data were removed from the annual disposal rates. For landfills that reported a single bulk waste category, disposal rates were adjusted downward by applying the average percent per year reported to be C&D, inert, or other specific waste streams by reporters that provided data in the three main categories. This modified bulk waste value, excluding any actual or estimated inerts, C&D, or other non-food waste material-specific categories, was used as the basis of annual waste tonnage rates for the analysis.

For GHGRP bulk waste data or modified bulk waste data, the percent of landfilled MSW that was food waste from the EPA Facts and Figures composition of landfilled MSW data was applied to calculate an annual national estimated food waste disposal tonnage. See *Appendix A* for the percent of food waste in each year for 1960 through 2020.



Archetype Landfills

The promulgation of the 1976 Resource Conservation and Recovery Act (RCRA) required operating landfills to have liner systems to prevent groundwater contamination. Clean Air Act amendments further required gas collection systems to mitigate air emissions. As a result, small, town dumpsites closed and larger, regional sanitary landfills have opened. The number of operating landfills in 1988 was 7,924 and in 2020 there were roughly 1,300 operating landfills (U.S. EPA, 2023a; U.S. EPA, 2001). While the total number of landfills decreased substantially, the average size of each landfill remaining in operation has increased as many landfills have transitioned to serve a larger regional area. These larger landfills have larger annual waste acceptance rates, providing the opportunity for larger amounts of waste disposal prior to when the landfill gas collection system may be installed. This timing is especially relevant for food waste disposal because food waste decays more quickly than other types of MSW.

Because landfills were much smaller, the safety concern for explosive methane gas was not well understood, and because the technology was not widely available, very few of the landfills that operated and closed prior to the 1980s installed a gas collection and control system (GCCS).

To reflect the variation in landfill operating practices from 1960 through 2020, ten archetypes for MSW landfills (i.e., 10 “model” landfill types) were created in this study. The parameters for the archetypes included average landfill open and closure years, presence of a gas collection system, and total waste-in-place amounts and were derived from the U.S. EPA Landfill Methane Outreach Program (LMOP) (U.S. EPA, 2021b). *Appendix C* details the landfill parameters of each of the 10 archetype landfills used for this indicator.

The 2,600 landfills in the LMOP database (U.S. EPA, 2021b) were partitioned into this set of 10 archetype landfills to identify the relative fraction of waste disposed across a variety of landfill parameters. Overall, there was robust coverage of landfills in the database with known closure year to develop the models. Nearly 90 percent of the total number of landfills, and 99 percent of the waste-in-place totals in the LMOP database, were reflected by the 10 models. The remaining 10 percent of landfills and less than one percent of waste-in-place totals had an unknown closure year and could not be assigned to one of the models.

The national tonnage of landfilled food waste was then allocated to the 10 archetype landfills. The food waste tonnage was divided proportionally using the total waste-in-place amounts among the landfills that operated each year. For example, if landfills operating in the year 1961 fit under only two of the archetypal landfills, then the national landfilled food waste tonnage was assigned proportionally among only those two archetypes. However, if landfills operating in 1982 resembled eight of the 10 archetypes, then the national landfilled food waste tonnage was divided proportionally among those eight archetypes. Since 1980, the majority of food waste has gone to landfills with landfill gas capture systems and was modeled as such. *Appendix C* details how the national food waste disposal quantities were assigned to each of the 10 landfill archetypes.

Key EPA Data Source

Landfill and Landfill Gas Energy Database (LMOP Database)

EPA’s Landfill and Landfill Gas Energy Database (LMOP Database) tracks key data for MSW landfills in the United States, including information about landfill gas energy projects. The database contains information about more than 2,600 closed and active MSW landfills. The LMOP Database cross-references the data reported under the GHGRP (40 CFR Part 98) and incorporates a subset of the reported data parameters into its database. It includes the latest GHGRP reporting year data as well as historically reported data to capture landfills that may have stopped reporting. The database is maintained by EPA’s Landfill Methane Outreach Program (LMOP), a voluntary program that works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills.

Food Waste Decay Rate

Methane emitted from landfills is a result of organic waste decaying under anaerobic conditions. Organic waste decays over many years after it is placed in a landfill. Temperature, moisture, pH, and type of organic waste impacts how quickly it decays. Because of this decomposition pattern, the estimated methane emissions in a particular calendar year are the sum of emissions that are generated from waste disposed over a historical time horizon. The emissions estimate for the period of interest (1990-2020) relies on estimated annual food waste disposal rates for the period of 1960 through 2019.

The decay rate is a first order reaction – the higher the rate, the faster the decay. For example, a decay rate of 0.02 means that half of the carbon has been degraded to methane in 34.7 years, whereas a decay rate of 0.2 means that half of the carbon has been degraded in 3.47 years. Organic materials have varying rates of decay, with examples shown in the table below. This analysis used the national average food waste decay rate (k) of 0.19 $year^{-1}$ from EPA’s Waste Reduction Model v15 (WARM) and methane generation potential of 109 m^3/Mg of food waste[2] based on WARM default degradable organic carbon content of food waste category (U.S. EPA, 2020b). These values were input into EPA’s Landfill Gas Emissions Model (LandGEM) to calculate methane generation for each of the 10 archetype landfills.

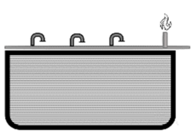
[2] Methane generating potential value of 1.62 $MTCO_2e$/short ton (WARM v15) equates to 109 m^3/Mg which is the required LandGEM input units of measure.

Table 1. Decay rates of various organic materials

Material	Decay rate (yr $^{-1}$)	Number of years over which ½ of the carbon has been degraded to methane
Branches (Yard)	0.02	34.6
Cardboard	0.03	23.1
Copy paper	0.04	17.3
Dimensional lumber	0.11	6.3
Food waste	0.19	3.6
Leaves (Yard)	0.22	3.2
Grass (Yard)	0.39	1.8

Source: EPA WARM v15

The WARM defaults for food waste decay rates (k) and food waste methane generation potential (L_0) serve as a commonly used source of landfill gas modeling parameters for the nation. The decay rates in WARM are based on a study by De la Cruz and Barlaz (2010) which measured component-specific decay rates in laboratory experiments, with a lab-scale decay rate for food waste of 0.3 yr^{-1}. The national average food waste decay rate from WARM of 0.19 yr^{-1} is a weighted average of component-specific decay rates from De la Cruz and Barlaz (2010) based on the share (as determined by EPA expert judgement in 2010) of waste received at four categories of landfills with different moisture scenarios (influenced by annual precipitation and leachate recirculation). The U.S. GHG Inventory uses a modified decay rate for food waste of 0.151 per year. The component specific decay rate from De la Cruz and Barlaz (2010) serves as a starting point for this value but a weighted average based on annual precipitation categories and population residing in each precipitation category is applied (U.S. EPA, 2022c). In reality, the decay rate could vary by landfill according to climate (temperature and precipitation), landfill operations (e.g., are liquids being recirculated or added at the landfill), and the type of food waste landfilled (Jain et al., 2021).



Landfill Gas Collection Systems

Methane collection in any calendar year will depend on a variety of factors, including the operating status of the landfill, whether or not the landfill has a landfill gas collection system installed, and the schedule for installing, expanding, and maintaining operation of the GCCS after waste is deposited.

This analysis estimated the fraction of landfills operating with and without active landfill GCCS based on data reported to EPA LMOP (U.S. EPA, 2021b). The presence or absence of a GCCS was identified and then the total fraction of waste disposed in each of the archetype landfills was determined to allocate the methane generation estimates to different GCCS scenarios. Each analysis assumes that the collection system remains operational in a *given area* of the landfill for a 30-year period. Based on the selected decay rate, at 30 years, food waste will have decomposed 99.6% of the anaerobically degradable carbon to methane and carbon dioxide. Thus, in this scenario, modeling food waste methane generation beyond 30 years is unnecessary.

Table 2. Landfill gas collection efficiency schedule

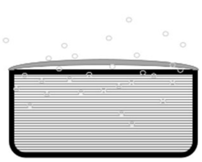
WARM default collection scenario	
Collection Efficiency	Years
0%	0 – 4
50%	5 – 9
75%	10 – 14
82.5%	15 – 20
90%	Final Cover

Source: EPA WARM v15

This analysis uses a phased landfill gas collection schedule with a four-year lag period before a GCCS is installed after waste is deposited, based on when landfills are obligated to install a gas collection system to comply with EPA's New Source Performance Standards (NSPS) and the state and federal plans that implement the EPA Emission Guidelines. These federal rules allow for an initial lag period to install a gas collection system of 30 months after the first nonmethane organic compounds (NMOC) report shows that the emission thresholds in the rule have been triggered. Once the system is installed the rules allow for expansion of the gas collection system at a schedule of every two years if the cell is closed and at final grade and five years for active cells. Based on public feedback and comments received on the proposed NSPS[3], most modern large landfills do not reach final grade within 2 years and a majority of landfills are complying with the 5-year gas collection system expansion provision (40 CFR 60, 2016). Therefore, a 4-year expansion lag time was assumed to represent the baseline.[4] The EPA WARM model assigned collection efficiencies to each phased expansion of the GCCS.

A phased collection accounts for landfill operations in which some part or cells of the landfill may be actively receiving wastes and, over time, more of the landfill is permanently covered. Collection efficiencies can vary widely depending on gas collection system operations and maintenance (Anshassi et al., 2022; Barlaz et al., 2009; Themelis & Bourtsalas, 2021). The schedules and collection efficiencies for gas collection system operations may vary depending on how well the gas collection system is designed and maintained, as well as how quickly an operator decides to install or expand its gas collection system coverage area. Even a well-operated gas collection system may experience periodic shutdowns to address system repairs, so these collection efficiency assumptions are not reflective of constant rates throughout the year. In addition to the operation of the gas collection system, other landfill operating practices such as landfill cover maintenance and removal of immediate cover during gas well installation may decrease the instantaneous gas collection efficiency and increase the release of fugitive emissions (Spokas et al., 2021).

After landfill gas is collected, it is routed to a control device. The control device can be an open or enclosed flare, or in the case of landfills with energy recovery projects the control device could be an engine, boiler, or gas processing equipment for generating electricity or equipment to upgrade the landfill gas into renewable natural gas. Regardless of the control device, the estimated methane destruction efficiency exceeds 99 percent any year where GCCS is anticipated to be operating at a landfill. A destruction efficiency of 99 percent was used for any collected gas based on EPA Best Available Control Technology (BACT) guidance for landfills (U.S. EPA, 2011). *Appendix D* provides a lookup table for landfill gas collection efficiency installation and operation schedule.



Methane Oxidized

Open MSW landfills apply daily cover over the waste actively being disposed of in the landfill. The daily cover materials are typically soils, though some states allow the use of alternative daily cover of green waste, waste derived materials (e.g., shredded tires), biosolids, and contaminated soil (U.S. EPA, 2022a). Intermediate covers are used once the landfill attains a certain height and active disposal will not occur again in that area for an

[3] 79 FR 41796

[4] See 60.765(b) and 60.762(b)(2)(ii) for initial and expansion lag times allowed by the NSPS regulations.

extended period (i.e., months or years). Once the landfill cell has achieved its maximal height and will no longer receive waste, a final cover system consisting of thick earthen materials and geosynthetics designed to minimize infiltration of liquids and soil erosion are placed (40 CFR 258). Each of these types of covers vary in thickness, soil or material type.

Methane that is not collected by the gas collection system moves to the surface of the landfill where it can escape to the atmosphere. Biologically active and well-maintained soil cover systems can oxidize methane to carbon dioxide. The magnitude of bio-conversion from methane to carbon dioxide is a function of soil type and moisture content, the flux or flow of methane, and other daily weather conditions (Chanton et al., 2009; IPCC, 2007; Schuetz et al., 2003; Yeşiller et al., 2022). In US landfill emission models, the oxidation credit is assigned based on the soil type and a simple coefficient ranging from 0-35 percent. The range of oxidation as a percentage of uncollected methane reflects poorly managed or exposed wastes to well-maintained and geo-engineered soil systems.

Unlike gas collection, which would be expected to expand or increase over time, methane oxidation is a function of soil type and landfill management, not necessarily landfill age. Landfills with final covers that include thick clay layers and possibly geomembranes are designed to prevent methane escape, substantially increasing methane collection but reducing methane oxidation. Alternately, intermediate covers can have strong oxidation potential (Barlaz et al., 2009; Chanton et al., 2009). Daily covers, applied in areas of active disposal, are primarily used for vector control (e.g., birds and other wildlife), to prevent food scavenging, and are not intended to oxidize methane. Because soil types are assumed, the modeling applied an oxidation rate of 25 percent for all years. While higher oxidation rates can be achieved, 25 percent was used as an approximate average. *Appendix D* provides a table of the gas collection, oxidation rates, and gas system destruction efficiencies used in the analysis.

Methane Generation

For this analysis, methane generated in years 1990 through 2020 was calculated by the U.S. EPA LandGEM model, which uses a first-order kinetic model of methane production in landfills. The modeling parameters used in the LandGEM model were as follows:

- Tonnage of landfilled food waste. See *Appendix C*.
- Landfill open and closure years – varies depending on parameters for each archetype landfill. See *Appendix C*.
- Food waste decay rate (k) – 0.19 per year based on WARM national weighted average based on moisture content of the landfill receiving the waste (U.S. EPA 2020c).Methane generating potential (L_o) – 109 m^3/Mg of food waste based on WARM default degradable organic carbon content of food waste category (U.S. EPA 2020c).
- Methane content of landfill gas – 50 percent (LandGEM model default). Landfill gas is typically composed of 50 percent methane, 50 percent carbon dioxide and less than 1 percent of nonmethane organic compounds by volume (U.S. EPA, 2005)

The fugitive methane emissions that are released into the atmosphere are calculated by modeling the estimated methane generation rates from the decay of landfilled food waste minus the methane collected and combusted, minus methane emissions oxidized by the landfill surface cover. LandGEM was used, with the parameters specified above, to calculate the estimated methane generation rates from landfilled food waste. The LandGEM model was run for each of the ten

Spotlight on EPA Tools

Landfill Gas Emissions Model (LandGEM)

An excel-based tool is used to estimate emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills. It can be used for determining whether a landfill is subject to the control requirements of federal regulations for MSW landfills laid out by the Clean Air Act. The model can also be used to generate annual and total emissions estimates for use in emissions inventories and air permits.

Waste Reduction Model (WARM)

Based on lifecycle assessment data, this tool provides total lifecycle GHG emissions estimates from different waste management practices, including landfilling.

archetype landfills, reflecting the years of operation and the annual tonnages of food waste disposed of in the landfill, resulting in annual methane generation estimates. Then, for the five archetype landfills that had a gas collection system, the landfill gas collection efficiency schedule, along with the 99 percent destruction efficiency of the landfill gas by combustion, was applied to the annual methane generation values. A methane oxidation rate of 10 percent was applied for all 10 of the archetype landfills. *Appendix F* provides the summed annual methane generation and methane emission estimates from landfilled food waste for 1990 to 2020.

Limitations

The primary sources of uncertainty for this analysis are the derivation of the landfilled food waste tonnages and limitations associated with using a simplified first-order decay model. Because no quantified uncertainty measurements are available for methane from landfilled food waste, the estimates of methane emissions could be higher or lower. Various parameters can influence the model-based estimates, such as variations in decay rate due to temperature and precipitation, the efficacy of gas collection systems, and other landfill maintenance practices such as the presence of a leachate recirculation system (Amini et al., 2012; Amini et al., 2013). Uncertainty in estimated methane emissions could affect conclusions drawn and the relationship between total U.S. GHG emissions and those specifically from landfilled food waste.

Several sources of uncertainty such as the amount of food waste disposed of in landfills each year are expected to be consistent across time and should not affect relative trends in food waste methane emissions. The decay value of food waste, which can vary depending on climate and temperature, can also create uncertainty and variability, although to a lesser extent than the uncertainty over the exact amount of food waste disposed of in landfills each year.

While the LMOP database used to create the representative model landfills is the most comprehensive national database of landfills available, the database focuses on landfills that are active or that have closed since 1990. Data received for inclusion in the LMOP database are reviewed for reasonableness and are corroborated via other data sources when possible. The database is incomplete for landfills closing prior to 1990. However, methane emissions from food waste disposed from these older landfills are not expected to have a significant impact on the methane emissions occurring in the period of 1990-2020 because most of the methane emitted from degrading landfilled food waste occurs within 30 years of its disposal (De la Cruz & Barlaz, 2010).

RESULTS & DISCUSSION

The purpose of this study was to estimate the quantity of methane emissions released into the atmosphere from degrading food waste in MSW landfills nationally from 1990 to 2020, to understand the impact food waste has on landfill methane emissions. The analysis relied predominantly on existing, widely-used EPA models and data sources, such as GHG Inventory, GHG Reporting Program, LMOP database, and the WARM and LandGEM models. See *Appendix E* for a data table of results.

The five main findings of the study are:

❖ *An estimated 58 percent of fugitive methane emissions from MSW landfills are from landfilled food waste.*

Methane emissions from landfilled food waste are a subset of the total methane emissions from MSW landfills. Landfilled food waste is contributing to more methane emissions than other landfilled materials because it degrades more quickly, and this quicker decay can occur before a GCCS is installed or expanded at the landfill.

In 2020, landfilled food waste was responsible for an estimated 58 percent of the total methane emissions from MSW landfills, emitting approximately 55 mmt CO_2e methane emissions based on a 100-year global warming potential (GWP). According to EPA's Greenhouse Gas Equivalency Calculator, this is equivalent to the annual GHG emissions from 15 coal-fired power plants (U.S. EPA, 2023b). See Table 3, below, for detailed information on 2020 landfill methane emissions. Results were also calculated with 20-year GWP, which estimates the energy absorbed by a gas over 20 rather than 100 years, since methane has a much shorter lifetime than carbon dioxide. In 2020, landfilled food waste emitted 180 mmt CO_2e based on a 20-year GWP.

Table 3. 2020 Snapshot: Estimated MSW landfill methane emissions

	Fugitive Methane Emissions			Methane Generation		
Contributions	mmt CO_2e (100 yr GWP)[5]	% Total	mmt CO_2e (20 yr GWP)[6]	mmt CO_2e (100 yr GWP)	% Total	mmt CO_2e (20 yr GWP)
TOTAL	94	100%	309	305	100%	1,000
Food Waste	55	58%	180	89	29%	293
Other Waste	39	42%	129	215	71%	707

Notes: Totals may not sum due to independent rounding. [a]100-year GWP of methane = 25 (consistent with the US GHG Inventory (U.S. EPA, 2022c). [b]20-year GWP of methane = 82 (U.S. EPA, 2023c).

❖ *An estimated 61 percent of methane generated by landfilled food waste avoids collection by landfill gas collection systems and becomes fugitive emissions (i.e., is released to the atmosphere).*

In 2020, an estimated 61 percent of the methane generated from landfilled food waste escaped to the atmosphere before it could be collected or oxidized.

Figure 2 illustrates total methane generated from landfilled food waste, breaking down (1) the amount that is emitted into the atmosphere as fugitive methane emissions (shown in dark blue) and (2) the amount that is captured by the collection system or oxidized by the landfill soil cover (shown in light blue).

[5] 100-year GWP of methane = 25 (consistent with the US GHG Inventory (U.S. EPA, 2022a))

[6] 20-year GWP of methane = 82 (U.S. EPA, 2022d)

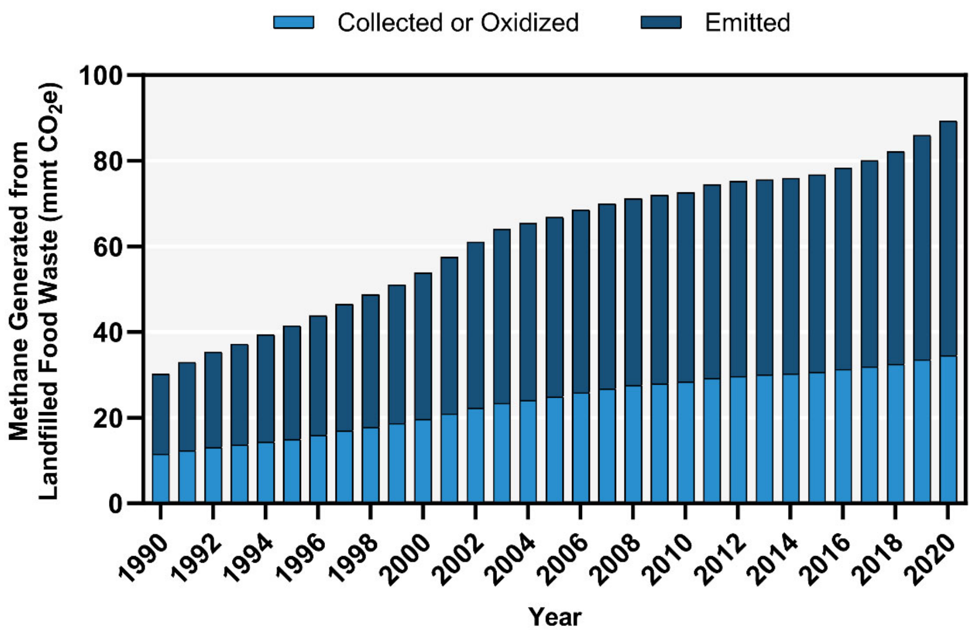


Figure 2. Fate of methane generated from landfilled food waste

❖ *While total emissions from MSW landfills are decreasing, methane emissions from landfilled food waste are increasing.*

As shown in Figure 3, total methane emissions from MSW landfills decreased by 43 percent from 1990 to 2020 as federal and state regulations for gas collection requirements expanded. This has led to improvements in national gas collection efficiencies as more landfills have controlled their emissions, particularly at later points of the landfill lifetime (where gas generation is dominated by paper products and other non-food waste components).

During this same time period, methane emissions from landfilled food waste increased steadily by 295 percent.

This is due to annual increases in the amount of food and all other MSW components being landfilled.

Food waste emissions occur earlier and landfill operators are collecting more gas later in the landfill lifetime. Thus, for materials like biodegradable textiles, paper products, and wood, which degrade more slowly, more of the landfill gas is collected.

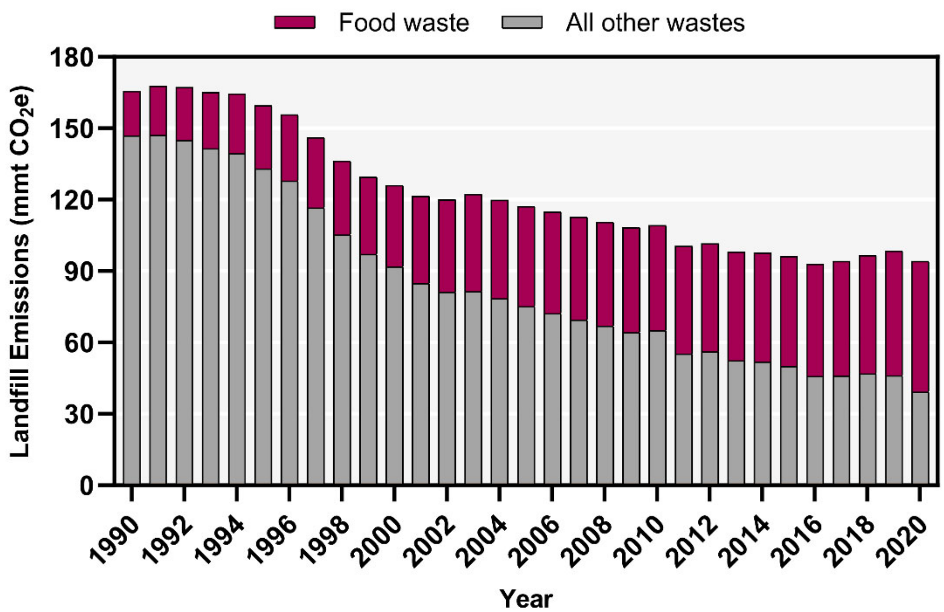


Figure 3. Contributions of food waste to methane emissions at MSW landfills.

❖ ***For every 1,000 tons (907 metric tons) of food waste landfilled, an estimated 34 metric tons of fugitive methane emissions are released.***

Using the modeling parameters as described in the methodology section, along with the same moisture and carbon content for food waste from the U.S. Greenhouse Gas Inventory (U.S. EPA, 2022f) for the carbon storage portion, it is estimated that for every 1,000 tons (907 metric tons) of food waste sent to a landfill, 22 metric tons of carbon originating from food waste remains as carbon stored in the landfill after 30 years, and 34 metric tons is emitted as fugitive methane[7] over a 30-year period after disposal. For every one metric ton of carbon dioxide equivalent ($MTCO_2e$) that is stored, approximately 16 $MTCO_2e$ were released as fugitive methane emissions.

❖ ***Reducing food waste by 50 percent in 2015 could have decreased cumulative fugitive landfill methane emissions by approximately 77 million $MTCO_2e$, compared to business as usual, by 2020.***

The amount of food waste disposed in landfills has steadily increased since 1990, with a corresponding increase in methane generation and emissions. There is increasing focus on preventing wasted food and reducing the amount of it that is disposed in a landfill. While this analysis did not project future tonnages of landfilled food waste and associated emissions, it can be used to examine the effects had landfilled food waste been halved in 2015 and held constant through 2020. The year 2015 was chosen because this is the year the U.S. set the National Food Loss and Food Waste Reduction Goal to halve food waste by 2030.

Based on the approach described earlier, using GHGRP landfill tonnages to derive an amount of food waste landfilled, this analysis estimated that nearly 46 million metric tons of food waste was disposed in landfills in 2015. If the U.S. had halved the amount of food waste to approximately 23 million tons starting in 2015 and held that constant through 2020, approximately 77 mmt CO_2e fewer methane emissions would have been emitted from MSW landfills in the subsequent five years. This emissions reduction is roughly equivalent to the carbon dioxide emissions from 21 coal-fired power plants or 15 million homes' energy use for a year (U.S. EPA, 2023b).

---

[7] Equivalent to 1,307 metric tons of CO_2e, based on GWP of 25 kg CO_2e / kg CH_4, from the IPCC AR4, 100-year time horizon or more than 4,200 $MTCO_2e$ based on a 20-year GWP for methane.

Figure 4 shows tonnage of food waste landfilled and total fugitive methane emissions from landfills each year from 1990 to 2020. The greenline shows the methane emissions based on the amount of food waste landfilled (as reported and derived from the GHGRP tonnages). The yellow line reflects the impact to methane emissions had the amount of landfilled food waste been cut in half in 2015 and held constant (hatch pattern).

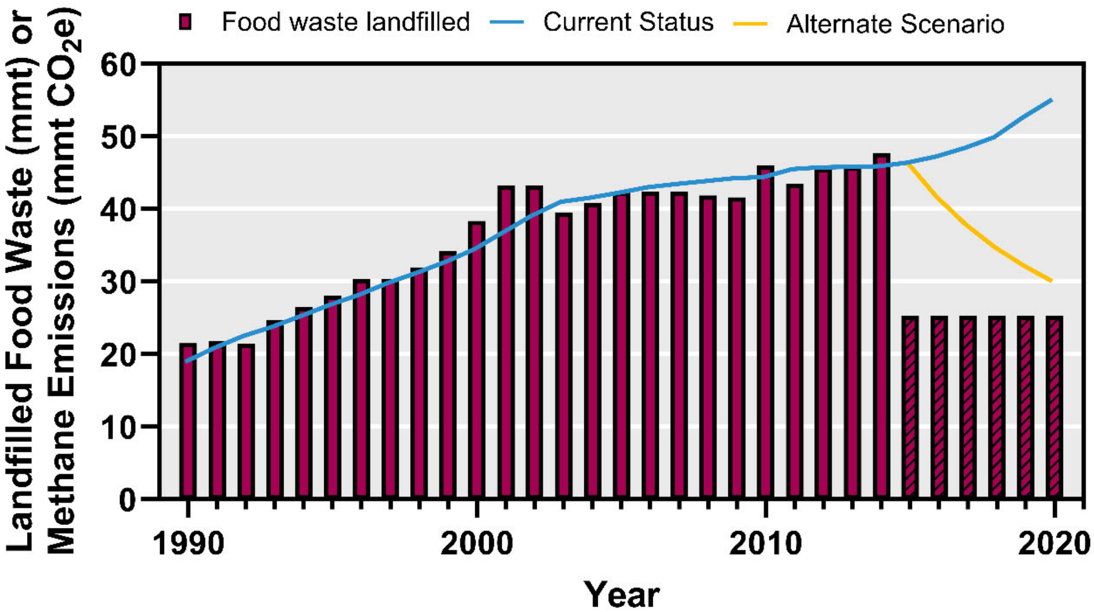


Figure 4. Amount of landfilled food waste and the methane generated from it.

IMPLICATIONS OF FINDINGS

While the potential to reduce methane emissions by reducing landfilled food waste has been well established (Hodge et al., 2016; Levis & Barlaz, 2011), this is EPA's first estimate of annual methane emissions from landfilled food waste in the United States. Because of its relatively fast decay rate, most of the food waste-based methane escapes to the atmosphere before it can be captured with a typical GCCS. Although food waste comprises 24 percent of the MSW stream, it constitutes an estimated 58 percent of annual landfill methane emissions. Thus, it can be reasonably stated that food waste has an outsized impact on landfill methane emissions. Reducing the amount of food waste disposed in landfills would be an effective way to reduce methane emissions from MSW landfills.

MSW landfills are a significant source of methane emissions in the U.S. for which landfilled food waste is a leading contributor. There are management options for food waste other than landfills that are less damaging to the climate. Comparative lifecycle assessment analyses evaluating management pathways for food waste have found that landfills are the least preferable pathway because they have higher greenhouse gas emissions (Morris et al., 2017). Landfilling food waste does not promote a circular economy because it fails to utilize the nutrient value of the food waste.

The most environmentally preferable approach is to prevent food from being wasted (Kibler et al., 2018). More than one-third of the U.S. food supply is not consumed, resulting in a "waste" of resources—including agricultural land, water, pesticides, fertilizers, and energy—and the generation of environmental impacts—including greenhouse gas emissions and climate change, consumption and degradation of freshwater resources, loss of biodiversity and ecosystem services, and degradation of soil quality and air quality (U.S. EPA, 2021a). Given the significant resource inputs (land, water, fertilizer, etc.) used to produce and deliver food to consumers, to then have it go to waste and be disposed in a landfill, generating methane emissions, compounds the environmental impacts of food waste.

WORKS CITED

40 CFR 60. - Subpart Cf - Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills. 2016. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-Cf.

40 CFR 98. - Subpart HH - Municipal Solid Waste Landfills. 2009. Code of Federal Regulations. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98/subpart-HH.

40 CFR 258. - Criteria for Municipal Solid Waste Landfills. 1991. Code of Federal Regulations. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-I/part-258.

Amini, H.R., Reinhart, D.R., Mackie, K.R. 2012. Determination of first-order landfill gas modeling parameters and uncertainties. *Waste Management*, **32**(2), 305-316. 10.1016/j.wasman.2011.09.021

Amini, H.R., Reinhart, D.R., Niskanen, A. 2013. Comparison of first-order-decay modeled and actual field measured municipal solid waste landfill methane data. *Waste Management*, **33**(12), 2720-2728. 10.1016/j.wasman.2013.07.025

Anshassi, M., Smallwood, T., Townsend, T.G. 2022. Life cycle GHG emissions of MSW landfilling versus Incineration: Expected outcomes based on US landfill gas collection regulations. *Waste Management*, **142**, 44-54. https://doi.org/10.1016/j.wasman.2022.01.040

Barlaz, M.A., Chanton, J.P., Green, R.B. 2009. Controls on landfill gas collection efficiency: instantaneous and lifetime performance. *Journal of the Air & Waste Management Association*, **59**(12), 1399-1404.

Chanton, J.P., Powelson, D.K., Green, R.B. 2009. Methane oxidation in landfill cover soils, is a 10% default value reasonable? *Journal of environmental quality*, **38**(2), 654-663.

Cusworth, D.H., Duren, R.M., Thorpe, A.K., Tseng, E., Thompson, D., Guha, A., Newman, S., Foster, K.T., Miller, C.E. 2020. Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations. *Environmental Research Letters*, **15**(5), 054012. 10.1088/1748-9326/ab7b99

De la Cruz, F.B., Barlaz, M.A. 2010. Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data. *Environmental Science & Technology*, **44**(12), 4722-4728. 10.1021/es100240r

Duren, R.M., Thorpe, A.K., Foster, K.T., Rafiq, T., Hopkins, F.M., Yadav, V., Bue, B.D., Thompson, D.R., Conley, S., Colombi, N.K. 2019. California's methane super-emitters. *Nature*, **575**(7781), 180-184.

Hodge, K.L., Levis, J.W., DeCarolis, J.F., Barlaz, M.A. 2016. Systematic Evaluation of Industrial, Commercial, and Institutional Food Waste Management Strategies in the United States. *Environmental Science & Technology*, **50**(16), 8444-8452. 10.1021/acs.est.6b00893

IPCC. 2007. 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 5 Waste. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html. Accessed on: 4/5/2022.

IPCC. 2019. Chapter 3 Solid Waste Disposal. in: *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, (Eds.) E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, Ngarize S., A. Osako, Y. Pyrozhenko, P. Shermanau, S. Federici, IPCC. Switzerland.

Jain, P., Wally, J., Townsend, T.G., Krause, M., Tolaymat, T. 2021. Greenhouse gas reporting data improves understanding of regional climate impact on landfill methane production and collection. *PloS one*, **16**(2), e0246334.

Kaplan, P.O., Decarolis, J., Thorneloe, S. 2009. Is it better to burn or bury waste for clean electricity generation?, ACS Publications.

Kibler, K.M., Reinhart, D., Hawkins, C., Motlagh, A.M., Wright, J. 2018. Food waste and the food-energy-water nexus: A review of food waste management alternatives. *Waste Management*, **74**, 52-62. 10.1016/j.wasman.2018.01.014

Levis, J.W., Barlaz, M.A. 2011. What is the most environmentally beneficial way to treat commercial food waste? *Environmental science & technology*, **45**(17), 7438-7444.

Mønster, J., Kjeldsen, P., Scheutz, C. 2019. Methodologies for measuring fugitive methane emissions from landfills–A review. *Waste Management*, **87**, 835-859.

Morris, J. 2010. Bury or burn North America MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental science & technology*, **44**(20), 7944-7949.

Morris, J. 2017. Recycle, bury, or burn wood waste biomass?: LCA answer depends on carbon accounting, emissions controls, displaced fuels, and impact costs. *Journal of Industrial Ecology*, **21**(4), 844-856.

Morris, J., Brown, S., Cotton, M., Matthews, H.S. 2017. Life-cycle assessment harmonization and soil science ranking results on food-waste management methods. *Environmental science & technology*, **51**(10), 5360-5367.

Schuetz, C., Bogner, J., Chanton, J., Blake, D., Morcet, M., Kjeldsen, P. 2003. Comparative oxidation and net emissions of methane and selected non-methane organic compounds in landfill cover soils. *Environmental science & technology*, **37**(22), 5150-5158.

Spokas, K., Bogner, J., Corcoran, M. 2021. Modeling landfill CH4 emissions: CALMIM international field validation, using CALMIM to simulate management strategies, current and future climate scenarios. *Elem Sci Anth*, **9**(1), 00050.

Themelis, N.J., Bourtsalas, A. 2021. Methane generation and capture of US landfills. *J. Environ. Sci. Eng. A*, **10**, 199-206.

Thyberg, K.L., Tonjes, D.J., Gurevitch, J. 2015. Quantification of Food Waste Disposal in the United States: A Meta-Analysis. *Environmental Science & Technology*, **49**(24), 13946-13953. 10.1021/acs.est.5b03880

U.S. EPA. 2020a. Advancing Sustainable Materials Management: 2018 Tables and Figures. https://www.epa.gov/sites/default/files/2021-01/documents/2018_tables_and_figures_dec_2020_fnl_508.pdf. Accessed on: November 2021.

U.S. EPA. 2011. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills. U.S. EPA.

U.S. EPA. 2022a. Chapter 6: Land Use, Land-use Change, and Forestry. in: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*.

U.S. EPA. 2020b. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM).

U.S. EPA. 2021a. From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste.

U.S. EPA. 2023a. GHGRP Waste Sector Profile. Waste Sector 2021. https://www.epa.gov/ghgreporting/ghgrp-waste-sector-profile. Accessed on: 06/01/2023.

U.S. EPA. 2023b. Greenhouse Gas Equivalencies Calculator. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results. Accessed on:

U.S. EPA. 2022b. Importance of Methane. https://www.epa.gov/gmi/importance-methane

Accessed on: 04/20/2023.

U.S. EPA. 2022c. Inventory of US Greenhouse Gas Emissions and Sinks 1990-2020.

U.S. EPA. 2005. Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide. EPA-600/R-05/047. U.S. EPA.

[dataset] U.S. EPA, Landfill Methane Outreach Program (LMOP) Landfill and LFG Energy Project Database, 2021b.

U.S. EPA. 2001. Municipal Solid Waste in The United States: 1999 Facts and Figures. EPA530-R-01-014.

U.S. EPA. 2023c. Understanding Global Warming Potentials. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials. Accessed on: 7/31/2023.

Yeşiller, N., Hanson, J.L., Manheim, D.C., Newman, S., Guha, A. 2022. Assessment of methane emissions from a California landfill using concurrent experimental, inventory, and modeling approaches. *Waste Management*, **154**, 146-159. https://doi.org/10.1016/j.wasman.2022.09.024

APPENDIX A. PERCENTAGE OF FOOD WASTE IN LANDFILLED MSW STREAM

The EPA Facts and Figures report makes landfilled waste composition data available for most years 1960 through 2018 in its most recent release (U.S. EPA, 2020a). This release provides data for 1960, 1970, 1980, 1990, 2000, 2005, and 2010 through 2018. To provide data for some of the missing years, data were obtained from the 2012, 2013, and 2014, and 2015 versions of the Advancing Sustainable Materials Management: Facts and Figures reports, as well as historical data tables that EPA developed for 1960 through 2018. Remaining years in the time series for which data were not available in Facts and Figures were estimated using linear interpolation matching. The missing values match those that are used in the U.S. Greenhouse Gas Inventory Chapter 6 – Land-Use-Land-Use Change, and Forestry (U.S. EPA, 2022c). Since the Advancing Sustainable Materials Management: Facts and Figures has not been updated since 2018, the percentage of landfilled MSW that is food waste for 2019 and 2020 were set equal to 2018 annual rates.

EPA has two data sets for annual tonnages of landfilled waste. One data set is the tonnages of broad categories of landfilled material as reported by landfills to the EPA GHGRP which was described earlier. The second data set is EPA's Facts and Figures which estimates the tonnages of materials or wastes generated by sectors and how that material is managed (recycled, composted, landfilled, incinerated, etc).

For food waste, the EPA Facts and Figures applies sector specific (i.e., residential, institutional, and commercial) food waste generation factors and information on how the food waste is managed (ex. composted, anaerobically digested, landfilled) to estimate the amount of food waste generated and the portion that is landfilled. EPA estimated wasted food generation from residential, commercial, and institutional sources, using data from sampling studies and industry-specific studies in various parts of the country in combination with demographic data on population and national, industry-specific business statistics. Management pathway estimates (including amount landfilled) relied on various industry-specific studies, as well as facility-reported anaerobic digestion data and state-reported composting data.

The approach used in this analysis of deriving an estimated amount of food waste from modified GHGRP landfilled tonnages compared to the approach employed by Facts and Figures for estimating the amount of landfilled food waste result in significant differences in annual tonnage values as shown in the table and figure A1 below. The GHGRP data inputs are significantly larger than the EPA Facts and Figures in the most recent years. For example, in 2018, the EPA Facts and Figures reports 35 million tons of food waste landfilled (U.S. EPA, 2020a), whereas the amount of landfilled food waste based on the GHGRP data, with the application of the waste composition percentage of food waste comprising 24 percent of the tonnage disposed in MSW landfills, is 58 million tons.

Table A1. Composition of food in landfilled MSW by year 1960-2020.

Year	Overall % food waste in MSW	Source[8]
1960 -1969	14.8%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
1970 -1979	11.3%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
1980 - 1989	9.5%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
1990	13.6%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
1991	14.0%	US GHG Inventory, Chapter 6 working calc file for 1990-2019
1992	13.9%	US GHG Inventory, Chapter 6 working calc file for 1990-2020
1993	14.0%	US GHG Inventory, Chapter 6 working calc file for 1990-2021
1994	14.2%	US GHG Inventory, Chapter 6 working calc file for 1990-2022
1995	15.0%	US GHG Inventory, Chapter 6 working calc file for 1990-2023
1996	16.2%	US GHG Inventory, Chapter 6 working calc file for 1990-2024
1997	15.8%	US GHG Inventory, Chapter 6 working calc file for 1990-2025
1998	15.9%	US GHG Inventory, Chapter 6 working calc file for 1990-2026
1999	15.5%	US GHG Inventory, Chapter 6 working calc file for 1990-2027
2000	17.3%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
2001	17.8%	US GHG Inventory, Chapter 6 working calc file for 1990-2027
2002	17.7%	US GHG Inventory, Chapter 6 working calc file for 1990-2028
2003	18.3%	US GHG Inventory, Chapter 6 working calc file for 1990-2029
2004	18.1%	US GHG Inventory, Chapter 6 working calc file for 1990-2030
2005	18.5%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
2006	18.7%	US GHG Inventory, Chapter 6 working calc file for 1990-2030
2007	19.1%	US GHG Inventory, Chapter 6 working calc file for 1990-2031
2008	19.9%	US GHG Inventory, Chapter 6 working calc file for 1990-2032
2009	21.3%	US GHG Inventory, Chapter 6 working calc file for 1990-2033
2010	21.0%	1990-2018 edg file from Table 4 Materials Landfilled in U.S. MSW Stream
2011	21.3%	
2012	21.0%	
2013	21.0%	
2014	21.7%	
2015	22.0%	
2016	21.9%	
2017	21.8%	
2018	24.1%	
2019	24.1%	same as 2018 percentages
2020	24.1%	same as 2018 percentages

[8] U.S. EPA. Sustainable Materials Management (SMM) - Materials and Waste Management in the United States Key Facts and Figures https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=C9310A59-16D2-4002-B36B-2B0A1C637D4E

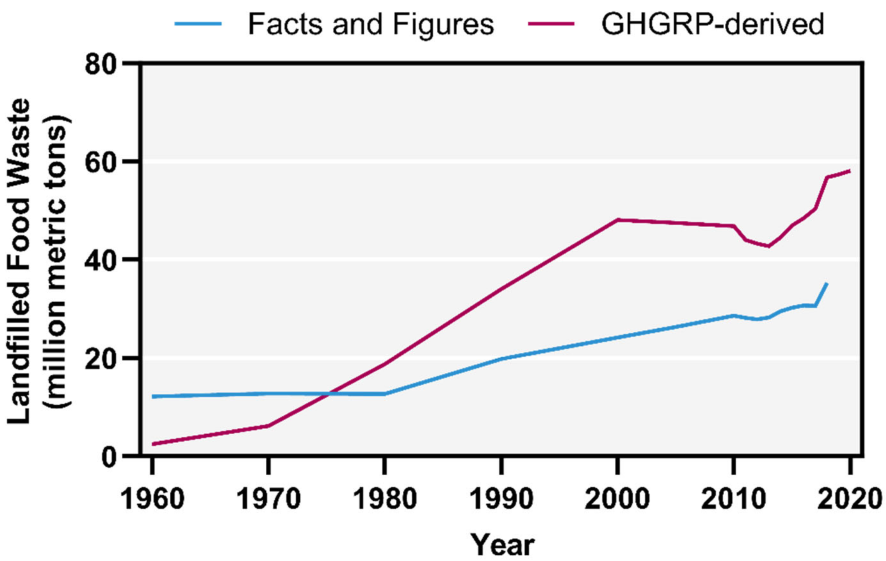


Figure A1. Comparision of estimates of food waste disposed in MSW landfills from Facts & Figures and those reported and derived from GHGRP.

APPENDIX B. ARCHETYPE LANDFILL PARAMETERS BASED ON LMOP DATABASE QUERY

Archetype ID	Criteria	Note	# of Landfills in LMOP database meeting criteria	Avg Landfill Open Year	Avg Landfill Closure Year	Total Waste in Place (short tons)	% of waste in place overall
1	Closure Year <1987, Landfill gas (LFG) Collection System in Place = Yes or Shutdown	1987 is the year RCRA permit program was established	61	1962	1982	265,258,326	2.08%
2	Closure Year <1987, LFG Collection System in Place = No or Unknown		43	1962	1980	51,303,945	0.40%
3	Closure Year >=1987 and <=1996, LFG Collection System in Place = Yes or Shutdown	1996 NSPS federal regulations for gas collection were finalized	191	1967	1992	795,766,476	6.23%
4	Closure Year >=1987 and <=1996, LFG Collection System in Place = No or Unknown		438	1973	1993	325,238,895	2.55%
5	Closure Year >1996 and <=2006, LFG Collection System in Place = Yes or Shutdown	10-year increment	141	1972	2000	719,276,991	5.63%
6	Closure Year >1996 and <=2006, LFG Collection System in Place = No or Unknown		175	1974	2000	113,004,184	0.88%
7	Closure Year >2006 and <=2016, LFG Collection System in Place = Yes or Shutdown	2016 year that NSPS regulations for gas collection were revised	78	1972	2011	626,202,646	4.90%
8	Closure Year >2006 and <=2016, LFG Collection System in Place = No or Unknown		65	1977	2011	51,381,777	0.40%
9	Closure Year >2016, LFG Collection System in Place = Yes or Shutdown	10-year increment	750	1979	2060	9,074,438,867	71.03%
10	Closure Year >2016, LFG Collection System in Place = No or Unknown		412	1983	2067	754,288,284	5.90%
		Total for All 10 Models	2354			12,776,160,391	

APPENDIX C. PORTIONING NATIONAL TONNAGE OF LANDFILLED FOOD WASTE AMONGST THE 10 LANDFILL ARCHETYPES

Year	National Food Waste Landfilled (short tons)	Landfill Archetypes									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
1960	2,240,494	83.8%	16.2%								
1961	2,709,591	83.8%	16.2%								
1962	3,009,831	83.8%	16.2%								
1963	3,295,539	83.8%	16.2%								
1964	3,424,092	83.8%	16.2%								
1965	4,063,917	83.8%	16.2%								
1966	4,272,020	83.8%	16.2%								
1967	4,426,659	23.8%	4.6%	71.5%							
1968	5,191,921	23.8%	4.6%	71.5%							
1969	5,371,402	23.8%	4.6%	71.5%							
1970	4,986,164	23.8%	4.6%	71.5%							
1971	5,506,283	23.8%	4.6%	71.5%							
1972	6,397,592	10.8%	2.1%	32.4%		29.3%		25.5%			
1973	11,998,049	9.5%	1.8%	28.6%	11.7%	25.8%		22.5%			
1974	12,856,725	9.2%	1.8%	27.5%	11.2%	24.8%	3.9%	21.6%			
1975	13,651,479	9.2%	1.8%	27.5%	11.2%	24.8%	3.9%	21.6%			
1976	14,355,937	9.2%	1.8%	27.5%	11.2%	24.8%	3.9%	21.6%			
1977	16,169,821	9.0%	1.7%	27.0%	11.0%	24.4%	3.8%	21.2%	1.7%		
1978	17,217,522	9.0%	1.7%	27.0%	11.0%	24.4%	3.8%	21.2%	1.7%		
1979	17,959,584	2.2%	0.4%	6.6%	2.7%	6.0%	0.9%	5.2%	0.4%	75.5%	
1980	16,125,307	2.2%	0.4%	6.6%	2.7%	6.0%	0.9%	5.2%	0.4%	75.5%	
1981	16,707,403	2.2%		6.6%	2.7%	6.0%	0.9%	5.2%	0.4%	75.8%	
1982	17,123,711	2.2%		6.6%	2.7%	6.0%	0.9%	5.2%	0.4%	75.8%	
1983	17,861,594			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1984	18,371,039			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1985	18,808,725			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%

Year	National Food Waste Landfilled (short tons)	Landfill Archetypes									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
1986	19,139,267			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1987	19,436,502			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1988	19,708,723			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1989	18,926,801			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1990	27,300,277			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1991	27,630,599			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1992	27,161,674			6.4%	2.6%	5.8%	0.9%	5.0%	0.4%	72.8%	6.1%
1993	29,340,098				2.8%	6.2%	1.0%	5.4%	0.4%	77.8%	6.5%
1994	30,541,833					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
1995	32,410,830					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
1996	35,023,203					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
1997	35,022,294					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
1998	36,860,282					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
1999	39,494,975					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
2000	44,288,350					6.3%	1.0%	5.5%	0.5%	80.0%	6.7%
2001	46,250,549							6.0%	0.5%	86.4%	7.2%
2002	46,281,208							6.0%	0.5%	86.4%	7.2%
2003	42,225,256							6.0%	0.5%	86.4%	7.2%
2004	43,638,932							6.0%	0.5%	86.4%	7.2%
2005	45,319,668							6.0%	0.5%	86.4%	7.2%
2006	45,270,279							6.0%	0.5%	86.4%	7.2%
2007	45,313,558							6.0%	0.5%	86.4%	7.2%
2008	44,736,010							6.0%	0.5%	86.4%	7.2%
2009	44,518,482							6.0%	0.5%	86.4%	7.2%
2010	49,233,853							6.0%	0.5%	86.4%	7.2%
2011	46,478,244							6.0%	0.5%	86.4%	7.2%
2012	45,658,443									92.3%	7.7%
2013	45,915,014									92.3%	7.7%
2014	47,705,780									92.3%	7.7%
2015	50,596,724									92.3%	7.7%

Year	National Food Waste Landfilled (short tons)	Landfill Archetypes									
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
2016	52,169,185									92.3%	7.7%
2017	54,420,675									92.3%	7.7%
2018	61,385,991									92.3%	7.7%
2019	62,387,910									92.3%	7.7%
2020	62,479,750									92.3%	7.7%

APPENDIX D. GAS COLLECTION EFFICIENCY INSTALLATION AND OPERATION SCHEDULE

Year From Waste Placement	Collection Efficiency	Destruction Efficiency for Collected Methane	Oxidation Rate*
0	0.0%	N/A	25%
1	0.0%	N/A	25%
2	0.0%	N/A	25%
3	0.0%	N/A	25%
4	0.0%	N/A	25%
5	50.0%	99%	25%
6	50.0%	99%	25%
7	50.0%	99%	25%
8	50.0%	99%	25%
9	50.0%	99%	25%
10	75.0%	99%	25%
11	75.0%	99%	25%
12	75.0%	99%	25%
13	75.0%	99%	25%
14	75.0%	99%	25%
15	82.5%	99%	25%
16	82.5%	99%	25%
17	82.5%	99%	25%
18	82.5%	99%	25%
19	82.5%	99%	25%
20	82.5%	99%	25%
21	90%	99%	25%
22	90%	99%	25%
23	90%	99%	25%
24	90%	99%	25%
25	90%	99%	25%
26	90%	99%	25%
27	90%	99%	25%
28	90%	99%	25%
29	90%	99%	25%
30	90%	99%	25%
31	90%	99%	25%
32	90%	99%	25%
33	90%	99%	25%
34**	90%	99%	25%
35	0%	0%	25%
36 - 139	0%	0%	25%

An oxidation rate of 25% was used for all archetype landfills, even the five archetypes that did not have landfill gas collection systems.

*Allows for 30 years of gas collection in the area it was installed

*Allows for 30 years of gas collection in the area it was installed

APPENDIX E. MODELED LANDFILLED FOOD WASTE EMISSION RESULTS

Year of Emissions	Total Methane Emissions - from Landfilled Food Waste based on GHGRP, WARM collection efficiency scenarios						
	m^3/yr			million metric tons CO2e/yr (GWP of methane = 25)			
	Methane Generation (m3/yr)	Methane Emissions - After Collection and Oxidation (m3/yr)	Methane Emissions - Post Combustion (m3/yr)	Methane Generation	Methane Emissions - After Collection and Oxidation	Methane Emissions - Post Combustion	Total Methane Emissions
1990	1.784E+09	1098640816	3189969.336	30.22	18.61	0.05	18.66
1991	1.948E+09	1212249283	3314126.917	32.99	20.54	0.06	20.59
1992	2.089E+09	1309410917	3431151.867	35.39	22.18	0.06	22.24
1993	2.198E+09	1382725551	3540542.31	37.23	23.42	0.06	23.48
1994	2.325E+09	1471121352	3637858.745	39.39	24.92	0.06	24.98
1995	2.452E+09	1561118824	3701054.27	41.53	26.44	0.06	26.51
1996	2.588E+09	1640815212	4006546.004	43.85	27.79	0.07	27.86
1997	2.747E+09	1739704354	4271602.199	46.53	29.47	0.07	29.54
1998	2.878E+09	1822370380	4478785.191	48.75	30.87	0.08	30.95
1999	3.018E+09	1910053754	4710650.398	51.12	32.36	0.08	32.44
2000	3.179E+09	2012411741	4960498.313	53.86	34.09	0.08	34.17
2001	3.396E+09	2151247476	5274322.65	57.52	36.44	0.09	36.53
2002	3.609E+09	2285379673	5615893.301	61.13	38.71	0.10	38.81
2003	3.785E+09	2396889981	5895819.396	64.12	40.60	0.10	40.70
2004	3.861E+09	2431342273	6195376.487	65.41	41.19	0.10	41.29
2005	3.949E+09	2471255104	6535511.836	66.89	41.86	0.11	41.97
2006	4.05E+09	2513751042	6981199.644	68.60	42.58	0.12	42.70
2007	4.133E+09	2542039934	7432595.892	70.01	43.06	0.13	43.19
2008	4.202E+09	2565958643	7806374.82	71.18	43.47	0.13	43.60
2009	4.249E+09	2586779992	8001612.53	71.98	43.82	0.14	43.95
2010	4.285E+09	2596617810	8223819.444	72.58	43.99	0.14	44.12
2011	4.395E+09	2659862912	8489019.972	74.46	45.06	0.14	45.20
2012	4.439E+09	2675268534	8723268.81	75.20	45.32	0.15	45.47
2013	4.462E+09	2677265048	8918318.013	75.58	45.35	0.15	45.50
2014	4.484E+09	2685329163	9038521.093	75.96	45.49	0.15	45.64
2015	4.534E+09	2714995977	9141267.301	76.81	45.99	0.15	46.15
2016	4.625E+09	2765069960	9386118.828	78.35	46.84	0.16	47.00
2017	4.728E+09	2833168924	9504932.613	80.09	47.99	0.16	48.15
2018	4.852E+09	2920563053	9578536.128	82.19	49.47	0.16	49.64
2019	5.075E+09	3083132546	9641137.704	85.97	52.23	0.16	52.39
2020	5.277E+09	3226428285	9748241.859	89.39	54.65	0.17	54.82

U.S. Environmental Protection Agency
Office of Research and Development